Simulation and Experimentation of Single Point Incremental Forming of Different Geometries

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Abstract:

Incremental Sheet Forming is a rather new forming process which is used to obtain complex three dimensional parts by stretching the sheet with a pin tool whose path is controlled by a CNC machine. This study presents a new fixture design for Single Point Incremental Forming (SPIF) and experiments conducted for two profiles. Single Point Incremental Forming is used for small and batch production. The fixture presented in this study was made using mild steel and the results were compared with that of Simulations for the same profiles using the analysis software, ABAQUS. The experiments were carried out using Computer Numerical Control (CNC) machine.

1. INTRODUCTION

Incremental sheet forming (ISF) is a sheet metal forming process which is used to produce complex 3D sheet metal parts by employing computer numerical control. The process is performed on CNC milling machining center with a simple tool and fixture to hold the blank. The metal sheet is gradually deformed into the complex 3D shape using controlled tool motion as seen in Fig 1. The process works such that at any time only a trivial part of the product is actually being pressed causing local deformation and with programmed trajectory over the entire product, the desired geometry is achieved. The geometry of the part to be manufactured is modeled as a surface model in CAD software and the tool path possesses number of contours with constant spacing between each contour. The main advantage of this process is that useable parts can be formed directly from CAD data without specialized tooling thus reduces cost. The formability of material in ISF is also better than the conventional deep drawing and stamping processes. The process can be used for aluminum, steel, magnesium and titanium alloys. The process has potential applications in rapid prototyping, low volume production, bio-medical and automotive industries. ISF also have some drawback such as Limited geometric accuracy, low surface quality and long processing times but, by proper selection of process parameters and providing compensation for deviation, reasonable accuracy and quality can be obtained.
Incremental sheet forming can be classified according to the forming method, the part geometry, the forming path and tool path strategy, the applied tools, etc. The most usual classification is done according to the forming method viz. single-point, two-point and hybrid processes. Single-point incremental forming (SPIF) often termed as negative incremental forming and two-point incremental forming (TPIF) termed as positive incremental forming. The difference is contact points between forming tool and the sheet. In SPIF, tool is rotated and moves down to press on the sheet metal to cause locally plastic deformation. But in TPIF, there is second point between the static post and the sheet creating when the tool pressed into the sheet. Further classification according to the forming method may also be done whether the process can be done in a single stage (this is the most frequent type) or as a multi-stage process. Considering the geometry of formed sheet, we can also distinguish symmetric and asymmetric incremental forming. The major advantage with incremental forming is its die less nature and simple tooling. Fig 2 shows some application of ISF process.

There are many literatures found in SPIF starting from selection of tool, design of fixtures, control of trajectories, section of machining parameters, formability behaviors and method of process simulation. Some important literatures are discussed as follows. Dai et al. (2000) examined theoretical and experimental behavior of axially symmetric SPIF for even metal flow deformation. The authors showed that by loading small stiffness and low deformation area at the start and with reduced loading time on boundary, better control of metal flow and forming locus is possible. Kopac and Kampus (2005) tested SPIF with aluminium alloys in CNC milling machine with varying parameter and tool path behavior. The experiments are conducted varying parameters such as tool diameter and clamping frame shape. It is reported that smaller ball tool and directing the forming from center to edge will provide good quality and better forming. M. Skjoedt (2007) presented a new type of Single Point Incremental Forming in which they used a dummy plate to carry out the forming process on a
desired plate. The effect of using dummy plate is analyzed by making truncated pyramid and a hyperboloid structure. Various properties like wear, formability, bulging of planar sides and surface quality were analyzed to observe the influence of using a dummy plate. Ji and Park (2008) reported the feasibility of SPIF on magnesium alloys and analyzed the deformation characteristics by Finite element simulation. Tool with hemispherical end was used to form local deformation. The result shows that when higher inclination angle can be used for progressive incremental forming. Skjoedt et al. (2008) employed five stage forming strategy to develop a circular cylindrical cup in Single Point Incremental Forming. This multi stage method proved that a cup of right angle drawing is possible in SPIF and reveals that the strain distribution is largely dependent on the geometry of tool path and tool direction. P.A.F. Martins (2009) carried out Single Point Incremental Forming on polymers. They analyzed five different thermoplastic materials by obtaining cone structure on each of them with increasing wall angle. They came to a conclusion that it is indeed possible to obtain complex structures on polymer sheets. Ziran et al. (2010) studied about the behavior of two types of tool viz. hemispherical and flat ended, on accuracy of profile and sheet formability. It is reported that the lower forming force and better accuracy are achieved with flat end tools compared to hemispherical end. Also it is found that the tool radius is immaterial for formability. Essa and Hartley (2011) examined the SPIF based on backing plate, kinematics of tool and trajectory through finite element simulation. It is found that tool kinematics reduces spring back, backing plate reduces sheet bending and tool trajectory extension across the bottom of sheet will eliminate the pillow effect. Dejardin et al. (2010) also conducted finite element analysis on the effect of shape distortion and spring back during SPIF which he verified experimentally. The use of shell element in FE model could predict the effect of spring back quite accurately. Zhu et al. (2012) applied different FE models to predict the effect of pressing direction through digital simulation. Many observations are reported such as decrease in thinning range and strain on middle area with increase direction angle. Amar Kumar Behra (2017) has analyzed the progress and advancement in the technology of Single Point Incremental Forming over the period of 2005-2015 to determine its current state in the forming area. A lot of sectors have been researched like forming mechanics, force estimation, failure mechanism, toolpath, etc. to identify its current state and future prospects of this technology.

All these reviews provide opportunities to use finite element simulation to study the behavior of sheet forming in SPIF. In this work, ABAQUS is utilized as FE tool to study the stress and strain distribution on Aluminium sheet for two different shapes and sizes. The pattern of deformation of simulation was verified with experiments. The results are accurate for cylindrical geometry of smaller dimensions.

2. EXPERIMENT SETUP AND DETAILS

2.1 SPIF Process requirement

The work is performed in two stages. Selecting appropriate tool material, workpiece sheet and tool trajectory, the simulation of SPIF is performed in ABAQUS. Later using an in-house fabricated fixture and selecting a suitable CNC machine, the experiments are conducted. The results are validated for accuracy. The following paragraphs explains the selection of process requirements.
2.1.1 Tool selection:

The single point forming tool which plastically deforms the sheet metal to perform incremental forming is the most important element. There are two types of forming tool viz. hemispherical end type and ball end type. Incremental forming is usually performed by solid hemispherical tools head as it ensures a continuous contact between tool and the sheet. As the forming to be performed had steep angle walls, tool with smaller shank than the sphere diameter became necessary. Careful tool path generation makes sure that the contact between shank and sheet is avoided.

For most applications, the material of the hemispherical-head is chosen as steel and the same is selected to perform our experiments. Various tool diameters ranging from 3mm to 100mm are available depending upon the power, machining time and also the scale on which the manufacturing is required. We chose the diameter of the tool to be 5 mm as our experiment has low power, shorter cycle time and small scale geometry.

Tool Path Generation:

Tool path generation is a very integral part of the incremental forming as it has an influential impact on surface finish, thickness variation, formability and dimensional accuracy of the experiment. Spiral tool path has an advantage over conventional contour tool path as it results in a more uniform thickness distribution part. Contour tool path is the most common technique characterized by fixed height increments between consecutive contours. It has a disadvantage that it leaves trace marks when transitioning between contours which is avoided in spiral tool path. We chose the contour tool path because surface finish was not a major concern for our experiment and it has an advantage over spiral tool path as it requires less time. It also has a cost advantage over spiral tool path.

Tool path trajectory is created using Matlab to generate the G Codes which are fed to CNC machine for controlling the tool movement. Following is a Matlab Code used to generate circular profile and the geometry of circular trajectory generated is shown in Fig. 3.

```
z=0;
x=14.8;
for i=1:50
fprintf('G02 X%0.1f Y0 R%0.1f
',x,x)
fprintf('G02 X-%0.1f Y0 R%0.1f
',x,x)
z=z+0.1;
x=x-0.2;
fprintf('G01 X-%0.1f Z-%0.1f
',x,z)
end
```

*Figure 3 Circular Profile Visualisation*
2.1.2 Sheet material selection:

Incremental forming is performed on Aluminium Sheet (120mm X 120mm) because it has been gaining interest in recent years due to its low weight. This property is useful for the purpose of reducing fuel consumption. Properties which make aluminum a high demand metal are its strength (high strength to weight ratio) which makes it durable and stable under high load conditions, good formability which helps to form it in complex shapes with ease, excellent corrosion resistance and its low fabrication costs.

The specifications of the sheet and tool are listed below in the table.

| S.No | Basic Requirements | Property             |
|------|--------------------|----------------------|
| 1    | Sheet material     | Aluminium            |
| 2    | Modulus of Elasticity | 71 GPa            |
| 3    | Sheet Metal Density | 2.71 $\text{kg/m}^3$ |
| 4    | Sheet metal thickness | 1mm                |
| 5    | Sheet Size         | 120mm X 120mm       |

2.1.3 CNC Machine:

CNC (Computer numerical control) is a computer controlled machine which can be used to manufacture complex machinery. Askar Smart mill-600 Vertical Machining Center CNC Machine is used to perform single point incremental forming with the specification shown in the figure below.

![CNC Machine](image)

Figure 4 CNC Machine

Two wooden pieces (160mm X 40mm) are used to support the frame in the machine which have holes in them aligning with those in the frame so that it is fixed properly and doesn’t move in the experiment. SAE – 40 lubricating oil is used to minimize the friction between tool and sheet. The path
of the tool is generated through the Matlab code and is input to the Fanuc controller to obtain the desired circular and square profiles.

2.1.4 Fixture:

Fixture has been designed in two phases. At first the sheet is analysed by subjecting point loads at various location to study the behaviour stress distribution and later the fixture is design using the data from the analysis for suitable clamping. The stress analysis was performed on the sheet metal using Hyperworks and the results shown in Fig 5. A normal force of 500N is applied on the sheet metal at a position on the outermost point of the forming tool path. This is to check whether it is feasible to perform forming operation without deforming the edges considerably. It can be seen from the Fig 5 that the areas near the holes are under high pressure and so the fixture is designed in such a way that there are no holes near the edges of the sheet metal.

![Figure 5 Stress Analysis Results](image)

The design of the fixture is shown in Figure 6 (a & b). The fixture contains two parts namely top part and the bottom part. The design of the parts is performed in Solid Modelling software, PTC Creo. To avoid the stress concentration in sheet near holes, holes for screws are provided in the frame itself. A slot of 2mm is provided in the bottom part of the frame in which sheet metal is placed and a protrusion of the same height is given to the top part of the frame to constrain the sheet in all the three axes.

![Figure 6 (a&b) Top and Bottom Parts of the Fixture and (c) Fabricated fixture](image)

The fixture is fabricated in the CNC machine and the material used is mild steel. Figure 6(c) shows the fabricated fixture.
3. RESULTS AND DISCUSSION:

3.1 Simulation:

ABAQUS software is used to perform simulations of the jobs performed experimentally to compare the stress and strain values and check the validity of results. 2-D Elements of shell type and 3mm size are used in the simulations. Isotropic Aluminium sheet metal is simulated with the same properties as listed in the Table 1. Kinematic Contact method is used to establish the interaction between tool and sheet.

3.2 Description of Incremental Forming Simulation:

**Boundary Conditions:**

A Dynamic, Explicit step is created named ToolMove with Nlgeom ON. In the Amplitude module 3 Amplitudes are defined namely XAMP, YAMP and ZAMP which are used to input the coordinates from the user defining the movement of tool in X, Y and Z directions. 13 Boundary Conditions are defined for the simulation. The first 6 boundary conditions are used to fix the tool in the centre of the sheet for the initial step for all 6 Degrees of Freedom. In 7th Boundary Condition the edges of the sheet metal are constrained with ENCASTRE option making all the 6 degrees of freedom 0. From 8th to 10th Boundary Condition tool is moved to the corner of the desired profile and given amplitudes defined in the amplitude module for X, Y and Z directions. Last 3 boundary conditions are for rotation which are given 0 as input.

![Figure 7 Boundary Conditions](image)

**Square Profile:**

The square profile is simulated with side 40mm and the depth is given as 15mm. The length of the side is reduced by 0.5mm for every 0.5mm increase in depth. The experiment is also performed with the same specifications. Tool diameter is 5mm.
Circular Profile:

The circular profile is simulated with radius 14.8mm and the depth is given as 5mm. The radius of the circle is decreased by 0.2mm for every 0.1mm increase in height. The experiment is also performed with the same specifications. Tool diameter is 5mm.

Simulation Results:

![Figure 8 Square Strain and Stress Simulation Results](image)

![Figure 9 Circle Strain and Stress Simulation Results](image)

It is evident from Figure 8 that stress and strain in square profile increases uniformly as the depth of the forming is increased and by comparing these values to those of circular profile from Figure 9 it can be seen that the maximum stress achieved in square profile is more than that of circular one because the depth of the square profile is 15 mm whereas that of circular profile is 5 mm. This result is accurate according to the stress strain curve of aluminium.

3.3 Experimentation Validation:

The Aluminium Sheet with 1mm thickness was experimentally prepared with laser engraving squares of 1mm² on the back of the sheet. The experiment was performed on the other side of the sheet. This was done to measure the strain after deformation by calculating the change in area of the squares and comparing these strain values to simulated values. 5 microns was the depth of the laser marking. Fig. 10 shows the experimentally obtained deformed circular and square profiles by CNC machine and Table 2 shows the change in the size of mesh after the experiment.
Table 2. Mesh Size of Circular and Square Profiles:

| Profile | Data Point | Initial Mesh Size (mmxmm) | Final Mesh Size (slope) (mmxmm) |
|---------|------------|---------------------------|---------------------------------|
| Circular | 1          | 5 x 5                      | 5.2 x 5.35                      |
|         | 2          | 5 x 5                      | 5.35 x 5.25                     |
|         | 3          | 5 x 5                      | 5.55 x 5                        |
| Square  | 1          | 10 x 10                    | 12.5 x 10                       |
|         | 2          | 10 x 10                    | 12.9 x 10                       |
|         | 3          | 10 x 10                    | 13.1 x 10                       |

The data points 1, 2 and 3 lie on the slope of Circular and the Square profiles. The same points on the experimental sheet metal are selected and the corresponding Stress and Strain values are compared. Change in the mesh size is used to calculate the experimental strain. The results are shown in Table 3. From the Table 3 it is observed that the experimental and simulation results for the square profile are nearly the same. The difference in stress and strain values between simulation and experiment can be attributed to the sliding of the sheet metal in the experiment which is not taken into account in the simulation. The variation in stress and strain can also be accredited to the friction coefficient which is taken as 0.3 in the simulation which can vary in real life. The results for the square profile are found to be more accurate than that of the circular profile. This could be because of the circular profile being small (in radius 14.8mm and depth 5mm). Thus, the manufacturing process, Single Point Incremental Forming can be simulated with the right parameters.

Table 3. Stress and Strain values comparison of Circular and Square Profiles:

| Profile | Data Point | Experimental Strain (at slope) | Simulation Strain (at slope) |
|---------|------------|-------------------------------|------------------------------|
| Circular | 1          | 0.1128                        | 0.0989                       |
|         | 2          | 0.1235                        | 0.1385                       |
|         | 3          | 0.11                          | 0.1187                       |
| Square  | 1          | 0.25                          | 0.2449                       |
|         | 2          | 0.29                          | 0.2876                       |
|         | 3          | 0.31                          | 0.3089                       |
4. CONCLUSION:

A fixture for holding the sheet metal for performing Single Point Incremental Forming was fabricated. Two truncated cone profiles, Circular profile and Square profile were formed using SPIF process with depths 5mm and 15mm respectively. The experimentally obtained strain values were compared with the strain results from the simulations of the same profiles using the analysis software, ABAQUS. The results obtained from simulations and the experiment were found to be accurate with error 10.77% for circular profile and 1.07% for square profile. The results for the square profile are found to be more accurate than that of the circular profile. This could be attributed to the measurement errors in circular profile because of its size being small (in radius 14.5mm and depth 5mm) as compared to the square profile (side 40mm and depth 15mm).

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