Automatic generation of 3d spiral tool path for incremental sheet metal forming of mechanical parts with complex geometry

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Abstract. Incremental sheet metal forming is a flexible manufacturing technology that allows to form of various components on the same milling machine, without expensive tools. A hemispherical tool moves along a CNC-controlled tool path and deforms the sheet into the desired shape. The tool path has a significant role in the geometric accuracy of the final part. There has been very little research on the problem of the forming of sophisticated parts with asymmetric wall angles. This paper presents a new approach to generating optimized tool paths for single-point incremental sheet forming (SPIF). At first, a strategy is proposed for the automatic generation of a 3D tool path during forming in a single-step operation. Then, a systematic technique of creating intermediate shapes is investigated by defining tool paths interpolated from the final part shape. The proposed methodology is applied to form a hip cup prosthesis. This part has a complex asymmetric geometry with important angles, a multi-step approach is used. The proposed methodology to define the different tool paths was implemented in Matlab. A numerical simulation of the incremental forming process is performed to predict the final geometry of the aluminum sheet. A comparison of desired and predicted geometries shows the reliability of the proposed method.

1. Introduction

Incremental forming at a single point SPIF is a die-less forming process that uses a moving tool head to locally deform sheet metal along a predetermined path, reaching greater forming limits [1, 2] than traditional sheet metal stamping. As a result, SPIF offers a cost-effective and efficient method of producing low-volume, bespoke functional sheet products without the need for a die. The goal of this project is to create automated 3D spiral toolpaths for SPIF.

According to published SPIF literature, toolpath has a considerable impact on forming limitations [3], geometric precision, surface quality, thickness variation, and shaping time. Although some attempts have been made to investigate various sorts of toolpaths and their impact on the aforementioned features, they are either part-specific or based on trial-and-error methods. Many academics have conducted experiments to see how different types of toolpaths, such as outline, radial, and multi-passes, affect the quality of the produced component. The majority of them utilized contour toolpaths created by commercial CAM systems designed for
machining applications’ surface milling modules. Forming in a contour toolpath is biaxial at the beginning and endpoints of each contour, and near to plane strain in the middle. The potential for fracture at the start and endpoints of each shape has been observed to be greater than when the rest of the shape is being created. A contour toolpath also causes stretch marks at the beginning of each contour. Wang et al. [4] recommended using a 3D spiral toolpath to eliminate equibiaxial stretching and tool marks at the end points of each contour.

However, because of the simultaneous needs of high forming angles [5, 6, 7, 8] and precision demands to retain component functioning as requested by the client, the fabrication of complicated 3D parts utilizing Single Point Incremental Forming (SPIF) is typically hard. Incremental forming [9, 10, 11] has been used on a variety of materials, including metals, which have low forming limits, which are normally specified by a maximum wall-angle at which no failure occurs. Furthermore, various attempts have been undertaken to increase part correctness. Verbert et al. [12], for example, devised a feature-based strategy that takes into consideration the behavior of specific features such as planes, rules, freeform, and ribs to produce components with high precision. The triangulated CAD model parts accessible in STL file format are utilized to detect features in this method. To build a compensated CAD model, the vertices of individual features are translated depending on actual deviations of a test component or models of projected deviations.

Verbert’s feature-based technique is only shown for basic feature behavior, such as planes much below the failure wall angle. For parts on the verge of failure, this simple technique cannot be used to apply compensation strategies. Behera et al. [13] propose employing Multivariate Adaptive Regression Splines as a mathematical compensatory approach (MARS). This approach, on the other hand, is not well suited to pieces that are near the shaping limit. Similarly, pieces created in a multi-step process might help to extend the process window.

Despite these approaches, there is a need to create tool path procedures that can assist in the production of components with high shaping angles and high precision. There is also a requirement to design an automated and methodical multi-step part manufacturing technique. The multi-step technique has previously been demonstrated for basic ruled features like cones and cups, where the development of intermediate forms is visible as the final portion has a well-defined variation in wall angles. However, there is no systematic process for generating intermediate forms for sections with changing wall angles in the literature. Another challenge is that the manufacturing of complex forms with concave and convex features and forming limitations beyond failure has yet to be proved, since the traditional multi-step technique fails for such components.

As a result, an attempt was made in this study to establish a multi-step-based tool path generation approach for producing high-accuracy parts, particularly those with high forming angles. Case studies are offered to show how the suggested technique has been implemented successfully.

2. Materials and methods
2.1. Geometry and Materials
In this contribution, the test geometry is a hip cup prosthesis [14, 15] (cf. Figure 1), which has the following characteristics:

- Changing the wall angle with the depth of the part
- 120 mm in length
- Asymmetrical part
- Complex part

Aluminium (AA 1050-O), whose mechanical properties are listed in Table 1 and composition in Table 2, was employed for the appropriate investigations. The tests were carried out on
Aluminium is a low-density metal (2.6989 g/cm$^3$ at 20 °C), easy to work with, and has excellent electrical and thermal conductivity as well as corrosion resistance. Aluminum crystallizes in a face-centered cubic (A1) lattice, making it a metal that may be formed cold or hot [16].

**Table 1.** Materials mechanical characteristics [17].

| Material  | E [MPa] | $R_{p0.2}$ [MPa] | Rm [MPa] | A [%] |
|-----------|---------|------------------|----------|-------|
| AA1050-O  | 70000   | 300              | 535      | 40    |

**Table 2.** Chemical composition of the material (wt.%) [18].

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Ni  | Zn  | Ti  | Ga  | V   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         | 0.089 | 0.28 | 0.002 | 0.001 | 0.001 | 0.003 | 0.005 | 0.011 | 0.016 | 0.007 |

2.2. **Methods**

The approach is taken to develop tool path techniques that can aid in the production of parts with high forming angles and high precision. The following are the main steps, which are
Figure 2. The developed methodology

summarized in Figure 2: A computer-based FPIF module is used to recognize features and adjust the CAD model of the part to be formed; the updated CAD model is used to generate a toolpath on the MATLAB software to simulate the forming model; and the realized part is extracted to generate a point cloud, which is compared with the original CAD to generate an accuracy plot.

Because it affects formability, surface finish, thickness variation, processing time, and dimensional accuracy, the tool path is critical in the design of SPIF processes. The digital control provides the tool route (CNC). The tool follows a succession of contour lines with a vertical increment step size of \(\Delta z = 0.2\ mm\) between them in a single forming step. The punch had a diameter of 2 mm. With a diameter of 120 mm and a thickness of 1 mm, the aluminium sheet was modeled in a round shape. The part is shaped by the tool’s trajectory, as shown in Figure 3.

We start with a triangular depiction of the cup to specify the tool’s trajectory in the incremental shaping phase. Indeed, the desired shape is modeled by a space mesh of triangles that define the cup’s surface. We chose a spiral trajectory due to the curvature of the cup, and the trajectory is specified by multiple successive passages to lessen the stress imposed on the portion. The spiral is described by the following equation in the horizontal plane generated by the x and y axes:

\[
x(t) = (R_i + (R_f - R_i) \frac{t - t_i}{t_f - t_i}) \cos(wt); \tag{1}
\]
Figure 3. Tool trajectory one step

\[ y(t) = \left( R_i + (R_f - R_i) \frac{t - t_i}{t_f - t_i} \right) \sin(\omega t). \] (2)

with \( R_i \) and \( R_f \) the initial and final radii of the spiral, \( t_i \) and \( t_f \) the initial and final times of passage of the spiral and \( \omega \) a parameter which regulates the spacing between the turns of the spiral, i.e. the angular speed of the rotation.

Then we identify the triangle that contains the point with coordinates \((x(t), y(t), z_0)\) and declare \( z(t) = z_0 \) for each pair \((x(t), y(t))\) on the spiral. As a result, the route \((x(t), y(t), z(t))\) is a tool path. Consecutive spirals are combined to perform many passages by alternating the values of \( R_i \) and \( R_f \) and assigning progressive values to \( z(t) \):

\[ z(t) = \frac{i}{N} z_0 \] (3)

with \( N \) the total number of passages and \( i \) the current passage’s index \((1 \leq i \leq N)\).

While stepwise product shaping is used in many manufacturing processes, morphing is particularly useful in some manufacturing processes. The use of a source item and a target object is the fundamental notion of morphing. The input items in this study are triangulated models in STL format. The morphing problem must be handled in two phases: the correspondence problem and the interpolation step, because the STL format is a boundary representation technique. Furthermore, because various features behave differently in incremental formation, the mapping procedure must take feature behavior into account. Figure 4 depicts an illustration of this approach for morphing graphics.

2.3. Modeling
The standardized hip cup prosthesis was created using the incremental forming technique, as previously indicated. A hemispherical tool, a die with a negative model of the inner shape, and a blank holder are required for this technique. The numerical simulation was carried out
using the program Abaqus 2018 (Dassault Systems, France), which was followed by a simulation of the blank springing back after the forming process. The yield curve of commercially pure aluminum, as determined by the above-mentioned tensile tests, and the anisotropic coefficients were utilized to define the material law of Hill’48, which was employed to do this numerical research. At room temperature, the material data was obtained. A substantial anisotropy of strain hardening was reported for uniaxial stress, resulting in a 30% variation in uniform tensile elongation between the extreme circumstances [18]. As a result, we’ll account for anisotropy in our numerical simulation. Table 3 lists all of the discovered anisotropy coefficients and their values.

Table 3. Anisotropy coefficients for AA1050-O [18].

| Orientation[°] | r  |
|---------------|----|
| 0             | 0.61|
| 45            | 0.21|
| 90            | 0.93|

The blank was modeled using fully integrated rectangular shell components with 5 integration points throughout its thickness, with material yield calculations performed at each node. The rigid parts were employed for the die and the blank-holder. The friction coefficient between the blank and the tools was adjusted to 0.1.

3. Results and discussions
The standardized human hip cup’s produced components were first visually inspected in Figure 5. Simulating the preforming process at room temperature produces acceptable outcomes, with a 20 percent reduction in blank thickness.
Figure 5. Thickness distribution of the first step

Figure 6. Thickness distribution of the incremental forming in one step

Figure 6 shows the thickness reduction of the aluminum blank as a consequence of modeling the one-step incremental forming process at room temperature. According to the modeling results, one-step incremental forming at room temperature would result in a 74 percent reduction in blank thickness, which is considered that it has exceeded tolerable limits and a rupture may occur. Because of its thinning by more than 25%, which is regarded as a limit to prevent the risk of cracking, this technique is difficult to complete without having a cracked blank at the end. Meanwhile, simulations reveal that multi-step incremental forming for aluminum blanks might lower the thickness of the blank by around 25%. Simulating multi-step incremental forming at the same temperature produces superior results in blank thickness. The aluminum blank and its thickness reduction as a consequence of modeling multi-step incremental forming at room temperature are depicted in Figure 7.

The modeling of both one-step and multi-step incremental forming procedures on an aluminum blank reveals that multi-step incremental forming of this blank at room temperature appears to be the most practical way for producing the prosthetic acetabulum.

As a result, a further step is required.

After that, a comparison is made between the simulation findings and the specified hip cup target. Catia V5 (Dassault Systems, France) was used to create the geometry of a 3D scan of
Figure 7. Thickness distribution of the incremental forming in multi-step

Figure 8. Comparison between theoretical and simulated profiles

the target component for this comparison. To find the best match, the digitized geometry was compared to the simulation results. Matlab was utilized in this experiment. Figure 8 depicts the results of the best fit and deviation analysis. The dimensional deviation study (Figure 8) revealed a minimum variation of 0.4633 mm in the edge region and a standard deviation of 0.2 mm for the entire dimensional deviation. As a result, there is a high level of agreement between the simulation and the theoretical component.

As a consequence of this finding, it is concluded that numerical simulation should reflect reality as it has been demonstrated.

4. Conclusion
A forming procedure has been designed based on the numerical analyses presented in this study. To begin with, a newly created standard acetabular/hip cup component is made using a preforming procedure. Individualization is achieved by an incremental shaping process using a sleeve and a backstop to adjust to the unique fit.

When the numerical findings of incremental forming the hip cup prosthesis are compared to
theoretical and numerical research, it is discovered that the aluminum blank may be reduced in thickness by up to 26% without causing material damage. This criterion was used to establish the optimal forming parameters in the simulation of incremental forming the human standardized hip cup. This verification demonstrates that incremental forming may be used to manufacture the intended standardized human hip cup prosthesis.

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