The forming characteristic in the single-point incremental forming of a complex shape

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Abstract: Incremental sheet forming is popularly applied because of its reduced cost, flexibility, and applicability for small batch production. To reduce the manufacturing cost and time consumption, the incremental forming of a complex shape is implemented by combining two forming methods into one process: positive and negative incremental forming. The experiments were done to confirm the applicable ability of the method with the material aluminium Al3004-P. The finite element simulation was done with the ABAQUS explicit finite element code, and its results were compared with the experimental results.

Keywords: single point incremental forming; complex shape; finite element simulation.

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1 Introduction

Incremental sheet forming (ISF) is an innovative process to manufacture sheet metal products by the computer numerical control (CNC) movement of a rounded forming tool (Iseki et al., 1992). Based on the mechanics of forming, ISF is classified into two groups: single-point incremental forming (SPIF) and two-point incremental forming (TPIF). Additionally, SPIF is a negative incremental forming process and TPIF is a positive one.

Potential applications and fundamentals of ISF are comprehensively described in Jeswiet et al. (2005), and the basic components of the process are schematically shown in Figure 1, including the blank, the blank holder, the fixture with the backing plate (beneath the blank), and the forming tool.

In SPIF, the unique contact point is between the tool and the sheet where the tool works on the concave surface of the part. The blank can be fixed, in TPIF the sheet is simultaneously deformed in two points: the tool-sheet contact point and sheet-blank holder contact point. The sheet is clamped around its periphery with a blank holder that moves synchronously with the tool in a vertical direction, and the forming tool moves along a trajectory on the convex surface of the part, from the top to the bottom of the geometry.

Many studies have been done on SPIF in order to understand its deformation mechanics and improve formability as well as part accuracy. The effects of the process parameters-tool type, tool size, feed rate, friction at the interface between the tool and sheet, plane-anisotropy of sheet on the formability have been investigated in experiments and FEM analyses (Kim and Park, 2002). A new theoretical model for the different modes of deformation in SPIF is built upon membrane analysis and ductile damage mechanics (Martins et al., 2008). The influence of tool paths on the work piece quality was done using the FEM coupled with the continuum damage mechanics (CDM) model (Wu et al., 2012). A study was carried out to evaluate the influence of various forming parameters on the local springback in forming components (Singh and Goyal, 2014). A classification-based intelligent process model (IPM) was proposed to predict springback in SPIF (Khan et al., 2015).

Figure 1 (a) Single-point incremental forming (b) Two-point incremental forming

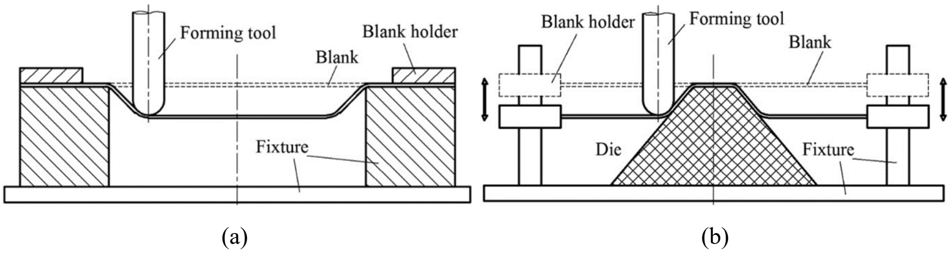
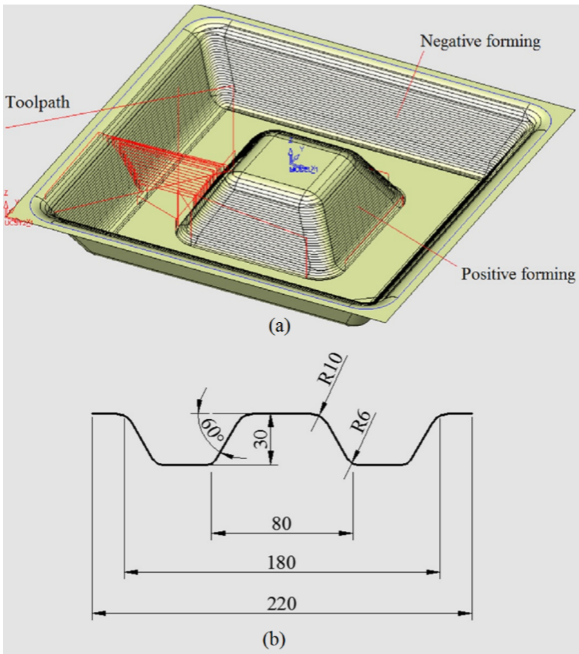


Figure 2 (a) CAD model of a complex die shape (b) Dimension in the symmetric cross section (see online version for colours)



Additionally, most of the published studies about TPIF in recent years have confirmed the improved accuracy and surface quality in comparison with SPIF. Attanasio et al. (2008) investigated tool path optimisation strategies with the objective of improving the overall surface quality and geometric accuracy of an automotive component produced by TPIF. The experimental measurements of the deformation mechanism of SPIF and TPIF through the sheet thickness have been carried out for a truncated cone to verify the stretching and shear in the radial-axial plane (perpendicular to the tool direction) and shear in the tool direction (Jackson and Allwood, 2009). The paper analytically and experimentally investigated and compared the deformation mechanics of SPIF and TPIF. The authors claimed that geometric accuracy of incrementally formed parts produced by TPIF with partial die is better than that of parts fabricated by SPIF due to the smaller elastic recovery upon unloading, and the wall thickness of TPIF parts follow the sine law (Silva and Martins, 2013). The study was the experimental evaluation of the tool path to optimise the dimensional accuracy, the surface quality, and the sheet thinning in TPIF (Attanasio et al., 2006).

In industrial manufacturing, the parts almost all take the form of complex shapes. The manufacturing process needs to be quite flexible and not time-consuming. In previous studies, SPIF and TPIF were separated because they use different types of blank holders. It is impossible to make a complex shape included convex and concave surfaces using one process. This study presents the combination of positive and negative incremental forming into one process in order to reduce the manufacturing time and cost as well as enhance the part accuracy. Figure 2 shows the computer aided design (CAD) model to make the wood die complex in shape. This model was also used to generate the tool location data for incremental forming after compensating for the sheet thickness. The outer valley wall was made by negative forming. The truncated pyramidal shape in the centre was made by positive forming and compared with the same size one made by negative forming.

2 SPIF of a complex shape

2.1 Material properties

The material used in this study is Al3004-P with a thickness of 0.5 mm. The mechanical properties are shown in Figure 3 and Table 1.

Figure 3 The stress-strain curve from the uniaxial tensile test for the flat Al3004-P sheet

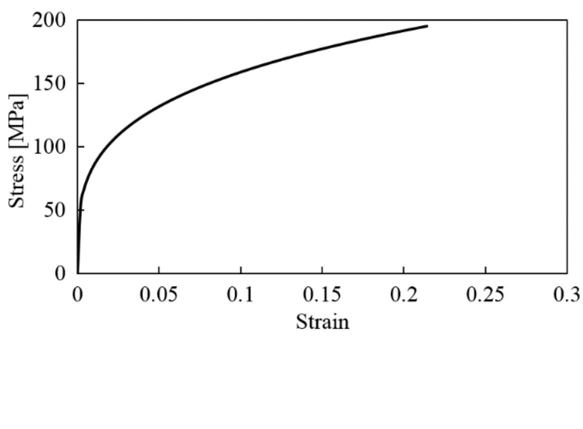


Table 1 Mechanical properties of material Al3004-P

	Flat Al3004-P
σ_Y[MPa]	60.5
σ_{TS}[MPa]	183
E [GPa]	70.0
Strain hardening exponent, n	0.30
Strength coefficient, K [MPa]	312
Elongation [%]	20
Plastic anisotropic coefficient, R	0.59

2.2 Forming limit curve at fracture

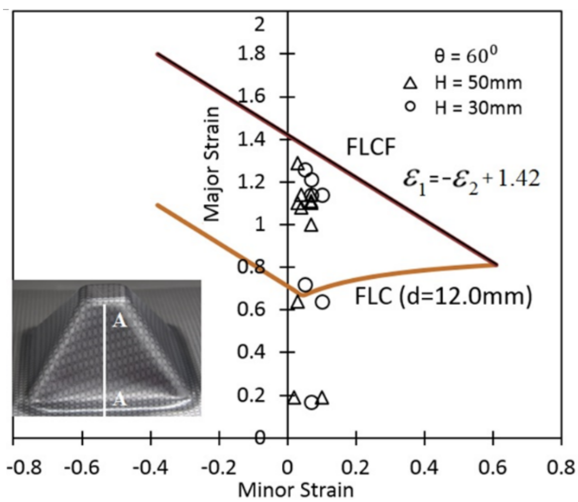
The material deformation under the incremental forming condition is a combination of bending and stretching. Most of the forming limit curve at fracture (FLCF) appears to be a straight line with a negative slope in the positive region of the minor strain. The FLCF was derived using a program developed by the researchers (Nguyen and Kim, 2013; Nguyen et al., 2011.

The forming limit at the fracture is represented by the following equation:

$$\varepsilon_1 = -\varepsilon_2 + 1.42 \tag{1}$$

Figure 4 shows the strain distribution of the truncated pyramid shapes with a forming angle of 60° and different forming depths of 30 mm and 50 mm. A grid with a circle diameter of 2.0 mm was printed on the specimen to analyse the strain. The strain of the deformed grids on the symmetric cross section A-A was measured after forming.

Figure 4 The strain distribution and forming severity evaluated using the FLCF (see online version for colours)



2.3 Comparison of positive and negative forming

In this study, we made the complex shape using positive and negative combined forming with the truncated pyramid in the centre and the same-size pyramid made by negative forming in the reverse direction (Figure 6). All experiments were done with full chemical wood die and the same forming parameters by the CNC machine, as shown in Figure 5.

Figure 5 The CNC milling machine used in this study (see online version for colours)

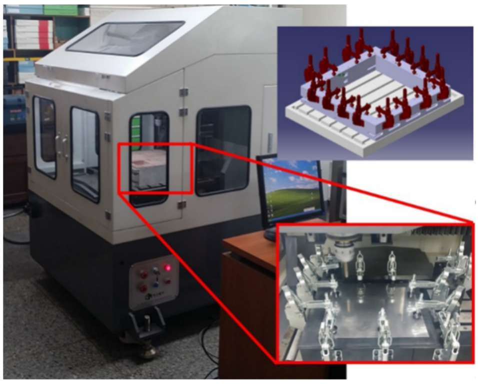
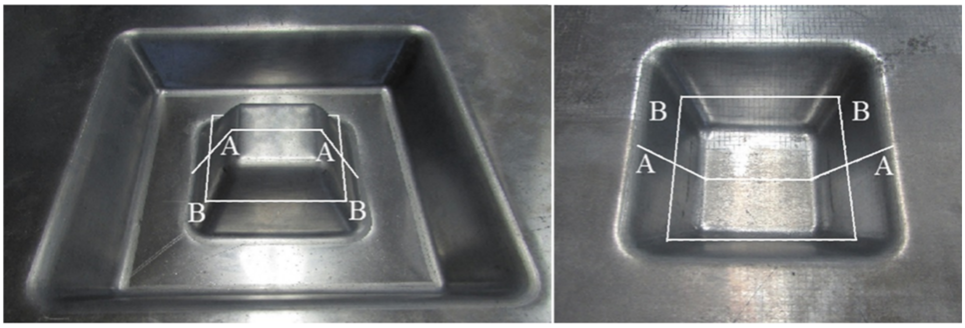


Figure 6 (a) Truncated pyramidal shape made by positive forming (b) Negative forming with cross sections A-A and B-B (see online version for colours)



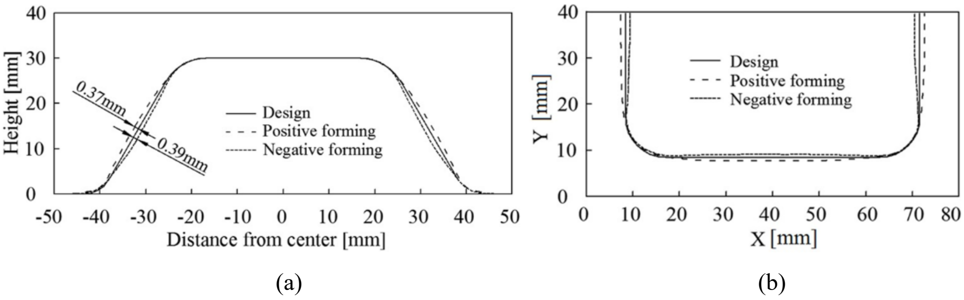
(a) (b)

After making the parts, we compared the accuracy of truncated pyramidal parts made by positive forming and negative forming. Cross section A-A goes through the vertically symmetric surface of the parts, and cross section B-B goes through the horizontally symmetric surface at the forming depth of 15 mm. At the forming depth of 15 mm, the surface deflection (springback) is usually the maximum corresponding to the minimum sheet thickness, and failure also occurs here (Kim et al., 2015b). The surface deflections are measured by coordinate measuring machine (CMM).

Figure 7 shows the surface deflection in the cross sections A-A and B-B. The deflection tendencies for the positive and negative forming parts differ because of the opposite contact side between the tool and the surface. The deflection values are 0.37 mm and 0.39 mm for positive and negative forming compared with the CAD design shape, respectively. The results are largely in agreement with previous findings (Jackson and

Allwood, 2009; Silva and Martins, 2013). In both positive and negative incremental forming, the deformation is a combination of stretching, shear, and pressing on the tool-contacted surface through the thickness of the sheet. Shear also occurs perpendicular to the tool direction in both positive and negative forming, which is more significant in negative forming, causing a piling up of the material at the centre of the forming surface.

Figure 7 (a) Surface deflection (springback) in cross section A-A (b) in cross section B-B



3 Finite element simulation

3.1 Finite element model

In this study, software ABAQUS version 6.14 was used to simulate the SPIF process. This software gives elastic-plastic and rigid-plastic simulations of metal forming for large deformations. The elastic-plastic simulation was used; the material density was 2.7E-9 ton/mm^3; the Young modulus was 70 GPa; the Poisson ratio was 0.3; the stress-strain curve was evaluated by $\sigma = K\varepsilon^n$ with a strength coefficient (K) of 312 MPa and a strain hardening coefficient (n) of 0.3. The ABAQUS explicit finite element code was used with the anisotropic material parameters $r_0 = 0.57$, $r_{45} = 0.59$, and $r_{90} = 0.65$ (Kim et al., 2015a). The simulation results are well adaptive to the experiment results.

Figure 8 Full FEM model for a complex shape (see online version for colours)

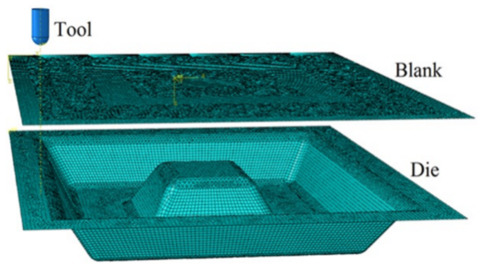


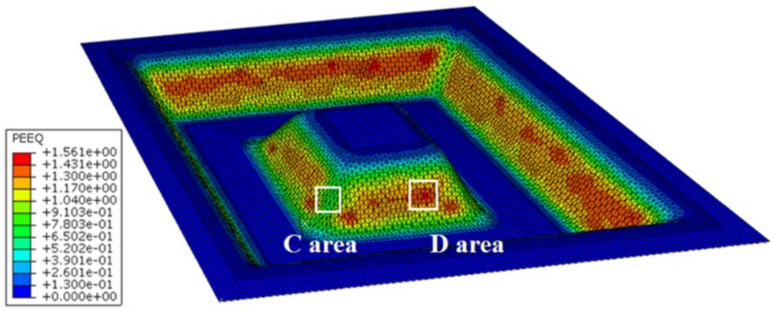
Figure 8 shows the finite element model for the ISF process for a complex shape. The quarter model is known to reduce the simulation time, but it did not ensure accurate results because the symmetry condition is impossible to describe the anisotropic material characteristics and forming mechanism especially the shear perpendicularly to the tool direction. Only the full model can lead to simulation results that correspond well to the experimental conditions.

The tool with a diameter of 12 mm is rigid. The die and holder are rigid and meshed by the R3D4 element. For the non-forming areas of the sheet, the element is a 2 mm quadratic shape, S4R type, and integrated in five points through thickness in Gauss integration. For the forming area, the element is triangular in shape with the same edge size. The friction coefficient between the tool and aluminium sheet is 0.05 and between the sheet and die is 0.15.

3.2 Result and discussion

Figure 9 shows the equivalent plastic strain distribution of the complex shape. At a depth of 15 mm, the equivalent plastic strain has the maximum value. That explains why failure normally occurs at this depth.

Figure 9 Equivalent plastic strain distribution (see online version for colours)



To confirm the accuracy of the simulation, the deflection of the thickness distribution in cross section A-A was measured to compare these data with the experimental data. Figure 10(a) shows the deflection comparison of the truncated pyramid cross section A-A with a difference of 8.18%. Figure 10(b) shows the thickness distribution in which the minimum thickness occurs at the same depth of 15 mm. In addition, the maximum thickness reduction is 56% and 61% for the experiment and simulation, respectively. This value is obviously smaller than the maximum reduction of 75.8% calculated at the major strain of 1.42 in the FLCF. The fracture did not occur at this forming angle.

Figure 10 Compare experiment and simulation for, (a) deflection (b) thickness distribution

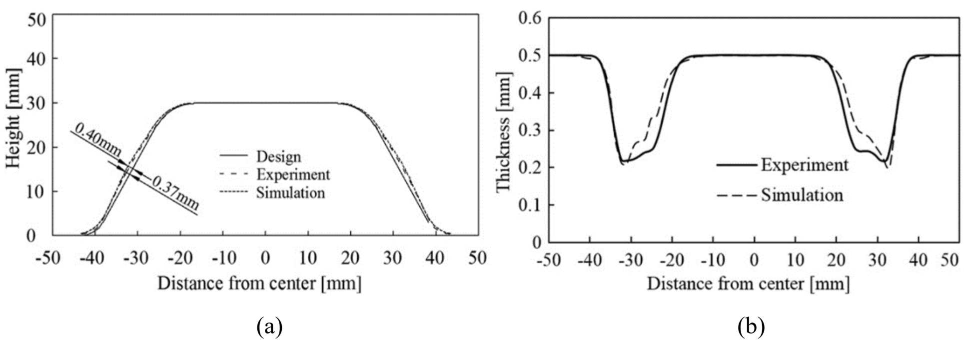
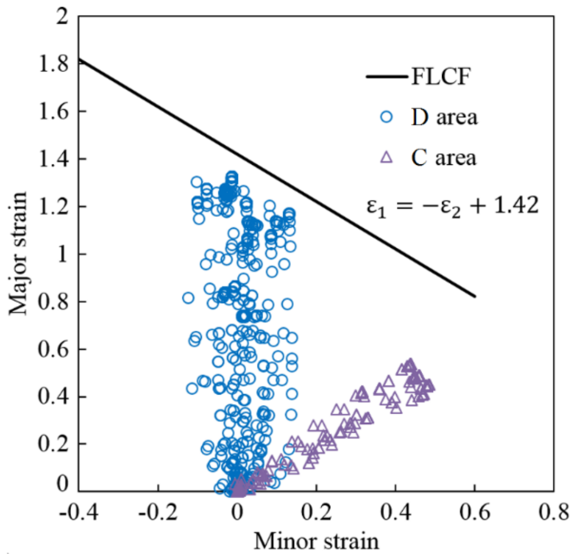


Figure 11 shows the FE simulation results of the evolutions of the strain paths of the blank elements compared with FLCF. In Figure 11, the data of two elements were taken: the first element was taken at the corner (C area) and the second element was taken at the centre of the wall (D area), as indicated in Figure 9. The strain path of the first element is close to the equi-biaxial, and the strain path of the second element is close to the plane strain. Both strain paths are below the FLCF, indicating a safe forming case.

Figure 11 The plastic strain evolution for the elements in comparison with FLCF (see online version for colours)



4 Conclusions

ISF combining positive and negative forming into one process to make a complex shape was done via an experiment and FEM simulation. The forming characteristics for the truncated pyramidal shape with Al3004-P material are similar to those obtained from separate processes. This can be effectively applied in manufacturing complex shapes in the car industry that typically include convex and concave surfaces.

To further expand upon and validate these results, further research with non-standard complex shapes and high-strength steel material such as automotive body parts should be done with the springback compensation.

The springback compensation strategy is implemented through repeated CAD model modification. After the first trial part is made by incremental forming, the cloud data of measured points are taken by a CMM. The springback value could be obtained in comparison with the corresponding data of the CAD model. According to these deviation values, the new geometric model based on the reverse design of a portion of these points is imported in the computer-aided manufacturing (CAM) program. In addition, the revised tool path could be generated by CAM programming to make the corrected part.

This correction procedure can be applied several times until a specified springback value is met.

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