Analysis of Anisotropic Effects in Single Point Incremental Forming

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Abstract. Incremental Sheet Forming (ISF) has great potential to form complex sheet metal parts without using component specific tooling. Formability in ISF process is higher than the conventional forming processes but achieving good geometrical accuracy is a challenging task. Anisotropy of material causes variation of thickness with respect to rolling direction, which affects stiffness, spring-back and accuracy. Variation of thickness and spring-back with rolling direction is studied using experimental and numerical analysis for a conical geometry formed using extra deep drawing steel having high anisotropy. Comparison of anisotropy and isotropy is done using numerical analysis. Results showed that, thickness is low in the direction with low ratio of width to thickness strain (r-value), resulting in higher spring-back. This directional property has to be considered in tool path design to enhance the accuracy. When material is assumed to be isotropic, variation of thickness and spring-back with respect to direction is insignificant.

1. Introduction
Incremental Sheet Forming (ISF) is gaining importance because of its flexibility to form complex geometries without part specific tools/dies. In ISF, sheet metal is clamped in a fixture with an opening and simple tools are programmed to move in pre-defined paths giving shape to the sheet by progressively deforming in small regions. Review articles by Jeswiet et al. [1], Cao et al. [2], Emmens et al. [3], Reddy et al. [4], Behera et al. [5] have summarized the advantages and challenges of ISF. Advantages of ISF over conventional sheet metal forming processes are high formability, less lead time, low forming forces, flexibility to form complex shapes using simple tools. Whereas, the challenge is to form components with good accuracy, surface finish and favorable mechanical and metallurgical properties. Single Point Incremental Forming (SPIF), Two Point Incremental Forming (TPIF) and Double Sided Incremental Forming (DSIF) are the different variants of ISF. SPIF uses one hemi-spherical tool to form the component and does not have any support from other side of sheet. Hence, the parts formed using SPIF have high deviation from desired geometry at component opening because of bending due to lack of support [6]. TPIF uses partial or full pattern to provide support which enhances the accuracy. However, the flexibility of process gets reduced. DSIF uses two tools, one to form the geometry and the other to provide local support to enhance accuracy. In all these variants, accuracy of component is effected by tool and sheet deflection due to forming forces. Asghar et al. [6] developed an analytical model that predicts and compensates the tool and sheet deflection during SPIF to enhance accuracy. Their model considers the material to be isotropic. Lingam et al. [7]
extended the analytical model of Asghar et al. [6] to DSIF in which bending near component opening region is reduced by providing local support using second tool. The challenge in case of DSIF is to maintain the contact of support tool, which is possible only when the sheet thickness distribution, tool and sheet deflections are predicted accurately [7].

Deformation mechanics of incremental forming is extensively studied both analytically and experimentally. Silva et al. [8] developed analytical model to estimate forming stresses using membrane analysis. They assumed plane strain deformation and the material to be isotropic. Jackson et al. [9] experimentally studied the strain distribution through the thickness for parts formed using SPIF and TPIF processes and compared them with stamping. They concluded that stretching is high in meridional direction (perpendicular to tool movement direction) and shearing is high in circumferential direction (parallel to the tool movement direction) both in SPIF and TPIF. Li et al. [10] investigated the deformation mechanics of SPIF using finite element analysis (FE analysis) of conical geometry, considering the material to be isotropic. They observed that the effective plastic strain increases with increase in forming depth and upper side elements (in contact with tool) and lower side elements (not in contact with tool) have different strain distribution. This difference in strain is mainly due to bending during deformation. They concluded that deformation in ISF is combination of stretching, shearing and bending [10]. Moser et al. [11] attempted explicit FEA of DSIF to find suitable FE analysis parameters to minimize computational time. Thickness and strains predicted using their model are in good agreement with experimental results, whereas forces and geometry have significant deviation.

Palumbo et al. [12] studied the effect of the ratio of tool diameter (D) to incremental depth (Δz) on surface finish and thickness by carrying out FE analysis of car door panel geometry. Note that D/Δz represents the amount of overlap in deformation zone. They concluded that the use of high D/Δz ratio results in good surface finish and uniform thickness. They used anisotropic material properties of Ti6Al4V during FE analysis. However, they did not study the effects of anisotropy.

Seong et al. [13] analyzed the necking phenomenon in SPIF using stress based criterion. They performed FEM of truncated pyramid geometry, formed using aluminium alloy 6022. Material is assumed to yield according to Hill’s 1948 anisotropic yield criterion. They found that the effective strain in middle layer is lower than top and bottom layers. They reported that stress throughout the thickness did not exceed critical stress at the same time. Hence, necking is suppressed and higher forming limits are achieved in incremental forming. Though anisotropic material properties are used in FE analysis, they did not study the effects of anisotropy.

Literature presented above indicates that the existing deflection compensation methodologies [6, 7] do not consider the anisotropy of sheet material. Although there are attempts to consider material anisotropy in FE simulation of incremental forming [12, 13], anisotropic effects are not studied in detail. Initial sheet material used in incremental forming in general has anisotropy leading to non-uniformity in thinning, stresses, strains and spring-back which affects component accuracy. In the present work, effect of anisotropy on thinning, spring-back and geometrical accuracy are studied for a conical geometry.

2. Methodology

To study the effect of anisotropy, effect of other parameters like geometry and clamping conditions have to be minimized. In this regard, the best geometry to study is a cone formed using a sheet clamped along circular boundary. To study anisotropic effects, a conical geometry with wall angle of 60°, component opening diameter of 60 mm, depth of 25 mm is formed using Extra Deep Drawing (EDD) steel sheet of thickness 0.73 mm and 8 mm diameter tool. Sheet is clamped circumferentially at 80 mm diameter to ensure symmetric boundary condition. Spiral tool path with 0.25 mm incremental depth is used to form the components.
Material properties of EDD steel are measured by conducting tensile tests using samples taken along rolling (0°), diagonal (45°) and transverse (90°) directions. Stress vs Strain curve in the three directions is shown in figure 1. Average of the three stress-strain relations is given by $\sigma = 523\epsilon^{0.2211} MPa$. Anisotropic strain ratios (width strain/thickness strain) for EDD are $r_0 = 1.76$, $r_{45} = 1.47$ and $r_{90} = 2.1$ ($r_{45} < r_0 < r_{90}$).

**Experimental procedure:** Conical component is formed using incremental forming machine with two independently controllable tools (one on either side of sheet). In this work, one tool is used to form the component, whereas the second one is used to measure the local spring-back (figure 3).

**Thickness measurement:** Formed component is cut along its rolling (0°), diagonal (45°) and transverse (90°) directions using wire electric discharge machining. Thickness of the component is measured along the cut sections using pointed micrometer having 0.01mm least count. During measurement, normality is maintained between micrometer tips and the component at the measuring point as shown in figure 2.

**Spring-back measurement:** When tool moves from a point $P$ to a diametrically opposite location $Q$, the distance moved by the point $P$ in depth direction is taken as spring-back. Setup for measuring spring back (shown in figure 3) consists of a pointed metal needle placed in the collet and is insulated from the machine as shown in figure 3 (a). A LED bulb connected between needle and component is used to indicate the contact between them. Spring-back at a point is measured on the outer surface of the component as measuring tool can access only the outer surface. Forming tool, moving along spiral path, is stopped at point $P$ (note that the tool is in contact with work piece) and depth at $P'$ is measured (figure 3 (b)). Then tool is moved to diametrically opposite location $Q$. Again tool is stopped at $Q$ and depth at $Q'$ is measured.
During FEA simulation

Figure 4. Material orientation during FEA simulation

Figure 5. Spring-back measuring locations (a) Initial position of points (b) Position of points during deformation

(figure 3 (c)). Spring-back at point $P$ is calculated as:

$$\delta P = P'_Q - P'_P$$

(1)

Numerical simulation: Finite element analysis of SPIF of a conical geometry is carried out using ABAQUS static-implicit analysis. Sheet material is modelled as deformable and the tool is modelled as analytical rigid. Circular sheet with 80 mm diameter, fixed along its boundary, is meshed using four noded shell elements (S4R). Material orientation is selected such that x-axis is parallel to rolling direction and y-axis is parallel to transverse direction as shown in figure 4. Stress-Strain relation in rolling direction ($\sigma$ is parallel to rolling direction and y-axis is parallel to transverse direction as shown in figure 4.) with respect to rolling direction, calculated using following expressions, are used for material properties.

$$R_{11} = 1; \ R_{12} = \sqrt{\frac{3\rho_0(r_0+1)}{(2r_45+1)(r_0+r_90)}} \ R_{22} = \sqrt{\frac{\rho_0(r_0+1)}{r_0(r_0+r_90)}} \ R_{23} = 1; \ R_{33} = \sqrt{\frac{\rho_0(r_0+1)}{(r_0+r_90)}} ; \ R_{13} = 1$$

(2)

For EDD, anisotropic stress ratios are $R_{11} = 1; \ R_{12} = 1.069 ; \ R_{22} = 1.031 ; \ R_{23} = 1; \ R_{33} = 1.226; \ R_{13} = 1$. For isotropy simulation, only stress-strain relation in rolling direction is used. Frictionless contact is assumed between the tool and sheet. Tool path to form the cone is generated using an in-house developed software [14, 15] and is given as input to FEA software in tabular form.

3. Results and discussion

Variation of thickness and spring-back with respect to rolling direction of sheet due to anisotropy is analyzed both experimentally and numerically. Three points on a contour $P_1, P_2, P_3$ (figure 5 (a)) along 0°, 45° and 90° with respect to rolling direction, which are at 23.1 mm radial distance on undeformed sheet, are chosen to study the spring-back history in depth and radial directions. Selected points reached to 10 mm depth on the formed component. Tool moving in spiral path pushes the material (close to it) outward in radial direction and downward in depth direction. When the tool moves away from a point spring-back takes place in both depth and radial directions. Figure 6 (a), (b) shows the position history of points $P_1, P_2, P_3$ in depth and radial directions. Sudden variation in depth and radial distance corresponds to the time when tool is close to the point being studied. When the points $P_1, P_2, P_3$ are in deformation zone they are continuously pushed outward (tool position 1 to tool position 2 in figure 6 (c), hence their radius increases. As the tool progresses in depth direction, the stiffer fillet created by tool moves away from the selected point (tool position 3 in figure 6 (c)). Hence spring-back takes place in radial direction. It can be observed from figures 6 (a), (b) that the spring-back in both
depth and radial directions is different for \( P_1, P_2, P_3 \) which are along 0°, 45° and 90° directions with respect to rolling direction.

**Effect of anisotropy on thickness:** Thickness distribution is studied along three profiles 0°, 45° and 90° with respect to rolling direction (figure 5 (b)). Comparison of thickness in the wall region of the cone (figure 7 (a)) is shown in figure 7 (b). This region is selected to avoid the effect of bending near component opening. Anisotropic ratios of the material used for forming are in the order of \( R_{45} < R_0 < R_{90} \). This should result in more thinning in 45° direction followed by 0°, 90° directions. The same can be clearly seen in the thickness distribution measured as well as predicted using FEA (\( t_{45} < t_0 < t_{90} \)) (figure 7 (b)). When the material is assumed to be isotropic, predicted thickness along 0°, 45°, 90° direction has maximum difference of 4.3 \( \mu m \). Whereas, considering anisotropy, difference between thickness along 45° and 90° directions is around 30 \( \mu m \), which is 7 times that of isotropy assumption. Thickness in isotropic case is close to the thickness along 0° direction in anisotropy as the stress-strain relation along 0° direction is used in both simulation.

**Effect of anisotropy on spring-back in depth direction:** Tool moving in spiral path moves the sheet material downward in depth direction. When tool moves away from point \( P_1 \) to diametrically opposite point \( Q_1 \), point \( P_1 \) undergoes local spring-back as shown in figure 7 (d). Spring-back of points \( P_1, P_2, P_3 \) at 10 mm and 15 mm depths, obtained experimentally is compared with numerical predictions in figure 7 (e). Here, spring-back of \( P_1, P_2, P_3 \) represents the vertical movement of the points when tool moved from \( P_1 \) to \( Q_1 \), \( P_2 \) to \( Q_2 \) and \( P_3 \) to \( Q_3 \) respectively (figure 5 (b)). In the experimental measurement it is clearly observed that the spring-back of \( P_2 \) is high, which is along 45° direction. Along 45° direction more thinning occurred as anisotropic ratio (\( R_{45} \)) is minimum; resulting in low stiffness and high spring-back. Spring-back in isotropic and anisotropic cases is compared using numerical simulations. At 15 mm depth, difference of spring-back in 0° and 45° directions is 0.2 \( \mu m \) when isotropy is assumed. When anisotropy is considered in predictions difference of spring-back in 0° and 45° directions is 5.2 \( \mu m \), which is 26 times that of isotropy assumption.

**Effect of anisotropy on spring-back in radial direction:** Effect of anisotropy on spring-back in radial direction is analyzed using FE analysis along a contour at a radius of 23.1 mm on un-deformed sheet which reached to the wall region of deformed cone at a depth of 10 mm and does not get affected by the bending at opening region. Radius of contour after completion of deformation is shown in figure 7 (c). It is observed that the radius of contour decreased continuously from 0° direction to 45° direction and then increased up to 90° direction. Radii of contour in 0°, 45°, 90° directions are 23.89 mm, 23.85 mm, 23.91 mm respectively, indicating that the spring-back is in the order of \( 45° < 0° < 90° \) as expected from the order of anisotropic ratios \( R_{45} < R_0 < R_{90} \). When the material is assumed to be isotropic, variation of spring-back in radial direction is less than 5 \( \mu m \). Whereas, when anisotropy is considered, variation of spring-back is 60 \( \mu m \), which is 12 times that of isotropy assumption.
Figure 7. (a) Portion of profile along which thickness distribution is studied (b) Thickness distribution in wall region (c) variation of spring-back in radial direction (d) Local spring-back of node P (e) Variation of spring-back in depth direction at 10 mm and 15 mm depth

4. Conclusion
In the present work, effect of anisotropy on thickness and spring-back during incremental forming is studied by forming a conical geometry. It is observed that higher thinning occurs in the lowest width to thickness strain ratio direction, which results in less stiffness and causes more spring-back. In both depth and radial directions, spring-back is highest in the lowest anisotropic strain ratio direction which causes variation in geometrical accuracy. Comparison of predictions using isotropic and anisotropic material properties showed that there is significant effect of anisotropy on thickness and spring-back during incremental forming. Work is in progress to predict and compensate the effects of anisotropy to enhance the accuracy.

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