The forming tool, primary start position and toolpath angle movement effect on the geometry accuracy "springback", part C

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Abstract. Incremental Forming process, IF is a technology for producing 3D-dimensional complex sheet profiles. The advantages of the process involve simple set tools, fixture and forming tool, shorter time for producing the pattern, and flexibility. While the main limitation of the process is the springback that represent geometry accuracy, the part profile precision limits the difficulty of forming toolpaths, including the wall angle. This work presents the forming toolpaths effect in the IF process. The supporting space and the product base dimension including wall angle is used to study the springback effect through the incremental forming process. Sheet metals Aluminium-A1025 are used for manufacturing the products. The research goals are to comprehend the springback defect behaviour which is affected by the supporting space-toolpath angle and the supporting space-product base ratios. The strain distributions and the thinning percentage of the final product section have been considered and analyzed in detail.

1. Introduction

Incremental Forming, IF is a new innovative, flexible and combination process of machine with computer technology [1]. IF is a high potential forming process for rapid prototype and for small amounts production. The process it does not need a specialized dies (just type of a fixture). Computer Aided Manufacturing, CAM software is used for programing the tool path, editing and submitted to the NC milling machine for accomplishment [2]. IF process assists for producing the complex forms without expensive die sets. Therefore, leads to reduce the time for marketing. The applications of the process, adding of the prototyping are producing the parts for automobiles, biomedical and aerospace industries [3]. The main problems in IF process are the low accuracy in geometrical concave features which involve the irregular thinning distribution, the limited wall angle, and the surface quality.

The forming parameters considered in IF technology are: geometrical shape (flat and curvatures surfaces), material type of the die- tool set, tool geometry, tool path parameters (step size, wall angle and forming speeds (rotation and feed rate), lubrication, sheet thickness before and after forming process. Each parameter is affecting to overall forming and their influences on detected effects.

Forming toolpath: first step the models created by Computer Aided Design CAD for incremental forming, and using commercial software to generate forming toolpath, as a second step. Transition method (step or ramp) are using to create a tool contours and connect it [4]. Each step down and each contour is caused a surface roughness due to the physical indentation on the surface blank [5].
Forming angle: is the angle that resulted from the horizontal xy-plane and the side walls of a part. The range of this angle mainly depends on sheet thickness and material properties. On the other hand, IF profiles are determined by the highest forming angle, $\Psi$. Martins et al. calculated the highest forming angle referring of the forming parameters and material properties as in equation (1) [6].

$$\Psi = \pi/2 - e^{\xi t}$$  

(1)

The equation (1) represents the beginning of fracture, combines the concepts of both the maximum forming wall angle and the fracture forming limit in the principle strain space at the onset of crack. Where, $\xi_t$ is the thickness strain and $t$ is representing the thickness at fracture at the limit of formability. In this equation can be calculated using the through-thickness fracture limit strain $\xi_t$, as resolute of equi-biaxial stretch test or a plane strain.

Depending on the sine law shown in equation (2), impossible to make the right angle walls 90° because of the thickness distribution of the part wall would be equal zero.

$$h = h_0 \sin \left( \frac{\pi}{2} - \alpha \right) = h_0 \sin(\Psi)$$  

(2)

where $h_0$ is the initial thickness, $h$ is the final thickness, and $\alpha$ is the spinning angle.

The toolpath represents the main variables that are select by the designer depending upon, basically the product profile. Therefore, this variable can be modified and controlled to improve the part accuracy. Tool path is also the reason of the surface roughness and springback, and because of the wide range of the forming tool paths, many researches are trying to find relevant strategies to control this variable.

Predict the translation is developed analytically and experimentally validated of the rigid body in both in-to-out (IO) and out-to-in (OI) toolpaths [7]. The incremental forming process proposed a spiral toolpath method with constant scallop height and based on triangular mesh model [8].

A new parameterized forming strategy for the tool path optimization in SPIF was developed [9], in order to reduce the manufacturing time and homogenize thickness distribution of an asymmetric part. An effective tool path generation method, by generating Cutter-Location (CL) data directly from corresponding Cutter-Contact (CC) data, has been developed [10].

FE model of the truncated cone product was performed for a single and double pass forming process and analyzed. In addition, 3D toolpath as a basis of coordinates for building up the boundary condition (displacement and moving tool) was loaded [11]. Incremental process is upgraded by a coupling methodology for correcting the deviations during the toolpath movement [12]. As well, for predicting the forming forces a systematic and a robust method is improved by derive the elastic model and FE simulation.

A feature-based toolpath generation method has developed [13]. The surface quality, geometric accuracy and thickness distribution properties of the traditional incremental toolpath are compared with feature-based toolpath generation method by using three studies including a car fender, a nonsymmetrical cone and a truncated cone with double bottoms.

The conventional trajectory (Single Slope) 'from out to in and from up to down' can improved in order to compensate the irregular thinning. Several methods were proposed experimentally to solve this defect. Decremental Slope is a suggested method based on to apply over-slop, where the blank is typically less stretched. Next, a lower angle by the forming tool is imposed and the restricted over-thinning appears. Depending on this concept, the offset of + or - units was applied to the forming tool movement [14]. A novel tool feed path generation method was developed [15]. The idea is depending on FE analyses of the multi-passes incremental forming by hydraulic bulging. The results of hydraulic bulging CAE analysis offered a series of approximating surfaces.

The influence of the processing tool paths on the accuracy of the parts and on strains and thickness reduction has been shown. Some approaches of implementing SPIF process using as technological equipment either CNC milling machines or serial industrial robots have been unrolled [16]. Both simulation and experimental data are presented.
This work presents the effects, primary start position (5-15 mm from die edge center with step 2.5 mm, plus 0.98 mm) and toolpath angle movement (that is a reflection of the start position, θ = 38.09°, 39.51°, 40.77°, 42.11°, 43.52°, 45.00°) of the forming tool on the springback in incremental forming. Aluminum alloy sheets (A1025) with thickness, t=0.9 mm are used to deform the product, truncate cone geometry. The study goals to build a ratio between the wall angle and primary start position of the tool forming. Adding, study of the step size effect on the strain distribution for the deformed part section and the elements are leading the final parts to fracture have been evaluated and discussed.

2. Development of FE Model

The incremental forming is represented by FE simulation model. The first stage includes physical profile of SPIF model, boundary conditions, and the process components (tables 1 and figure 1). The mechanical properties of Aluminum AA1050 material that used in this work are shown in table 2. The 2D-axis symmetric model components of the blank are used. The second stage reflects the shape evaluation and FEM analysis (success or failure product), in order to estimate the final product geometry. The third stage covers the calculation and conclusions for the final product.

**Table 1. Initial IF process data.**

| Variable          | Value   |
|-------------------|---------|
| Die radius, R_d   | 2.5 mm  |
| Forming tool, D_p | 5 mm    |
| Blank diameter, D_b| 226 mm |
| Blank thickness, t| 0.9 mm  |
| x and y step size | 0.1 mm  |
| Coefficient of friction, µ | 0.05    |

**Figure 1. Components of the IF process.**

**Table 2. Al (AA1050), material properties of the sheet.**

| Tensile Strength | Density, ρ | Poisson’s ratio, υ | Young’s modulus, E | Tangent modules, E_t |
|------------------|------------|--------------------|--------------------|----------------------|
| 105 - 145 MPa    | 2700 g/m³  | 0.3                | 75 GPa             | 0.5 GPa              |

The elements that have been chosen to represent the workpiece and the tool set illustrated in the previous researches [17, 18]. As well, the boundary conditions consider friction coefficient, non-linear analysis, and convergence criterion.

3. Results and Discussion

CAD profile and FE model are simulated of the cone shape with depth equal to 47 mm (figure 2). The boundary conditions are concerning the contact status-displacement, and the tool set motion-loading with specific profile of the constant speed as represented in figure 2-(1). The FE models develop the effect of the primary start position - toolpath angle was studied with constant values (dimension and materials) of fixture (die and blank holder) and blank.

The methodology covers two series (figure 2-(1), a and b), and both have the constant radius values of the die edge and forming tool, R=5 mm:

- Constant product base, P_base radius, 33 mm, with six values of the supporting space Ss, variance 2.5 mm for each model, and 0.98 mm Ss for calculating the failure statuses is used;
- Constant toolpath angle, 45°, with primary product base, \( P_{\text{Base}} \), radius, 33 mm, and six values of the product base \( P_{\text{Base}} \) (with variance \( S_s = 2.5 \) mm for each model), and 0.35 mm \( S_s \) for calculating the failure statuses is used.

Successive stages using the toolpath angle, 45° to create the IF part profile are displayed in figure 2-(2). The wall angle is a part of the deforming path effects on the stresses values. So, the highest stress distribution values appear to be a good signal to estimate the success or failure of the deformed model.

The evaluation of stress distributions during the incremental steps 1, 10, 20, 30, 40, and 47 mm in depth are indicated the local effect of the forming tool. Increasing the forming depth is a reason for increasing the supporting space, \( S_s \) which create elastic states towered the die circumference is called the springback. Increasing the step size 'forming depth' is caused increasing the contact area and the friction region that causes failure. As a result, increasing the supporting space causes increasing the springback. In other word, increasing the forming depth increase the stresses locally (under forming tool) and along the deformed part section. The supporting space area does not suffer plastic stress during deformation steps highly, therefore the thickness distribution is close the original.

![Figure 2](image1.png)

**Figure 2.** Methodology details of the primary start position - toolpath angle effect.

3.1. **Effect of space**

The springback and its increase with the space is appearance in both series a and b (figure 3 and 4), although fixed or changed the forming tool movement angle respectively. As well, changing the product base radius "reducing", it does not prevent increasing the springback with the space.
3.2. Effect of path

The highest spring value can be recognized at the middle wall of the product, 2.4 mm and 2.41 mm of the series a and b respectively. The nature of failure that resulted in the product changed with the space value as showed in figure 4.

The brief of the results are determined in the tables 3 and 4 of both series a and b as follows:

- Fixed or decrease the percentage $P_{\text{Base}}/ST$ (fixed or increase the forming tool movement angle), it does not have an effect on the springback.
- Fixed or increase the percentage $\alpha/\alpha_p$ (fixed or increase the forming tool movement angle), it does not have an effect on the springback.
- While, increasing the percentage $S_s/P_{\text{Base}}$, caused to increase the springback (fixed or increase the forming tool movement angle), because of the relation is involved the space variable too.
- The percentage relations $P_{\text{Base}}/ST$, $R_i/ST$ and $\alpha/\alpha_p$, are detected between increasing, decreasing and fixing with the space-angle ratio $S_s \rightarrow \alpha$, which is do not give the clear indicate of the space-angle-springback ration. While the relation $S_s/P_{\text{Base}}$ is clear in both series, increasing the forming tool movement angle and the space causes increasing. As well, this relation involves the effect of angle on the springback.
Table 3. Series a, effect of toolpath angle, $\alpha^\circ = 38.09 - 45.00$ - With product base fixed, $P_{\text{Base}} = 33.00$ mm.

| Ss $\rightarrow$ $\alpha^\circ$ | $P_{\text{Base}}$ | Ri, mm | ST, mm | $P_{\text{Base}}$/ST | Ri/ST | $\alpha^\circ/\alpha_p^\circ$ | Ss/$P_{\text{Base}}$ | SB, mm |
|-------------------------------|-------------------|--------|--------|----------------------|--------|--------------------------|------------------|--------|
| 4.02 $\rightarrow$ 38.09      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.00                     | 0.1218           | 0.4375 |
| 5.00 $\rightarrow$ 39.51      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.04                     | 0.1515           | 0.5491 |
| 7.50 $\rightarrow$ 40.77      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.07                     | 0.2273           | 1.5958 |
| 10.0 $\rightarrow$ 42.11      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.11                     | 0.303            | 2.3968 |
| 12.5 $\rightarrow$ 43.52      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.14                     | 0.3788           | 3.0281 |
| 15.0 $\rightarrow$ 45.00      | 33                | 90     | 95     | 0.35                 | 0.95   | 1.18                     | 0.4545           | 3.63   |

Table 4. Series b, effect of product base, $P_{\text{Base}}=43.35 - 33.00$ mm - With product angle fixed, $\alpha_p^\circ = 45.00^\circ$.

| Ss $\rightarrow$ $\alpha^\circ$ | $P_{\text{Base}}$ | Ri, mm | ST, mm | $P_{\text{Base}}$/ST | Ri/ST | $\alpha^\circ/\alpha_p^\circ$ | Ss/$P_{\text{Base}}$ | SB, mm |
|-------------------------------|-------------------|--------|--------|----------------------|--------|--------------------------|------------------|--------|
| 4.65 $\rightarrow$ 45.0       | 43.35             | 90     | 95     | 0.456                | 0.95   | 1.00                     | 0.1073           | 0.4299 |
| 5.00 $\rightarrow$ 45.0       | 43.00             | 90     | 95     | 0.453                | 0.95   | 1.00                     | 0.1163           | 0.7877 |
| 7.50 $\rightarrow$ 45.0       | 40.50             | 90     | 95     | 0.426                | 0.95   | 1.00                     | 0.1852           | 1.7017 |
| 10.0 $\rightarrow$ 45.0       | 38.00             | 90     | 95     | 0.400                | 0.95   | 1.00                     | 0.2632           | 2.3513 |
| 12.5 $\rightarrow$ 45.0       | 35.50             | 90     | 95     | 0.374                | 0.95   | 1.00                     | 0.3521           | 3.0854 |
| 15.0 $\rightarrow$ 45.0       | 33.00             | 90     | 95     | 0.347                | 0.95   | 1.00                     | 0.4545           | 3.63   |

3.3. Toolpath effect

Toolpath is reflecting of the angles that are component of the product geometry. Therefore, the relation of wall angle-springback is a brief of the toolpath-springback ratio. The both series a and b are showed the proportional ration of the supporting space, Ss and forming tool movement angle, $\alpha^\circ$ with the springback “Ss/$P_{\text{Base}}$ - SB ratio”, table 3, 4 and figure 6.

The aspect of series a, constant value of the supporting edge radius equal to R 5 mm. Forming tool center, with range of angle, $\alpha^\circ$ from 25° to 45°, as well as, the product base is constant r = 33 mm, increase the space from 2.5 mm to 15 mm. Adding S =0.98 mm to be close the edge radius and the gab equal to the thickness of blank.

The aspect of series b, supporting edge radius is constant R 5 mm, forming tool movement angle 45° and supporting spaces start 2.5 mm - with incremental level 2.5 mm until 15 mm, and with edge radius R mm respectively. Adding, the space 0.35 mm to be close to the blank thickness 0.9 mm, and squeeze the blank between the supporting edge radius and the forming tool.

In other words, testing plan is considered changing supporting space, Ss with constant edge radius of the supporting plate and fixed forming tool movement angle and changes it.

The primary fixture are more tough for vibration effect, when decreasing Ss, 15 to 2.5 mm. Increasing, Ss value make the contact area that under contact and deforming effect increase. As well as, the forming tool contact effect involves the largest surface area, and the largest deforming reign of the metal.

The deference in the thickness (thinning %) does not offer an indicator of increasing or decreasing the springback, as shown in figure 5.
The strain distributions divided into four regions form the tool center, 0-30 mm (series a), low levels of increasing appeared when compared to series b, (figure 7). The defenses are resulting due to the product dimensions, where the product base, $P_{Base}$ ranged from 43.35 to 33.00 mm. These dimensions in series b caused decreasing the strains with decreasing of supporting space $S_s$, while do not have real effect in $S_s-\alpha^\circ$ ratio. Reflecting of the decreasing in the strains (region, 0-30 mm), the strains increased at the region 30-50 mm from the tool center (figure 8). The region from 50-70 mm from tool center at the series a, have been a level of strain distribution higher than at the series b. The region from 70 to the end edge of the blank have been the same behavior profile of both series a and b. The strain distributions at local point of the forming tool are increasing with increasing $S_s$. Remind the strains values are constant of the both series a and b, without effect due to the effect of fixture.

4. Conclusions
The study is presenting the elements and influences of the supporting space - the angle toolpath and product base diameter ratios. Both series are respecting the correction formability in the incremental forming.

Two types of failure indicated in the resulted product, the deviation in the wall and wrap the blank part "under contact" around the forming tool. Therefore, mentioned as a nature of the failure.

The results show the supporting space with respect to the product profile ratios gives good results for reducing the springback effect. The important factor that caused increasing the springback is supporting space, which shared between both series.

The variations in strain distribution do not represent as indicator of the springback. The shared ratio, supporting space / product base, $S_s/ P_{Base}$, represent a better indicator of the springback defect.
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