Simulated 3-axis versus 5-axis Processing Toolpaths for Single Point Incremental Forming

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Abstract. Accuracy and productivity of the parts manufactured by single point incremental forming (SPIF) are influenced by the proper selection of toolpaths. CAM software packages are often used for generating the toolpaths for the process. Literature survey have revealed that contour curves and spatial spirals are the most used toolpaths for SPIF. These toolpaths are generated using 3-axis approaches, meaning that the tool axis is maintained parallel to the vertical axis. The 3-axis approach was justified using 3-axis CNC milling machines as the main technological equipment for SPIF. However, nowadays, the wide spreading of both 5-axis CNC milling machines and industrial robots, with far superior kinematic capabilities justifies the research of more complex toolpaths for unfolding SPIF. In this paper, 5-axis toolpaths, where the tool is oriented by normal to machining surfaces are proposed and compared with 3-axis toolpaths, by means of simulation.

1. Introduction

Single point incremental forming (SPIF) is a manufacturing process based upon a combination of three basic movements (figure 1), which made it suitable for implementation on CNC (computer numerically controlled) machine-tools.

Figure 1. Basic movements involved in the SPIF process [1].
Movement I represents the vertical displacement of the punch, performed along the Z axis using incremental vertical steps, while movements II and III are usually performed in a continuous way by the workpiece in the horizontal (XY) plane.

By combining the above-mentioned movements, various toolpaths may be generated for unfolding the process. Contour curves (obtained by sectioning the shape of the part with planes parallel with XY plane) and spatial spirals are considered by the literature [2-4] as the most used processing toolpaths. CAM software packages are used for generating these toolpaths, even they are designated for milling, not for SPIF. However, some researchers prefer to use other approaches to generate the toolpaths [5-8]. Some results presented in the literature have also pointed out the fact that the toolpaths influence not only the accuracy of the parts, but also the reliability of the FEM (finite elements method) simulations [9].

Different approaches for optimizing the toolpaths, either by means of CAM software or by combining CAM and manual interventions are presented in [9-16]. Software packages developed by authors for optimizing the toolpaths is another approach presented in the literature [17].

2. Particularities of using CAM software packages for SPIF

Software CAM packages are often used generating the toolpaths for SPIF, even if they are designed for cutting processed. Using them for SPIF have some particularities, with regards of the processing tool and the workpiece.

The cutting tool which has the closest shape as the forming tool (punch) is the spherical mill. As presented in figure 2(a), the characteristic dimensions are similar for both tools. Figure 2(b) and 2(c) presents the shape of a spherical mill, as considered by a CAM software. The cutting edges are shown in figure 2(b), while in figure 2(c) the tool is depicted as a simple cylinder with a hemispherical tip, shape which could be considered identical with a punch used for incremental forming. However, the user must consider the fact that even if the cutting edges are not visible, the CAM program will calculate the form of the final part by taking into consideration the amount of material removed by these edges, between the initial workpiece and the shape defined by the 3D model of the part.

![Image](a.png) ![Image](b.png) ![Image](c.png)

**Figure 2.** The tool: (a) Characteristic dimensions of a spherical mill; (b) Shape taken into consideration by CAM programs with visible cutting edges; (c) Shape without visible cutting edges.

Consequently, the spherical mill may be taken into consideration as substitute for the forming tool when using CAM software for generating the processing toolpaths and the NC code for incremental forming. However, this fact will lead to some alterations, with regards to the phenomena occurring during the process: instead of material removing by means of the cutting process (simulated by the CAM program), the real forming process will displace the material by means of local deformations. Thus, instead of using the cutting edges of the spherical tool to cut through the workpiece, the tip of the forming tool will just move the layers of material.

The most used method of defining the workpiece for SPIF is to consider a casting workpiece, which has a similar shape as the final part and a stock, which may vary according to the processing strategy. It
is here to notice that the real workpiece a simple sheet of metal, which cannot be used as such by the CAM program.

3. Processed part
To test the proposed approaches, a test part was considered. The main idea was to use a part which is different from the simple cone of pyramid frustum shaped parts which are used as test part for SPIF. The part used for the simulated tests is presented in figure 3 and has a highly irregular shape.

![Figure 3. The test part.](image)

4. 3-axis toolpaths
Usually the first approach when considering 3-axis toolpaths are the contour curves, obtained by sectioning the part with parallel planes equally spaced on Z-axis. A 3-axis toolpath consisting of contour curves spaced at 6 millimetres on Z axis is presented in figure 4. The 6 millimetres vertical increment was used only for visualization purposes.

![Figure 4. 3-axis toolpath – contour curves.](image)

![Figure 5. 3-axis toolpath – 3D spirals.](image)

The second most used approach when considering 3-axis toolpaths is the spatial (3D) spiral. A 3-axis toolpath consisting spatial spiral using 6 millimetres as the spiral step is presented in figure 5. Again, the 6 millimetres value for the spiral step was used only for visualization purposes.

5. 5-axis toolpaths
To ensure that the tool is always oriented perpendicular to the processed surface, two new types of toolpaths, 5-axis based were generated.

The first toolpath is based upon contour curves, but the tool orientation is kept normal to the processed surface. The tilting angles of the tools were limited between 30° and 90° for X and Y axis,
while for Z axis the limits were set between $0^\circ$ and $360^\circ$. An example of such toolpath is presented in figure 6. The 6 millimetres vertical increment was used only for visualization purposes.

The second 5-axis toolpath is based upon the 3D spiral (figure 7), yet again the tool axis is always kept perpendicular to the processed surface. Same domains were set for the tilting angles, between $30^\circ$ and $90^\circ$ for X and Y axis, while for Z axis the limits were set between $0^\circ$ and $360^\circ$. The spiral step was set to 6 mm, for visualization purposes.

5-axis toolpaths can be unfolded either on 5-axis CNC machine-tools or 6 degree of freedom industrial robots. However, the complexity of such toolpaths requires the use of a kinematic model of the technological equipment, to simulate the movements of the mobile elements.

![Figure 6. 5-axis toolpath – contour curves.](image)

![Figure 7. 5-axis toolpath – 3D spiral.](image)

When performing the movements for a 5-axis toolpath, the collisions may occur not only between the tool and the workpiece, but also between the moving element of the machines (slides and rotating tables). A kinematic model of a 5-axis machine used for the simulation during this research is presented in figure 8. From figure 8 it can be also be noticed how the variation of the coordinated on all five axes of the machine-tool.

![Figure 8. Kinematic model of a 5-axis CNC machine tool performing a 5-axis toolpath – 3D spiral.](image)

6. Conclusions
A comprehensive comparison between the 3-axis and 5-axis toolpaths is quite difficult to be made only by means of simulations. However, it is here to consider the following facts:
- Spiral toolpaths are superior to contour curves because their continuity (only one lead-in and lead out throughout entire toolpath). It is well known that lead-ins and lead-outs became stress concentrators and could favor cracks occurrence.
- Keeping the tool always perpendicular to the processed surface could favor the forming process and improve the accuracy of the part (this has to be proven by future experimental work).
  
Productivity is also paramount for the SPIF process, consequently the simulated overall processing time could be taken into consideration when evaluating the efficiency of the toolpaths. Table 1 presents the values of the overall processing time for the four presented toolpaths. Similar technological conditions were considered:
- Punch diameter, 12 mm
- Vertical step for 3-axis and 5-axis contour curves, 2.4 mm
- Spiral step for 3-axis and 5-axis 3D spiral, 2.4 mm
- Punch speed, 200 rev/min
- Working feedrate, 200 mm/min

Table 1. Overall processing time for the proposed toolpaths.

| Toolpath               | Time (mins and secs) |
|------------------------|----------------------|
| 3-axis contour curves   | 27 mins 37 secs      |
| 3-axis 3D spiral        | 27 mins 32 secs      |
| 5-axis contour curves   | 28 mins 59 secs      |
| 5-axis 3D spiral        | 37 mins 07 secs      |

From table 1 it can be noticed that the kinematic complexity of generating the 5-axis 3D spiral toolpath is also accompanied by a significantly larger overall processing time. On the other hand, 5-axis contour curves toolpath can be unfolded in an overall processing time which is only slightly larger than the ones for 3-axis toolpaths.

From a simulation point of view, 5-axis contour curves add the advantage of keeping the tool perpendicular on the processed surfaces, while increasing the overall processing time only by a small amount.

However, further extensive experimental work must be performed to assess the accuracy of the parts and compare the advantages offered by 5-axis toolpaths with the increased processing costs due the use of a much more complex technological equipment (5-axis CNC milling machine instead of 3-axis CNC milling machine).

Acknowledgments
This research was funded by grant number no. 1/AXA1/1.1.1.A/18.05.2018, Cod SMIS 2014+: 121359; ID: P_34_469, “Dezvoltarea departamentului de cercetare al societății COMPA SA și obținerea unor rezultate inovatoare în domeniul industriei auto/Development of the research department of COMPA SA and obtaining innovative results in the field of automotive industry”.

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