Study upon the kinematic simulation of the incremental forming carried-on using a serial industrial robot

R E Breaz¹, S G Racz¹, C E Girjob¹ and M Tera¹*

¹Lucian Blaga University of Sibiu, Faculty of Engineering, Victoriei, 10, Sibiu, 550024, Romania

*E-mail: melania.tera@ulbsibiu.ro

Abstract. Incremental forming with contact between tool-sheet metal workpiece in a single point is an unconventional process which allow the user to manufacture parts by combining the vertical movement of the tool along Z-axis and the horizontal movements of sheet metal workpiece, which are performed in XY plane. As technological equipment able to control coordinated movements on three axes, CNC machining centers and industrial serial robots with six degrees of freedom are the most suitable. The paper introduces a study regarding the use of robots as technological equipment for the process, by means of simulation. Supplementary degrees of freedom and singularities avoidance are also considered.

1. Introduction

At present the industry requires an enormous variety of parts in all fields. Thus, it can be observed that if we refer to the parts made of metal sheets, one of the most important technological processing processes are the plastic forming processes. Conventional forming operations, which are specifically designed to meet high productivity lack in terms of flexibility, required were small numbers of parts with different shapes and dimensions have to be manufactured by means of plastic deformation [1, 2].

Due to the growth of sheet metal parts simultaneously with requirements of reducing processing times, incremental forming with contact between tool-sheet metal workpiece in a single point is beginning to be an increasingly studied process, although not yet accepted fully by the industry.

Serial industrial robots have usually large workspace and advanced kinematic, thus allowing the incremental forming of larger parts, with complex shapes [3]. To this is added the great flexibility in terms of obtaining parts of different types and sizes or parts in small batch or even unique parts which made incremental forming process carried on industrial robots an important topic for research.

The tools used for single point incremental forming are very simple ones as one can notice in figure 1 (a) its compound of a punch with a spherical end 1, active plate 4, holding plate 2 and sheet metal 3 [4, 5].

The process is unfolded by coordinating the vertical movement of the tool (punch) I, along Z-axis, according to figure 1 (b) with the horizontal movement of the sheet metal workpiece II, which is usually carried-on in the XY plane. Usually, the vertical movement is a discontinuous one, performed in incremental steps, while the movement in XY plane is a continuous one. The horizontal movement is performed by the blank, in case of using a CNC machine where X and Y machine slides are moving. Or, when using an industrial robot, the horizontal movement can be carried-on by the punch. In figure 1 (c) one can notice the movement on the X axis marked with II. These steps are continued until the final form of the parts is achieved, in this case in figure 1 (c) is presented a conical part. As we can see the SPIF involve three basic movements of the punch and can be achieved on CNC machines tools or industrial robots.
Studies in this field reveal the use of industrial robots for SPIF but in general for parts obtained by simple trajectories without any difference from the technological process presented above, and which can be used identically on a CNC machine tool. So due to the fact the industrial robots has superior kinematics which allow coordinated multi-axes movements, incremental forming can be carried-on on robot in order to manufacture a conical part, as presented in figure 2 (a) [6-9].

Figure 1. Single point incremental forming process.

Figure 2. Obtaining a conical part by SPIF on industrial robots [3, 6].
2. Simulation of the process carried-on using a serial industrial robot

In order to simulate the machining process, a Kuka KR 210 R2700 Extra robot was used. The software used for simulation was Sprut CAM Robot. The simulation process requires a kinematic model of the robot, which is based upon the 3D geometric model provided on KUKA website. After saving every rotary axis of the 3D model as separate module, a new kinematic model is built, using the facilities of Sprut CAM Robot software. The kinematic model of the robot is based upon a specific template for KUKA robots (provided by Sprut CAM) and it is saved in .xml format.

Aside of using the standard 3D geometric model of the robot for building the kinematic model, the user has to model the end-effector of the robot, which in this case consists of the spindle motor (provided as standard for Extra class of KUKA robots and the forming tool – punch, which has to be modeled by the user).

The kinematic capabilities of the six degrees of freedom robot can be significantly enhanced by adding a supplementary unit, as working table. Thus, a supplementary Kuka DKP 400 rotary table was also used. KUKA company has specifically developed this unit to provide two supplementary degrees of freedom for the robots which are specifically designed for manufacturing tasks.

Sprut CAM Robot is a CAM software intended to be used as solution for manufacturing operations, both subtractive (milling, cutting) and additive (cladding). However, incremental forming is not supported by the software, so specific measures have to be taken:

- The punch was emulated by means of a spherical mill;
- The workpiece was emulated by taking into consideration the final form of the part and adding material to it (using the “casting workpiece” facility provided by the software);
- Forming processes involve the redistribution of the material, while cutting/cladding processes involve material removal/addition. Thus, the machining simulation was not able to represent the real incremental forming process.

A screenshot within the simulation process are presented in figures 3.Figure 4 present a detailed view of the part during SPIF process.

3. Trajectories used for incremental forming

The simulated machining layout allowed the use of several trajectories:

A. Circular trajectories where each circle was generated by intersecting the solid model of the workpiece using planes parallel with XY plane, at different values on Z-axis (increments). The tool axis keeps its orientation (Z axis) – figure 5 (a);
B. Circular trajectories where each circle was generated by intersecting the solid model of the workpiece by planes parallel with XY plane, at different values on Z-axis (increments). The tool axis remains always perpendicular on the workpiece surface figure 5 (b);

C. Spiral continuous trajectory, where the tool axes remain fixed - figure 5 (c);

D. 3D spiral continuous trajectory, where the tool axis remains always perpendicular on the workpiece surface - figure 5 (d).

The first two trajectories are discontinuous ones, because the tool has to performed lead-in and lead-out movements for each circle, while the last two trajectories are continuous ones. Only one lead-in and one lead-out movements are performed for the continuous trajectories.

Move-in and move-out movements on the sheet metal workpiece surface create stress concentrators on the surface of the sheet metal workpiece, which could finally lead to crack, thus continuous trajectories, which much less lead-ins and lead-outs are considered more advantageous.

On the other hand, keeping the tools axis perpendicular on the workpiece surface is believed to reduce the thickness reduction of the final part.

It is here to mention the fact that some of the elements of the proposed trajectories are generated automatically by the software, some elements have to be defined manually by the user (lead-ins, lead-outs for example), elements which can dramatically influence the plastic behavior of the processed parts. At this stage, the main purpose of the simulation was to test if the simulated experimental layout (robot + end effector with punch + working table) is able to generate and perform the above presented trajectories. The occurrence and removal of singularities and workspace limitation were also targeted by this work. Singularities can be identified by the CAM program, while workspace limitations can be avoided/removed by changing the initial position of the working table (related to the robot) and changing the initial position of the workpiece (related to the working table).

A comprehensive experimental program is now in progress to validate these assumptions.

![Figure 5. Generated toolpaths.](image-url)
4. Conclusions
In order to simulate single point incremental forming machining process, a Kuka KR 210 R2700 Extra industrial robot was used and a Kuka DKP 400 rotary table.

Several types of trajectories were chosen for study in order to obtain a conical part. So, first of all a two discontinues trajectories was proposed, and after that, in order to avoid stress concentrators on the surface of the sheet metal blank, it was designed two continues trajectories.

The study also suggested using for SPIF two methods for the position of the punch related to the sheet metal workpiece. Thus, the first is the classic method in which the punch is vertical, and then the second method in which the punch is perpendicular on the sheet metal was used.

Even if the simulation process had certain drawbacks, presented in the paper, because a CAM software which does not offer support for incremental forming was used, there are also certain advantages for the user. Among them, the fact that the limits of the working space of the robot could be tested, the singularities could be identified and removed and the possibilities of achieving specific trajectories were tested are the most significant.

Further researches will be performed in order to experimentally test how will affect the proposed tool paths the plastic behavior of the parts, mainly the thickness reduction and the strain and stresses. Also, the effects upon the shape and dimensional accuracy will be studied.

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