Research on manufacturing of pyramidal frustum parts using single point incremental forming process

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Abstract. The incremental sheet metal forming is a flexible "die-less" process used to manufacture sheet metal parts in cold pressing domain. Especially talking about single point incremental forming, it is a process which does not require a special die to allow the sheet metal forming. To implement this process, a fixing device and a simple rounded tool are needed. The paper presents some research on the influence of a support plate upon the parts dimensional precision. Because, the main advantage of single point incremental forming process is the flexibility, in experiments, a fixing device that it was initial designed for incremental deformation of frustum cone parts, is used to deform pyramidal frustum parts. Different configurations of pyramidal frustum parts are simulated using a finite element method and a special software tool named TMPG, to check if the sheet material, deep drawing steel DC05, can be deformed without fracture. The manufactured parts are measured using a 3D scanner, and a comparison with the 3D CAD models of the original parts is made.

1. Introduction

The products marked all over the world is in a continuous changing in the last years. The products from all the industry domains are now redesigned and revised more often than before to satisfy the final costumer’s needs. Taking into consideration those facts, most of the products manufacturers are now focused to implement in their plants, flexible manufacturing processes that can be able to produce different parts shape with minimal technological changes, in a short time and with minimal costs [1].

Incremental sheet metal forming (ISF) is a flexible manufacturing process in cold pressing industry. It uses a simple forming tool and a sheet metal fixing device to deform a sheet metal blank to a required shape. The deformation is caused locally by the forming tool, which follows a CNC programmed toolpath on a CNC machine. There are two generally types of incremental sheet forming process: single point incremental forming (SPIF) and two points incremental forming (TPIF) [2]. The main difference between those two processes is that in SPIF there is one single contact point between tool and sheet, and in TPIF there are two or more contact points between the forming tool and the sheet metal blank. The working principle for both processes are well known, being already described in many papers. Even if the process it is called “die-less” [3], [4] it is not totally true, especially for TPIF but also for SPIF [5], [6]. For both process implementation, a device for sheet metal blank fixing is needed, called fixing device. In this paper is presented how a component of the fixing device influences the dimensional precision of the final parts. Talking about precision, some researchers claim that, in cold pressing industry, the most of the sheet metal parts require a dimensional precision of less than ±1mm, or even less down to ±0.5mm [6]. Because of different reasons, the precision of the final parts processed using
ISF exceed those limits. There are many researchers who have made proposals to improve the dimensional accuracy of the parts manufactured using ISF. Essa and Hartley [7] proposed methods to improve the part accuracy for all part areas, for the upper radius area, the walls area and for the bottom area, those being verified through finite element method (FEM). To improve the part upper radius precision, Essa [7] proposes the use of a support plate as a component of the fixing device, to support the part flange as close as possible to its tapered wall. Essa also sustains that using a supporting tool on the other side of the part during deformation, will improve the walls accuracy, and extending the tool path to be processed also the parts bottom, the dimensional precision will be also improved in these part area. To improve the parts accuracy were proposed solutions such as [1]: using a smaller forming tool diameter and a smaller incremental step down [8] or forming the part using multi-pass toolpath strategy [9], [10], using FEM analysis to obtain the part dimensional deviations from the 3D model and then generate the forming tool path to compensate those deviations [11], using a modular device which support the part on the opposite side [12], or heating the blank to improve its plasticity using local or total material heating [13], [14]. In the literature can be founded many solutions to improve the ISF parts accuracy, presented by different authors in their papers.

2. Research description
One of the major advantage of the ISF processes and especially of the SPIF process in particular, is its high flexibility [1]. It means that using the same set of tools, fixing device and forming tool it can be processed many parts with various shapes. According to its advantage, using the same forming tool and more important, the same shape, dimensions and components of the fixing device, can be deformed different parts shapes with different dimensions - figure 1, with almost same result in terms of dimensional precision. Essa and Hartley presented in a paper [6], research based on FEM analysis regarding the influence of the support plate on the part upper radius precision, in SPIF. In the current research, the authors highlight how the shape and the dimensions of the support plate, generally designed for cone frustum shape parts deformation, influences the geometry accuracy when it is used for pyramidal frustum parts manufacturing. If the final parts will have a good dimensional precision even if is not used a dedicated support plate, can be concluded that the SPIF process has a very high level of flexibility.

Figure 1. Example of parts shape that can be deformed using SPIF.
In the research, a fixing device already designed and manufactured to be used for cone frustum shapes [4], is used to deform different configurations of pyramidal frustum parts. The fixing device component which has direct contact with the part flange is the support plate component. Its role is to provide a good support of the part flange as close as possible to its tapered wall to obtain a good dimensional accuracy of the part upper radius area. The existing fixing device is composed from a lot of components including the support plate which has a cylindrical hole with 101mm diameter. This hole allows incremental deformation of frustum parts which has a base cone diameter up to 100mm, keeping a small free space $S$ of 0.5mm between the support plate edge and the part wall to avoid a sudden sheet bending and the material fracture. In figure 2 are presented the fixing design components, details about the support plate and dimensional conditions for a cone frustum part deformation. Therefore, the research is focussed on the upper radius precision obtained on pyramidal frustum parts manufactured using the support plate that was initial designed to deform cone frustum parts.

![Figure 2](image2.png)

**Figure 2.** Example of parts shape that can be deformed.

The setup used for incremental deformation of the pyramidal frustum parts is composed from the fixing device above mentioned, a simple rounded forming tool which has a 12mm diameter and a 3 axis milling machine, Victor Vcenter-55 [15]. Five dimensional configurations of pyramidal frustum parts were processed. Each configuration was named according to its dimensions as is presented in figure 3: the name of the part shape PYRAMID, $LxL$ - the dimensions of the pyramid base, $H$ - the part height and $\phi$ - the part draw angle. The biggest pyramid base that can be deformed using the existing support plate is 79x79 mm. A unique incremental step depth $\Delta z=0.5mm$ was used for all parts. The sheet metal material is a deep drawing steel DC05 with 1mm thickness.

![Figure 3](image3.png)

**Figure 3.** The five pyramidal frustum parts configuration processed.
3. Process numerical simulation

Before to start manufacturing of all the five parts, the deformation process was first simulated using a finite element analysis, to check if using the mentioned conditions, the sheet material can be deformed without fracture. The FEM models preparation was done in ANSYS APDL software, the analysis was solved in LS-Dyna and the results were post-processed in LS-PrePost. For tool path implementation in ANSYS APDL was used the software tool TMPG developed by the authors [15] which allows to obtain the data for tool movements description in ANSYS APDL in a few minutes, using the tool path generated in CATIA V5, Advanced Machining workbench without parametric programing method [16]. An updated Lagrangian formulation is used, being the most suitable law to update the simulation conditions on each time increment in an ISF process. The sheet metal blank is defined as an elasto-plastic material, and the components of the fixing device are defined as rigid bodies. The “Form/1-way (FOSS)” type of contact is used between the forming tool and sheet metal blank using a friction coefficient of \( \mu = 0.08 \). All the components are designed as shell elements type, “Thin shell 163” [17].

The first simulation was done for the biggest part from all five configurations, continuing decreasing the dimensions until all the five parts were simulated. The FEM results were unexpected because, none of all configurations were able to be deformed without fracture. The first part that can be deformed according FEM was a part with the dimensions of the pyramid base 55x55mm, configuration PYRAMID-LXL-55x55-H20-\( \phi \)55. This configuration was not planned in the experimental plan. On a detailed analysis of the fracture occurrence in FEM for all simulated part, a detail was identified, that the fracture always occur when the forming tool is moving during one of the part planar face. In CNC, when the tool is moved along a linear path, as in case of pyramidal parts planar faces, the tool positions described in the CNC file are the start point and the end point where the tool has to arrive. In numerical simulation of the SPIF process, the deformation process are simulated in each tool position. In the case of long linear tool movement, in FEM simulations the tool path should be divided in multiple small linear segments, otherwise the material will be sudden tensioned, tending to brake. For circular interpolations on the part radius area, the tool path is already described as multiple small linear segments, the authors decided to force also the linear toolpath generated in CATIA V5 to be composed from multiple segments as is shown in figure 4.

![Figure 4. The tool path before and after the divided linear interpolations](image)

Using the above presented strategy, the parts deformation process was again simulated starting this time with the smallest configuration planned. Even using this strategy, the only part configuration able to be deformed without material fracture, according to FEM results, was PYRAMID-LXL-60x60-H20-\( \phi \)50. In figure 5 are presented the results for all the five part configurations. In this figure can be seen how the material for four of the configurations is bended, and even if the material fracture is not visible, on the obtained axial force plot can be seen a sudden force drop to 0.
Figure 5. Numerical simulation results for all five configurations of pyramidal frustum parts.

4. Parts manufacturing and measurements
Even if according to FEM simulations, the parts should have been unable to be deformed without fracture, all the five configurations were successfully deformed and they are presented in figure 6. For a better comparison in terms of dimensional precision, it was deformed also a cone frustum part which has an upper diameter of 100mm, and the same height and the same draw angle as the pyramidal parts had. The cone frustum part was named CONE-D100-H20-ϕ50.

Figure 6. Five pyramid frustum part and one cone frustum part deformed using SPIF.

All the parts were measured using a blue light 3D scanning technology [18]. The 3D scanner COMET L3D was used to scan all six parts and to obtain the clouds point for each part. Each cloud of points was processed in CATIA V5 software system by filtering and meshing, to obtain in a final CAD stage the scanned upper part surface. Each surface obtained through the 3D scanning method was compared with the theoretical surface meaning the surface designed as initial 3D model. In figure 7 are presented the section planes and the comparison between the CAD profile and the obtained measured profile for PYRAMID-LXL-60x60-H20-ϕ55 configuration in each section. For each section, a measurement of the deviation of the upper radius area in comparison with the designed CAD model is shown. All the deviations from the CAD model measured in both sections and also the free space S, between the part wall and the support plate are summarised in table 1.
Figure 7. The section planes and section profiles for PYRAMID-LXL-60x60-H20-ϕ50 configuration.

Table 1. Parts deviations according with the free space S.

| Part configuration | Deviation on 0º section plane (mm) | Space S on 0º section plane (mm) | Deviation on 45º section plane (mm) | Space S on 45º section plane (mm) |
|--------------------|-----------------------------------|----------------------------------|------------------------------------|----------------------------------|
| PYRAMID-LXL-60x60-H20-ϕ50 | 3.755 | 21.668 | 2.056 | 14.162 |
| PYRAMID-LXL-65x65-H20-ϕ50 | 3.718 | 18.749 | 1.797 | 10.033 |
| PYRAMID-LXL-70x70-H20-ϕ50 | 3.653 | 16.668 | 1.577 | 7.091 |
| PYRAMID-LXL-75x75-H20-ϕ50 | 3.435 | 13.917 | 0.707 | 3.2 |
| PYRAMID-LXL-79x79-H20-ϕ50 | 3.382 | 11.875 | 0.119 | 0.212 |
| CONE-D100- H20-ϕ50 | 0.696 | 0.5 | 0.696 | 0.5 |

The pyramidal frustum parts deviations were represented in two plots, one for the measurements in the 0º section plane and another for the measurements in the 45º section plane. It is easy to be observed that the parts have a better upper radius accuracy on the side corners areas (on 45º section plane), mean time on the middle of the plane surfaces (on 0º section plane), the deviations are much bigger. In the same time, from the first plot can be seen that even if the free space S decreases to almost half of the value for the first configuration, that means the flange has support closer to its wall, the part accuracy in the upper radius is not improved with more than a few tenths. From the second plot it can be observed that, on the side corner area, the upper radius accuracy has a better improvement when S decreases under a certain value and tending towards 0.

Figure 8. Graphical representations of the deviation function of free space S.

To highlight the influence of the support plate or the space S upon the upper radius accuracy on parts manufactured through SPIF process, another set of measurements were done for the biggest pyramidal frustum part, the configuration PYRAMID-LXL-79x79-H20-ϕ50. Both, the part deviation and the free space S up to the support plate were measured in many section planes starting in the middle of the part, from 5 to 5mm, up to the lateral radius corner. The space S has the biggest value in the middle of the part planar face and tends to decrease to 0 on the part radius corner. According to the curve slope presented in the plot from figure 9, the parts upper radius accuracy is considerably improved only when
the space $S$ is decreased under around 10mm, and the parts has a satisfactory dimensional precision when the space $S$ is smaller than 2mm. The side corners of the pyramidal shape, together with the bottom radius area, act as a reinforcement frame for this type of parts. The hole from the support plate allows the material deformation in axial direction and it should follow as close as possible the upper contour of the deformed parts, to ensure a constant support to the parts flange. Maintaining the same small space value $S$ between the part wall and the support plate edge, the dimensional precision of the manufactured part will be constant all around the upper radius contour.

![Figure 9. Measurements on PYRAMID-LXL-79x79-H20-ϕ50 part and graphic representation.](image)

5. Conclusion

In the paper is presented how several pyramidal frustum parts are deformed through SPIF using a fixing device which originally is designed and manufactured for cone frustum parts. The dimensional accuracy of the parts in upper radius areas are considerably influenced by one component of the fixing device, the support plate, which ensures contact surface for the part flange. A high value of the free space $S$ between the part wall and the support plate edge has a negative influence upon the upper radius accuracy. A part deviation, in comparison with CAD model, of less than 1mm in these area is obtained only when the space $S$ has a value less than 2mm. For comparison, a cone frustum part with the base diameter of 100mm was manufactured, being the part shape for which the fixing device was initially designed. The deformation process was also numerical simulated for all five pyramidal frustum parts, but the results are not totally satisfactory, indicating the material fracture for four of the five parts analysed.

The conclusion is that in SPIF, to obtain a well dimensional precision in the upper radius area, the support plate should follow the upper part contour as close as possible of the part wall. Therefore, for each part shape, a dedicated support plate should be manufactured. Thus, the SPIF process lose a little bit of its main advantage, the flexibility, but it is still much costs effective in comparison with a conventional process as deep drawing process, for small or production series or unique products processing [1]. To maintain the SPIF process flexibility, as a future research topic is the design and manufacturing of a new modular fixing device or a support plate composed of many modular components, which allows to manufacture different parts, keeping a uniform dimensional precision on the upper area.

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