Influence of vertical step on forces and dimensional accuracy of SPIF parts – a numerical investigation

M O Popp, G P Rusu, V Oleksik and C Biris
Lucian Blaga University of Sibiu, Department of Industrial Machinery and Equipment, Emil Cioran Street No. 4, Romania

E-mail: gabriela.rusu@ulbsibiu.ro

Abstract. Single point incremental forming (SPIF) is a new flexible sheet metal forming process characterized by low costs and the possibility to produce prototype parts without the need for a specific die. This is one of the reasons why this process is nowadays used for manufacturing of highly customized small series parts. The process involves the usage of a hemispherical punch which gradually deforms the sheet metal blank fixed by two simple clamping rings, by following a path until the final shape of the product is obtained. The aim of this paper is to investigate and analyze the influence of the vertical step over forces involved in the process and obtained geometrical accuracy, which is one of the main drawbacks for large scale implementation of the process. A numerical analysis was carried out through finite element method with different step size for frustrum pyramid shaped parts made from the same material. In this way, the most appropriate vertical step can be chosen for further experimental research in order to obtain the most accurate parts and with as little stress as possible on the equipment involved in the process.

1. Introduction

Current trends in the automotive industry and not only aim to reduce costs and production time as much as possible, so new methods are needed to keep up with the demand. If until now, when a new car concept appeared, it was necessary to modify some components of the car body, the engineers tried to optimize a mold as well as possible, and later different defects of the part were highlighted and this whole process was resumed again. Now with the help of the incremental forming process they can produce prototypes at a much lower cost given that this process does not require a mold, but only two retaining rings for the sheet and a punch to deform it. This process receives a lot of attention among researchers to be as optimal as possible, and the deformed parts to have the best possible accuracy and as few defects as possible.

During the incremental forming process, a punch follows a predefined toolpath gradually deforming the sheet fixed with the help of two retaining rings. Figure 1 shows the principle of single point incremental forming process. For implementation of this process it is suitable to use numerically controlled machines due to the high stiffness and rigidity of the machines [1, 2] or industrial robots [3] due to the high flexibility of the shapes that can be made with them [4, 5]. Some researchers tried to build their own equipment for this process such as in paper [6]. The toolpath design can be done with the help of CAM software dedicated for milling applications or other new custom software proposed by researchers which generates toolpaths like in paper [7].
Figure 1. Single point incremental forming process [8].

The incremental forming process has some important advantages, such as: low production costs [9], high flexibility and customization of parts [10] and the material deformation is high [11] and suitable for prototype size production [12]. However, this process comes with some disadvantages that prevent its industrialization and implementation in large series production. One of these disadvantages and perhaps even the most important is given by the low accuracy of the parts manufactured by this process, regardless of the variant of forming procedure (with punch / total or partial die / multipoint / etc.).

Researchers have shown a concern for various factors that may influence the dimensional and shape accuracy of the part, but also on its roughness. The toolpath that the punch follows can have different influences on the deformation of the sheet as highlighted by Verbert with his experiments performed in paper [13]. Among the parameters studied by them is the effect of temperature on the deformability of the material, a problem that was investigated by Duflou in paper [14] where he explained how to perform the process of incremental forming with a laser in order to observe the behavior of the material in these conditions. The influence of lubrication for this process is also important to be studied. The use of lubricants is essential for the contact between two or more components of a mechanism and any deformation process because the life of the punch can be extended due to reduced friction and wear, and also improved heat distribution [15]. The vertical step size of the punch is another parameter which is influencing the accuracy of the part shape and can cause the phenomenon of waves that can be seen in figure 2.

The purpose of this paper is to study the influence of the vertical step size on the accuracy of the part and on the forces, which take place during single point incremental forming process. In the paper done by Lu and his collaborators are presented differences between the conical parts made by incremental forming process with the size of vertical steps of 0.1 mm, 0.6 mm and 1.4 mm. The material used by the researchers is A 7075-O, and the results obtained showed that the parts for which the 0.1 mm vertical step was used have a better roughness and are more accurate. [16].

Figure 2. Waves effect on sheet metal according to vertical step size [16].
2. **Numerical investigation**

For the investigation of the influence of the vertical step size on the single point incremental forming process the sheet metal would be deformed in the form of a frustrum pyramid with the large base size 106mm, depth of 20 mm and the wall angle of 60°. In the first stage of the research that are presented in this paper four finite element analysis were performed with only one parameter varied that is the vertical step size. The FEM model is presented in figure 3 and consists of the following parts: two discrete rigid retaining rings, a analytical rigid tool and the deformable sheet metal which is the interest part. The undeformed shape of the sheet has the size of 200 x 200 mm and a thickness of 0.6 mm. The mesh of the steel sheet blank was performed using S4R elements (an 4-nodes, quadrilateral, stress / displacement shell element with reduced integration and a large-strain formulation) [17] with 6 points of integration. The blank used is made of structural steel S235 which according to the European standard EN10025 has the mechanical properties presented in Table 1. The material characteristics needed for finite element analysis were previously obtained by the tensile test, thus determining the plastic curve of the material.

![Analytical model with 60° wall angle frustrum pyramid](image)

**Figure 3.** Analytical model with 60° wall angle frustrum pyramid.

| Material | Yield stress Rp0.2 [MPa] | Tensile strength Rm [MPa] | Elongation A [%] |
|----------|--------------------------|---------------------------|------------------|
| S235     | 235                      | 360 – 510                 | 26               |

The two retaining rings are encastered so the sheet metal is held fixed and the tool has applied a displacement in all the directions, so it follows the trajectory necessary to create the frustrum pyramid.

3. **Results and discussion**

This section presents the results obtained from the finite element analyses that were performed. In figure 4 the profiles of the pieces are presented in comparison to the theoretical profile of the frustrum pyramid. It can be observed that in the case of the toolpath that uses the vertical step of 0.25 mm the profile is closer to the theoretical profile and that the sheet bending is much smaller compared to the other three variants.
Table 2 shows the differences in part accuracy obtained between the values of the vertical step and it can be seen that the most favorable case is when the step size of 0.25 mm is used.

Table 2. Springback, thickness reduction and maximum force on Z axis (Fz).

| Vertical step [mm] | Springback [mm] | Thickness reduction [%] | Maximum value of the force measured on vertical axis Z [N] |
|--------------------|-----------------|-------------------------|--------------------------------------------------------|
| 0.25               | 0.87            | 55                      | 1182                                                   |
| 0.5                | 0.88            | 56.7                    | 1287                                                   |
| 0.75               | 0.83            | 56.7                    | 1389                                                   |
| 1                  | 0.21            | 56.7                    | 1600                                                   |

Figure 5 presents the principal strains for all the vertical step size that were simulated and it can be observed that if the step is smaller the strains are bigger.

Figure 5. Principal strains for all the vertical step size.
The forces distribution in relation with the depth of the frustrum pyramid are shown in figure 6 and it can be observed that the smallest size of the vertical step presents the smallest $F_z$ forces whereas the 1 mm step size presents the highest forces on Z axis. The results show that the forces are reduced with 26% in the case when the step size is 0.25mm as against of 1mm. This means that the forces for the minimum step size are reduced with a quarter of the forces of the maximum size step.

![Figure 6](image)

**Figure 6.** $F_z$ distribution over depth of frustrum pyramid.

Thickness reduction is represented in figure 7 for the most favorable case of the vertical step, 0.25mm.

![Figure 7](image)

**Figure 7.** Thickness reduction for the vertical step size of 0.25mm.

4. Conclusions and further research
As can be seen from the results obtained from the numerical investigations performed using the ABAQUS / EXPLICIT finite element analysis for the 4 variations of the vertical step: 0.25 mm, 0.5 mm, 0.75 mm and 1 mm; the smallest vertical step brings the most advantages in terms of dimensional and shape accuracy, but also in the case of the forces obtained. Following these analyzes, it can be concluded that the smaller the vertical step is, the higher the precision of the part is and the forces can be reduced in the case of 0.25 mm to almost half of the values obtained in the case of 1 mm step size, and with the help of the research carried out in the field, it can be shown that a big vertical step size may affect the roughness of the part in such a way that it can be observed with the naked eye. In addition, it can be observed that by using different vertical steps there is no major influence on the thinning of the material.
Regarding future research, the authors of this article propose to verify the influence of various factors on the accuracy of the shape and size of the part using a KUKA KR210 industrial robot which is in the laboratories of the "Center for Studies and Research for Plastic Deformations" from University Lucian Blaga of Sibiu.

5. References

[1] Tera M, Breaz R, Racz S and Girjob C 2019 Processing strategies for single point incremental forming – a CAM approach Int. J. Adv. Manuf. Technol. 102 pp 1761-1777
[2] Bologa O, Breaz RE and Racz GS 2018 Using the Analytic Hierarchy Process (AHP) and fuzzy logic to evaluate the possibility of introducing single point incremental forming on industrial scale Procedia Computer Science 139 pp 408-416
[3] Breaz RE, Bologa O and Racz GS 2017 Selecting between CNC milling, robot milling and DMLS processes using a combined AHP and fuzzy approach Procedia Computer Science 122 pp 796–803
[4] Crenganis M and Csiszar A 2019 A Dynamic Model for KUKA KR6 in SPIF Processes Material Science Forum 957 pp 156 – 166
[5] Bârsan A 2019 A Brief Review of Robotic Machining Acta Universitatis Cibiniensis 71
[6] Allwood J M, Houghton N E and Jackson K P 2005 The design of an incremental sheet forming machine Advanced Materials Research 6-8 pp 471–478
[7] Tisza M 2012 General overview of sheet incremental forming Journal of Achievements in Materials and Manufacturing Engineering 55 pp 113–120
[8] Nasulea D and Oancea G 2018 Integrating a New Software Tool Used for Tool Path Generation in the Numerical Simulation of Incremental Forming Processes Journal of Mechanical Engineering 64 pp 643-651
[9] Micari F, Ambrogio G and Filice L 2007 Shape and dimensional accuracy in Single Point Incremental Forming: State of the art and future trends Journal of Materials Processing Technology 191 pp 390–395
[10] Filice L, Ambrogio G and Gaudioso M 2013 Optimised tool-path design to reduce thinning in incremental sheet forming process International Journal of Material Forming 6 pp 173–178
[11] Oleksik M 2018 Comparative study about different experimental layouts used on single point incremental forming process Acta Universitatis Cibiniensis. Technical Series 70
[12] Breaz R E and Racz S G 2019 Considerations Regarding the Industrial Implementation of Incremental Forming Process Materials Science Forum 957 pp 111–119
[13] Verbert J, Duflou J R and Lauwers B 2007 Feature Based Approach for Process Key Engineering Materials 344 pp 527–534
[14] Duflou J R, Callebaut B, Verbert J and De Baerdemaeker H 2007 Laser Assisted Incremental Forming: Formability and Accuracy Improvement Formability and Accuracy Improvement. CIRP Annals 56 pp 273–276
[15] Tisza M and Fulop T 2001 A general overview of tribology of sheet metal forming Journal for Technology of Plasticity 6 pp 11–25
[16] Lu H, Li Y, Liu Z, Liu S and Meehan P A 2014 Study on step depth for part accuracy improvement in incremental sheet forming process Advanced Materials Research 939 pp 274-280
[17] *** Abaqus documentation

Acknowledgments

This research presented here was partially financed by a grant of the Romanian Ministry of Research and Innovation CCCDI-UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0446/ nr. 82 PCCDI/2018, within PNCDI III, project title: “Intelligent manufacturing technologies for advanced production of parts from automotive and aeronautics industries”.