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Tool path definition for numerical simulation of single point incremental forming

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Abstract

Incremental sheet forming is a promising process for sheet metal prototyping and for bio-medical implants. The entire process cycle is computer integrated and part is manufactured on computer numerical control (CNC) milling machine. This process uses a spherical ended tool to press the sheet into required shape. The path of the tool is controlled by a part program generated using computer aided manufacturing (CAM) softwares. For the numerical simulation of the process tool has to follow the same path as in experimental work. But numerical simulation softwares normally do not accept the G-code file generated using CAM packages directly. In the present paper a methodology has been proposed to input the tool path trajectories generated using CAM packages in to numerical simulation softwares such as ABAQUS and Ls-Dyna. For certain sample symmetric and asymmetric shapes, this proposed methodology has been implemented in Matlab and Ls-Dyna. The results were found to be satisfactory.

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1. Introduction

Single point incremental forming is a flexible process which uses very simple tooling to make sheet metal prototypes and custom specific parts. In this, the sheet is clamped along its edges and a hemispherical headed tool is moved along required path so that it presses the sheet locally along the path. Better formability, simple tooling without any dedicated dies and low forming forces are some of the attractive features of this process.

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However, it suffers from some disadvantages such as long processing time, poor dimensional accuracy due to bending of the sheet near clamped edges. Tool diameter, step depth, feed rate, rotational speed of the spindle, sheet thickness, lubrication and tool path are some of the important process parameters which affect the process mechanics in incremental forming [1]. Tool path plays a vital role in the geometric accuracy of the part and homogeneous thickness distribution [2]. Thus the proper tool path selection is very important for successful production of parts in incremental forming. Other ways of improving the accuracy of the part is by using contour tool, partial or full die below the sheet. This process is generally called as two-point incremental forming in the literature [1]. Different steps to make the part in incremental forming are shown in Fig. 1.

2. Tool path strategies for incremental forming

Tool path has significant effect on dimensional accuracy, surface roughness, processing time and thickness variation. Thus tool path generation is an important step in incremental sheet forming (ISF). Three different methods have been used to generate the tool path for ISF in the literature (i) tool path generation using commercial computer aided manufacturing (CAM) softwares, (ii) Cutter location (CL) based approach, and (iii) cutter contact (CC) based approach [3]. Commercial CAM packages offer different tool path for the machining application. One tool path among them suitable for ISF application is the profile tool path. In profile tool path, tool moves in one plane till it reaches to its initial point. Thereafter it moves vertically downward direction by specified step depth. After reaching to next plane tool continues its motion in the same direction as that of earlier cycle. This process continues till the complete geometry is formed. Profile tool path can produce any complex geometry but it produces a scarring on the surface of the part. This scarring may not be permitted on parts which are aesthetically important. However, it can be minimized by diverting it to some converging surface or along the edges of the shape.

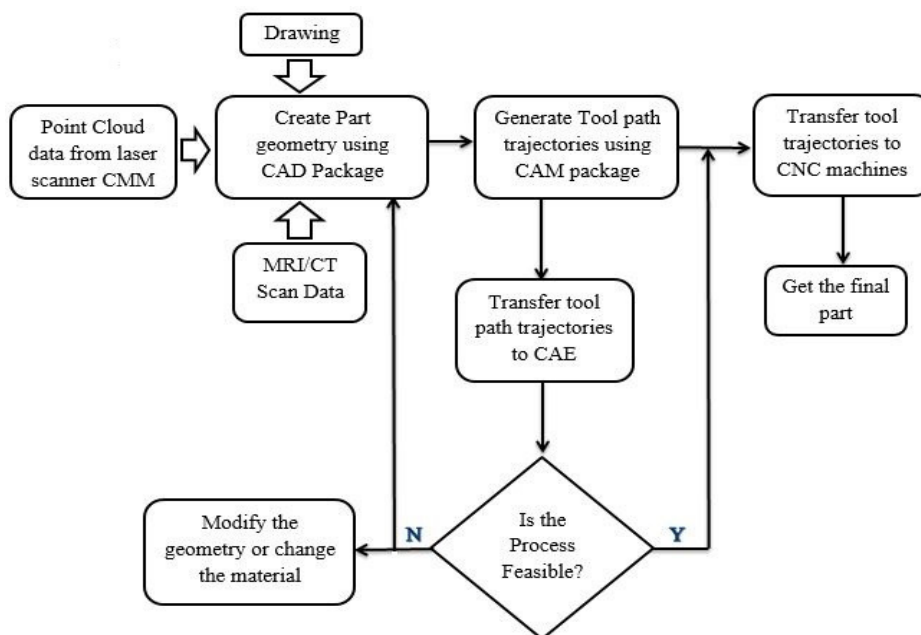


Fig. 1. Different steps to form the component in incremental forming.

From the above view point, helical tool path is more suitable for ISF. This helical tool path completely eliminates the scarring on the surface of formed component and produces homogeneous thinning. In helical tool path the tool

moves along the periphery while maintaining the gradual helix along the vertical direction (depth direction). The distance from one point on the cycle to the corresponding point on the consecutive cycle is constant and is equal to step depth. Helical tool path option in CAM packages works with axi-symmetric objects only. To overcome this problem Skjoedt et.al [4] proposed a methodology to convert the profile tool path in to helical tool path. This program will generate the helical tool path for any geometry provided with it's profile tool path. Sample profile and helical tool paths are shown in Fig. 2.

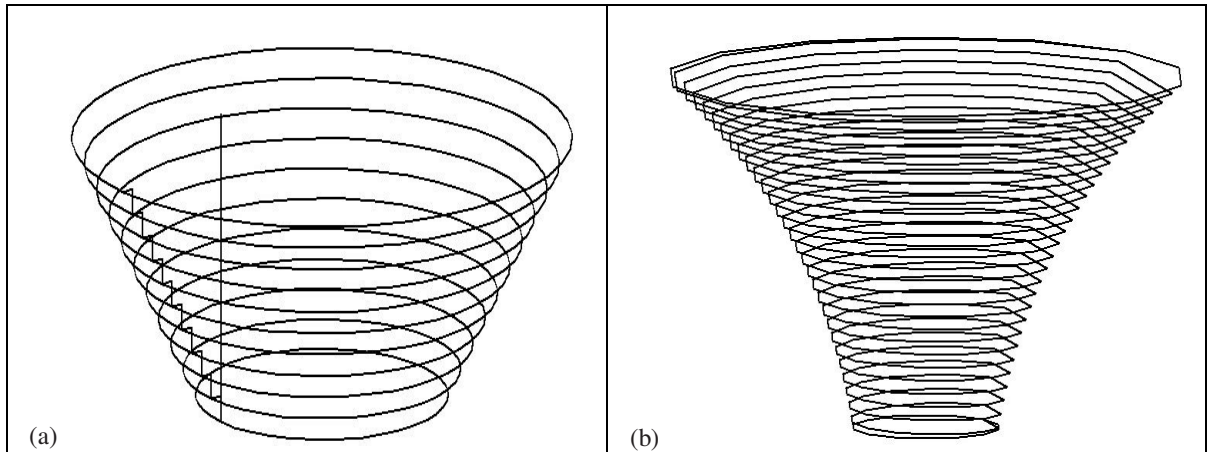


Fig. 2. Common tool paths used in ISF (a) Profile tool path; (b) Spiral tool path.

Jadhav [5] has observed twist and dent in parts formed using helical tool path. To overcome this problem a bi-directional profile tool path has been suggested. This tool path is similar to profile tool path except that in each subsequent cycle tool changes the direction of motion. This toolpath minimizes the twist and enhances the geometric accuracy of the formed component. However it may not be possible to divert the scar mark to unimportant area in all cases. He also proposed Bi-directional profile tool path with distributed increment, which is not in commercial CAM packages.

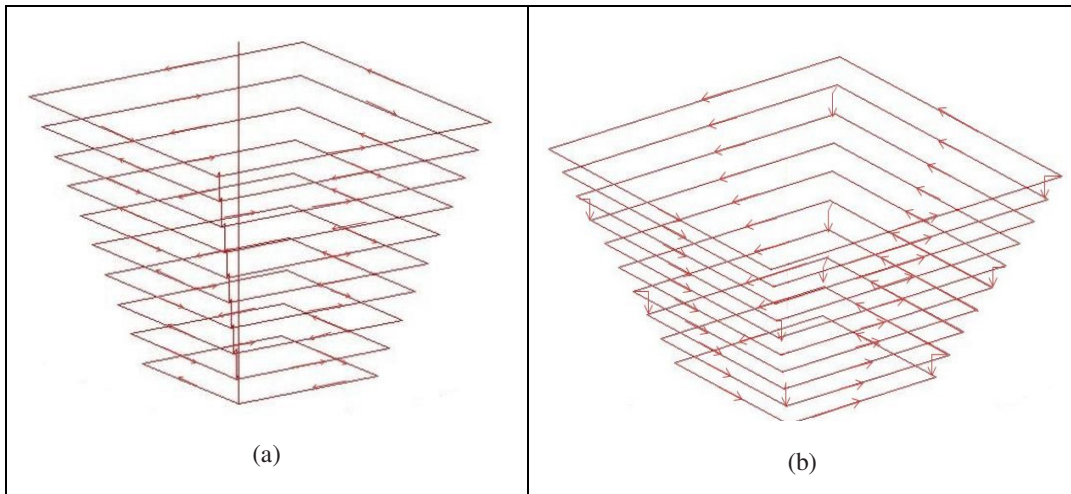


Fig. 3. Schematic showing (a) Bi-directional tool path; (b) Bi-directional tool path with distributed increment.

In the bi-directional tool path, the tool completes a cycle and a quarter of tool path cycle is added before it moves to next cycle. By doing this the position of tool change from one cycle to another cycle will change and scar mark is not be visible on the part geometry. Moreover by doing this forming force distributes uniformly along the edge of the geometry and enhances the geometric accuracy of the part. Bi-directional tool paths without and with distributed increment are shown in Fig. 3.

Blaga et al. [2] investigated the influence of profile tool path, spiral tool path and radial tool path on strain distribution, relative thinning and forces in ISF. They observed homogeneous strain distribution and lower strain values with spiral tool path over other tool paths. Forces are also more homogeneous with spiral tool path without any local peaks and valleys. Silvia et al. [6] observed that the movement of tool (upward or downward) has significant influence on thickness distribution and feasibility of producing sound cylindrical cups with vertical walls in multistage ISF. Some researchers [7] considered tool path as a variable and optimized the tool path for minimum thinning. By selecting appropriate tool trajectory it is possible to enhance the material formability. Mohamed Azaouzi and Lebaal [8] optimized spiral tool path using response surface methodology, sequential quadratic programming and finite element simulation. Their objective was to minimize the tool course subjected to the constraints on allowable thinning in the part. Most of the researchers used machining tool paths available in commercial CAM packages for incremental forming. Some efforts were made to generate the tool path specifically for incremental forming from STL files [3,9]. Rajiv Malhotra et al. [10] proposed a methodology to generate automatic spiral tool path with variable step depth for symmetric and asymmetric parts, by considering specified constraints on desired geometric accuracy and maximum specified scallop height while reducing the forming time. Rauch et al. [11] proposed a new approach for tool path generation to improve the accuracy of formed components. This new approach adapts the tool paths during the manufacturing of a part according to process data evaluations. Tool path adaptation is carried out by using CNC data. This ensures a high flexibility in incremental forming.

3. Methodology to get input file for numerical simulation

Different steps in numerical simulation of a general sheet metal forming process are shown in Fig. 4. Same steps are followed for numerical simulation of ISF also. But the tool path definition in ISF is very complex compared to other sheet metal forming operations. In conventional deep drawing and stamping this tool path is one dimensional and thus the punch/tool moves in one of principal directions. In case of spinning the tool path will have number of cycles which are two dimensional in nature, since only symmetric parts can be made by this process. Whereas, in incremental forming sheet is formed by continuous three dimensional motion of the tool. This tool path is generated by different procedures as explained in section 2.

Tool path generated by CAM package includes the position of tool center point followed by linear (G01) and circular interpolation (G02/G03). Circular interpolation can be clockwise (G02) or counter clockwise (G03). If tool is moving in linear path, it is represented as G01 followed by the destination point in the part program. If tool is moving in circular path, it is represented as G02/G03 followed by destination point co-ordinates and radius of the arc.

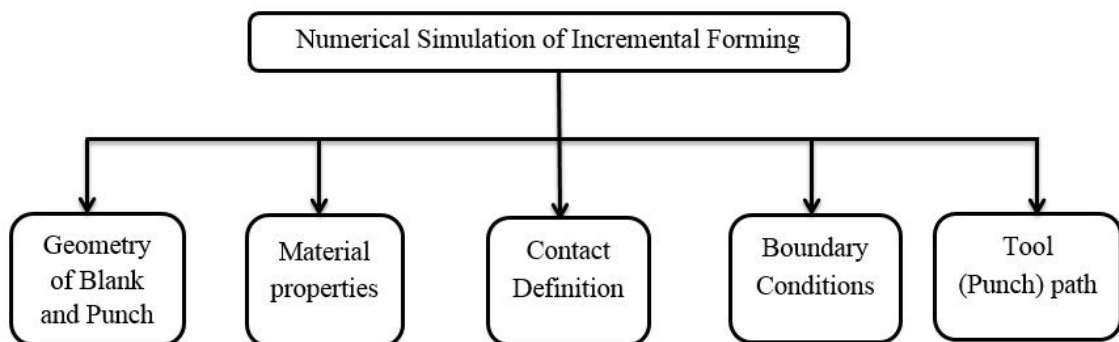


Fig. 4. Steps in finite element simulation of forming process

The part program generated using CAM package cannot be given as input for tool path in numerical simulation softwares. For numerical simulation the tool path should be defined in terms of position vs time, velocity vs time or acceleration vs time. In this section a methodology is proposed to convert the part program in to position vs time data in order to provide an input file for numerical simulation of incremental forming. A typical CNC part program is shown in Fig. 5.

```
G0 X0 Y0 Z10
G1 X-51.157 Y-28.244
G1 Z-5
G3 X-47.926 Y-32.052 R52.7673
G1 X-47.926 Y-32.052 Z-5
G3 X-45.438 Y-34.554 R55.0228
```

Fig. 5 A typical CNC part program

Linear interpolations are easy to assign whereas in circular interpolations, tool center point must be rotated around other center points generated by CAM software, which seems impossible to assign to the tool. Therefore in this study, the circular segments are divided into linear segments with chosen allowable error. The tool path in incremental forming is generally very long and it is difficult to do the position and time calculations manually. So in this study, Python is used to generate the ordered file from the part program generated using CAM package. This ordered file is an array of nX5 possessing type of interpolation, co-ordinates of tool position and radius of the arc. This ordered file is given as input to MATLAB to generate position vs time data.

The lines of nX5 matrix are read one by one by MATLAB program. Depending on the value of first element of row it is decided whether the interpolation is linear, clockwise or anticlockwise circular interpolation. For linear interpolation distance D between two points say (x_i, y_i, z_i) and $(x_{i+1}, y_{i+1}, z_{i+1})$ is calculated using equation (1).

$$D = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \quad (1)$$

For circular interpolation, the center of the circle is determined from the two given end points in the ordered file. In circular interpolation only x or y coordinate or both change. The z coordinate always remains same. For the two given end points, there are two possibilities of arcs. One corresponds to clockwise circular interpolation and other corresponds to counter clockwise interpolation. So, accordingly the center to be used is changed depending on the sense of interpolation. For example, as shown in the Fig. 6(a). there are two arcs having same end points (x_1, y_1) and (x_2, y_2) but when seen with respect to the center, one is clockwise and other is anticlockwise. The successive points on the circle are calculated using parametric equation of the circle given by equation (2).

$$\begin{aligned} x_{i+1} &= x_0 + r \cos(\theta_i + i\delta\theta) \\ y_{i+1} &= y_0 + r \sin(\theta_i + i\delta\theta) \\ 0 &\leq i \leq n \end{aligned} \quad (2)$$

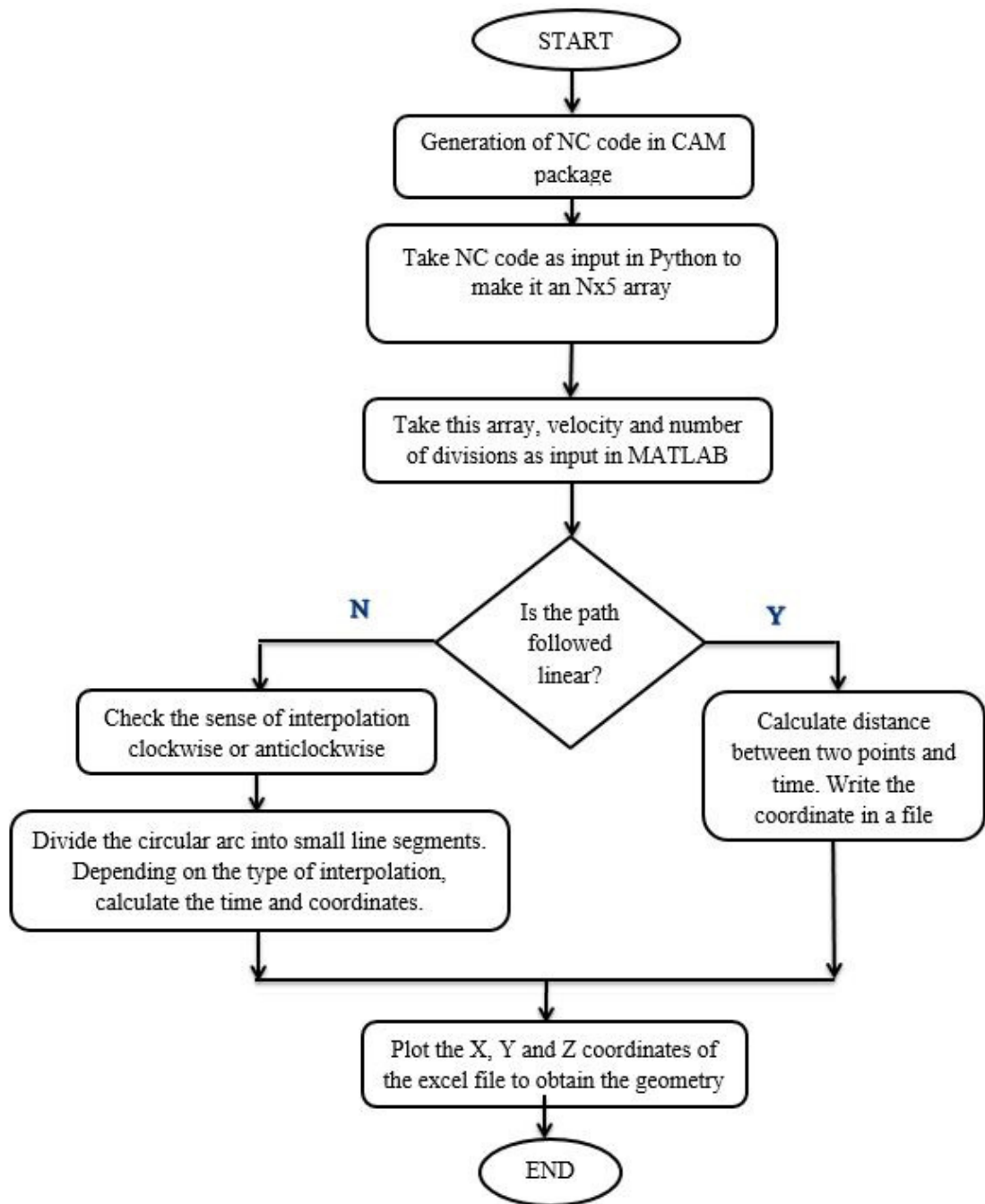


Fig. 7. Flowchart of proposed methodology for input files generation to CAE.

Where (x_0, y_0) is center of the circular arc, r is the radius of circle, θ_i is the angle with the positive X-axis measured in anticlockwise sense, $\delta\theta$ is the incremental angle calculated using equation (3) and n is number of divisions that satisfies the allowable error.

$$\delta\theta = \frac{\theta_f - \theta_i}{n} \tag{3}$$

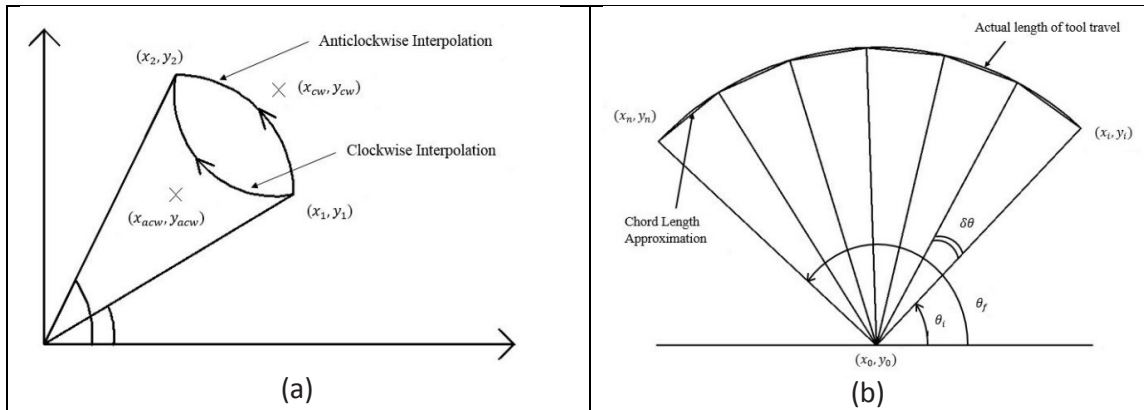


Fig. 6. (a) Schematic showing two arcs with same endpoints and different centers; (b) arc divisions.

Where θ_f is angle subtended by the end point of the arc with x-axis. Methodology of dividing the arc segment into number of linear segments is shown in Fig 6(b). The length of each line segment can be calculated using equation (1). The time required to cover each segment is calculated by multiplying the distance (D) with the average velocity of the tool (V). Fig. 7. shows the flowchart to generate the input file for numerical simulation of ISF using part program generated by CAM software.

4. Results and Discussion

Five different geometries are used for implementation of proposed methodology. First one is, Part with planar surfaces (pyramid), second one is part with curved surface (cone) , third one is part with curved and planar surfaces and fourth one is asymmetric geometry. The geometries were chosen so as to verify the current methodology for a variety of geometric shapes. Geometry of parts and generated tool paths are shown in Fig. 8 and 9 respectively.

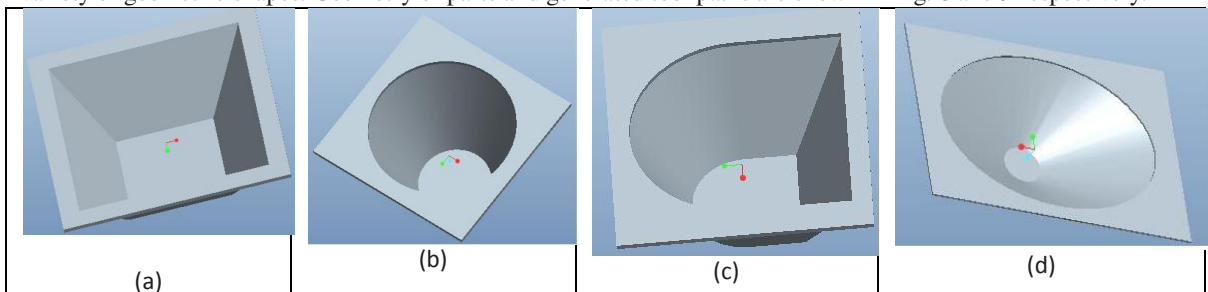


Fig. 8. Geometries used for testing proposed methodology (a) Pyramid, (b) Cone, (c) Part with curved and planar surfaces, (d) Asymmetric part geometry.

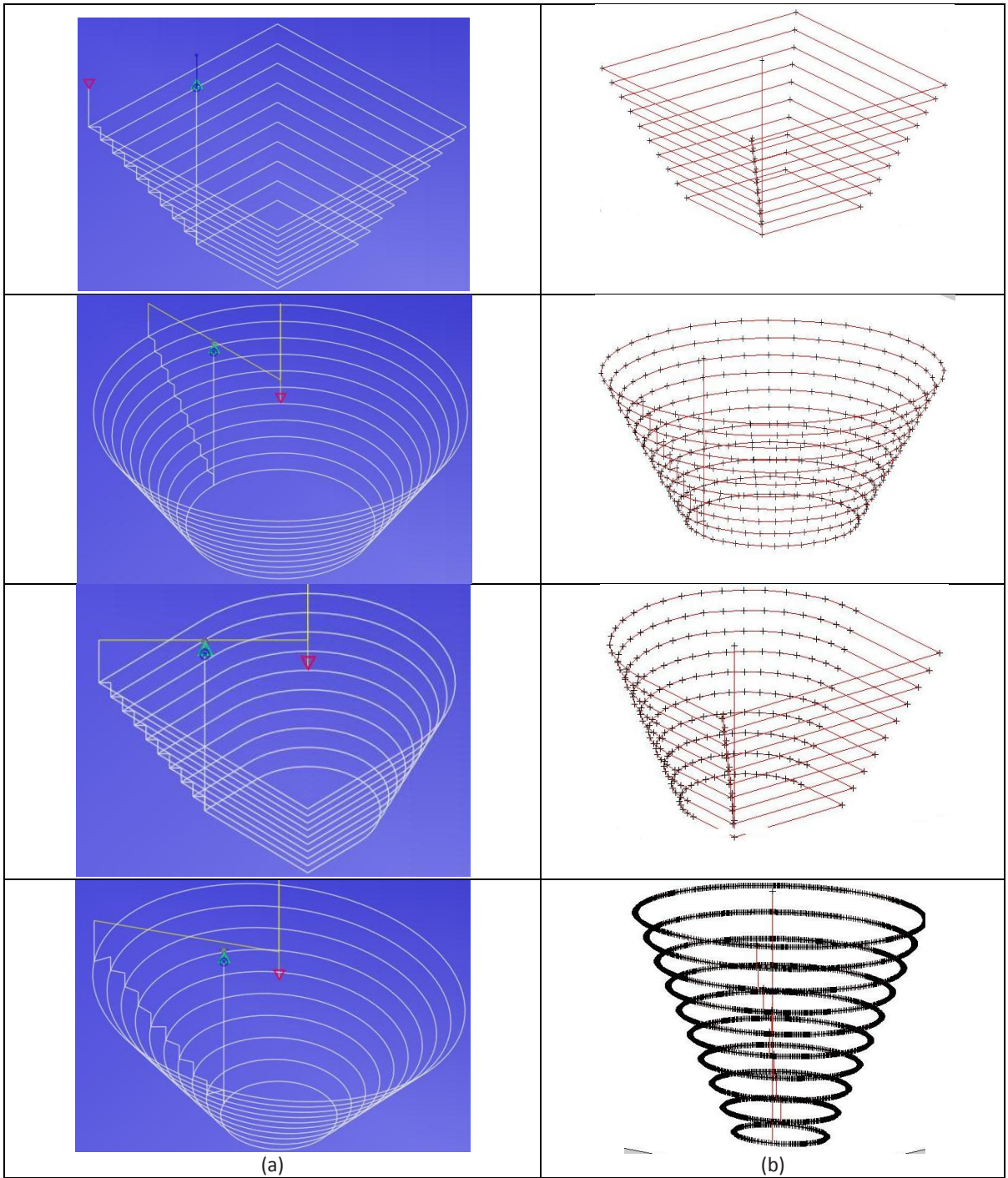


Fig. 9. Schematic showing (a) CAM tool path; (b) Tool path generated using proposed methodology.

4.1 Testing through numerical simulation

The position vs time data of tool, generated using current methodology and developed by implementation in Matlab is given as input to Ls-Dyna software to simulate the incremental sheet metal forming. Blank is defined as a deformable body and meshed with shell elements. The punch is defined as a rigid body and meshed with shell elements. The blank is fixed along its periphery. Two geometries as shown in Fig. 8(c) and 8(d) are chosen for numerical simulation. The deformed shapes at the end of the simulation in Ls-Dyna are shown in Fig. 10(a) and 10(b) respectively. It is evident from the Fig. 10 that the current methodology of tool path definition for numerical simulation works successfully.

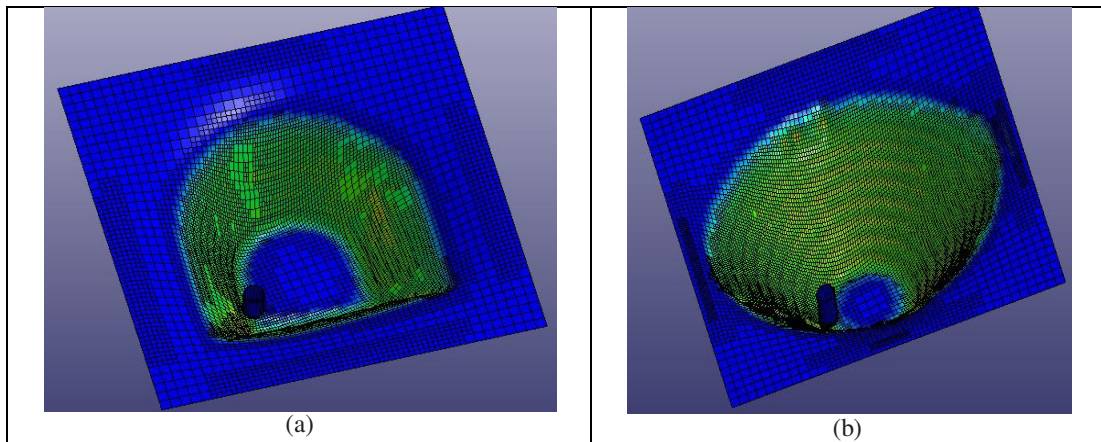


Fig. 10. Schematic showing deformed shape of (a) Asymmetric part; (b) Part with curved and planar surfaces.

4.2. Experimental Work

To verify the part program generated using CAM package, the experiments of incremental forming were carried out for part shown in Fig.8(d) on sample basis on CNC milling machine. Fig. 11(a) shows the experimental setup, 11(b) shows the hemi-spherical headed tool and 11(c) shows the formed part. Extra deep drawing (EDD) steel of 250 mmX250 mmX1 mm size held in fixture as shown in Fig. 11(a). A hemispherical headed tool of 10 mm diameter as shown in Fig. 11(b) is held in the machine spindle. The tool is made of EN 36 steel and heat treated to 60HRC. The fixture along with the blank is mounted on CNC milling machine table. The punch followed the specified path as per the part program and deformed the sheet in series of incremental steps until the final depth was reached. The shape of the part obtained after the end of forming is shown in Fig. 11(c).

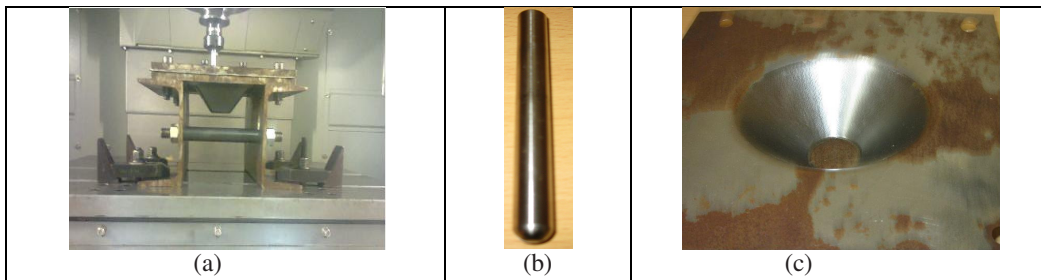


Fig. 11. Schematic showing (a) Fixture; (b) forming tool used for CNC ISF; (c) formed part.

5. Conclusions

From the Fig. 9 and 10, it is evident that the proposed methodology can generate the required tool path for numerical simulations directly from the NC part program generated using CAM package. The capability of program is verified with different kinds of geometries using numerical simulation package, namely Ls-Dyna as well as through actual incremental forming experiment. In all cases, the proposed methodology is able to generate the required tool path definition with good geometric and dimensional accuracy.

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