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Experimental Investigations and Numerical Analysis for Improving Knowledge of Incremental Sheet Forming Process for Sheet Metal Parts

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Abstract. The paper is related to the analysis of shape distortions and springback effects arising in Single Point Incremental Forming. An experimental set up has been designed and manufactured to carry single point incremental forming on small size sheet metal parts. The experimental set up is mounted on 3-axes CNC milling machine tool and the forming tool is attached and move with the spindle. Experiments have been carried out on sheet metal parts to obtain tronconical shapes. The forming strategy associated to the movement of the forming tool has been also investigated. The experiments indicate that shape distortions arising in the corners of the tronconical shape are clearly related to forming strategy. The springback of rings cut in the tronconical parts have been also investigated. It is shown that positive or negative springback could be also related to forming strategy. In order to enhance experimental investigations, Finite Element simulations of the incremental sheet forming have been performed. Results obtained from the simulations prove that if boundary conditions and forming strategy carefully are taking into account, the finite elements results are in good agreement with experiments. So it is then possible to use FEM as a design tool for incremental sheet forming.

Introduction

In the modern manufacturing world wide scenario, the requirements associated to customized production, cost reduction, life-cycle shortening are still growing. Scientists have to find answers to these urgent requests and new technologies seem to be a sustainable approach to reach such aims in various sectors of manufacturing technologies including sheet metal forming.
With a basic concept that strongly differs from classical sheet metal forming technologies, the introduction of incremental sheet forming may represent a progress in sheet forming processes development [1]. In Single Point Incremental Forming, the required geometry is generated through the movement of a simple tool controlled by a CNC machine which deforms a clamped blank. This concept allows to avoid to use traditional stamping or deep drawing die largely employed in conventional stamping processes.
Regarding the concept of such a technology, a set of advantages provided by SPIF can be listed. Incremental sheet forming technology allows to significantly reduce set-up costs and presents a very high flexibility [2, 3]. Indeed, in order to make a new sheet metal part, it is sufficient to modify the CNC program and the attachment on the CNC machine tool. Due to the specific stress state induced by the rotating punch during the local sheet deformation, the material formability is higher in comparison with conventional stamping operations [4]. The process can be used for rapid prototyping of new products, but also to make parts which have to be rebuilt as manufacturing of spare parts or in applications where the parts are in very small batch as for biomedical devices [5]. Nowadays, numerous industrial sectors, like automotive or aeronautic ones, that are using

conventional forming processes in order to produce complex shaped sheet metal components with a large variety of materials, represent a huge market where ISF could be used instead of standard sheet forming processes that are often economically unfeasible for such applications.
As SPIF is an emerging process, it remains to be improved and it is necessary to point out the main difficulties of ISF associated to the industrial suitability of the process. As the deformation is locally imposed through the successive positions assumed by the forming tool, incremental sheet forming is a relatively slow process. On the other hand, as the sheet is simply clamped in a frame without any dies, it is relatively free to bend during the process resulting in undesired rigid movements that have negative effects on the shape accuracy and induce elastic springback and sheet thinning.
In this sense, it is very important to increase knowledge about this technology through both experimental and appropriate numerical investigations. The reported study is based on well documented experiments completed by an accurate FE analysis of the process used to emphasize the necessity to control all process parameters in order to develop an industrially suitable technology. The forming strategy is taken as example to underline its influence on the resulting formed parts.

Experimental investigations

Experimental platform

Experiments were carried out using a 3 axis-controlled CNC milling machine as a plateform to develop the ISF process. An experimental tooling system, in which the sheet metal part is supported around its contour by a voided metallic plate, was mounted on the horizontal movable table of the machine. Simple clamps allow to maintain the sheet metal blank in position during the movement of the tooling system (Figure 1).

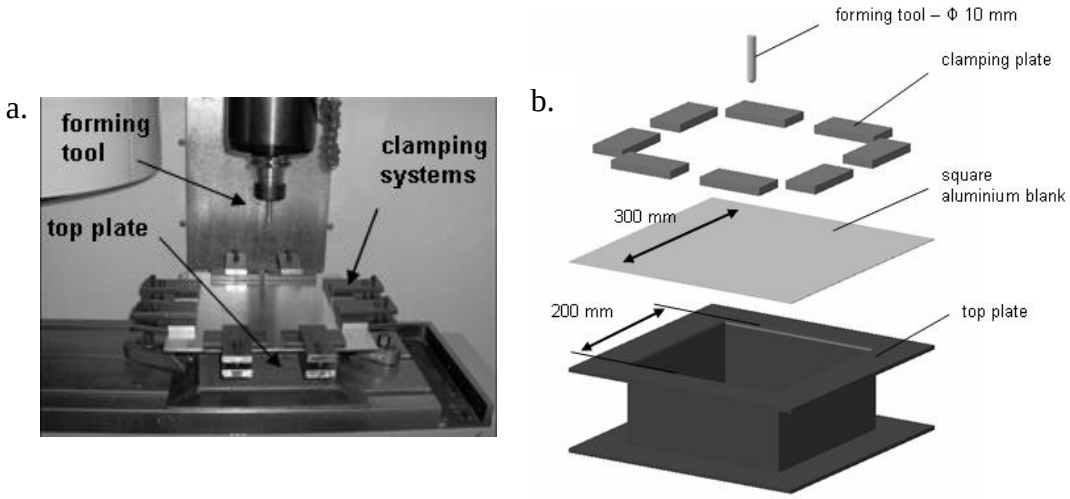

Figure 1: a. Experimental setup for SPIF experiments (3-axis milling machine tool – tooling and fixation systems) - **b**. Experimental setup: exploded view of forming fixture

A simple cylindrical tooling system composed of a 10mm diameter hemispherical head was used as a forming tool. The forming tool paths were specified from the CNC machine through a proper routine. The forming tool paths include both milling machine movement in the horizontal plane and movement of the incremental sheet forming tool in the vertical axis direction.

SPIF experiments

The material used for the investigations corresponds to a 1 mm thick Aluminium alloy (Al 1050).
The square sheet metal part, with size equal 300mm x 300mm, is supported around its contour with simple clamps as shown in Figure 1-b. The top plate has a 200mm x 200mm square orifice in which the blank should be formed.
The tool moves along a path that determines the contour of the shape investigated at a feed rate equal 2000mm.min^{-1} and a speed rotation equal 400 rpm. The tool path consists in a series of circular movements around the vertical axis of the milling machine combined with in plane transversal incremental displacements. The tool first has a vertical movement by penetrating the sheet metal over a distance equal to the desired vertical step (step 1 in Figure 2), then it moves along the path as shown in Figure 2 (step 2). Once the full circular rotation is completed, the tool moves in the horizontal direction (step 3) and penetrates the blank in the vertical direction to proceed with the next contour.

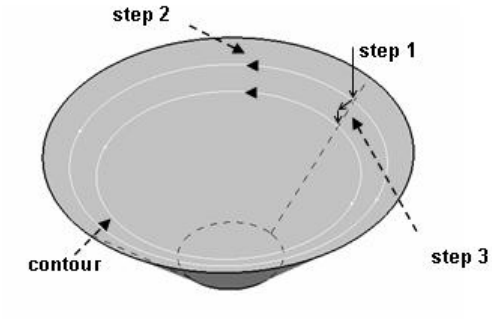

Figure 2. Schematic description of the tooling path

The investigated data are summarized in Table 1. The choice of process parameters results from several studies focused on the process parameters influence on the final sheet metal shape [6, 7, 8].

TABLE 1. Process Parameters and geometry dimensions	
Tool Diameter	10mm
Tool Depth Step	0.2mm
Rotation speed	400rpm
Feed rate	2000mm.min^{-1}
Major base	140mm
Height	50mm
Wall inclination	45°

Reported experiments are mainly related to the manufacturing of simple workpiece geometries, like truncated cones related in Figure 3.

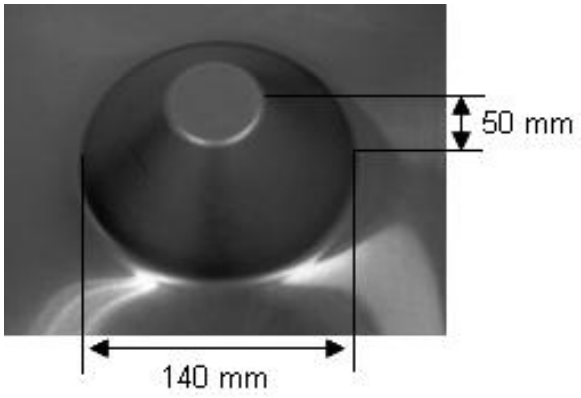

Figure 3. Experimental shapes investigated: a truncated cone with inclination equal 45°

Modelling and numerical analysis of SPIF

Incremental sheet forming conditions and material behaviour

The sheet metal is considered as isotropic and the flow has been accounted by means of a Swift type hardening law expressed as:

$$\overline{\sigma} = k.\left(\varepsilon_p + \overline{\varepsilon}\right)^n$$

This choice has been validated through a bulging test. The parameters are as follow: k = 111, n = 0.14 and ε_p = 75 MPa.
Concerning the forming conditions, the tool is considered as a rigid body and the corresponding boundary conditions are related to the path that it should follow during the process. Friction conditions between the forming tool and the sheet metal part have been accounted by means of a static coefficient of friction f = 0.3.
Several tests were carried out in order to analyse the influence of the blank holder pressure on the formed parts [9] and numerical results highlight that a pressure value higher than 0.5MPa (about 2% of the material yield strength) is enough to clamp the sheet metal part [10].

Finite element simulation of SPIF

As experimental researches are carried out all over the world to improve Incremental Sheet Forming technologies, the Finite Element Method that has been proved to be an efficient tool for the simulation and process design in sheet metal forming and different authors have used such a method for the simulation of ISF processes [11, 12]. As incremental forming is a progressive sheet metal forming process characterized by large displacements and localized strains, an explicit solution scheme was adopted, resulting in the choice of LS-Dyna® as the FEM simulation code.
According to the experimental tests and related data reported in section 2.2, the investigated shape used to perform the simulation is a truncated cone with 140mm major base diameter and 50mm height. The slope of the wall is fixed to 45°.
Due to the 3D tool path, a fully three-dimensional spatial analysis is required. As a consequence, shell elements with 4 nodes and 6 degrees of freedom per node (Belytschko-Tsai shell elements) and five integration points through the thickness were used. These elements are the so-called 3D reduced shell elements and have the property to properly considered thickness variations. Furthermore, an adaptive mesh refinement was performed in order to reduce element size when the distortion level reached a maximum value. These ingredients allow a proper modelling and simulation of the progressive deformation of the sheet by increasing the number of nodes in contact with the tool surface. The sheet was initially meshed with 3600 elements.
The deformed mesh reproducing the investigated shape is reported in figure 4.

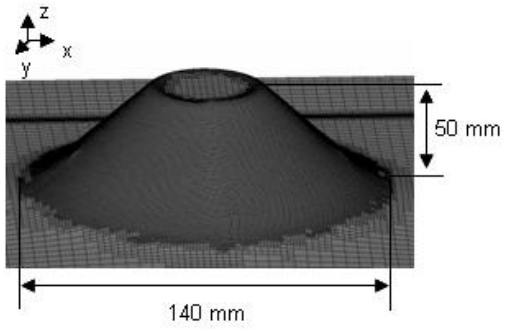

Figure 4. Deformed mesh of the tronconical axisymmetric part

In that paper, one propose to enhance the FEM simulation of ISF by using advanced simulation strategies and by a careful comparison of FE results with experiments previously reported.

Results and discussion

This section describes the obtained results with regards to the effect of different tool paths characterizing the incremental sheet forming process. In a first step, a validation of the FEM model is carried out through the comparison between geometrical profile of the part calculated through the simulation and the one measured experimentally. Then the investigated results are focused on the influence of the tool path on elastic springback related to the formed parts.

Geometrical accuracy

In order to set up and to validate the numerical simulation model, the final shape was measured after processing and several experimental profiles were measured and compared with numerical results. The experimental profile was obtained after a set of several series of measurements by means of laser method taking into account the transverse sections indicated in Figure 5.

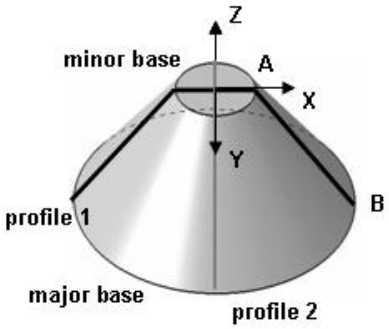

Figure 5. Definition of profiles used for measurement

Figure 6 relates the results of the profile measurements. As it can be noticed, geometrical profiles are almost exactly the same in both XZ plane (profile 1) and YZ plane (profile 2) that means that the part is properly formed and maintains its symmetry during forming. The only difference that could be noticed is located along section AB (see Figure 5) that corresponds to the area where a rotational movement of the tool is completed and where it moves deeper to perform the next contour (steps 1, 2 and 3 in Figure 2). The relative variation between both profiles reaches 3.7%. This difference can be explained by the deformation line due to the tool vertical movement along this section.

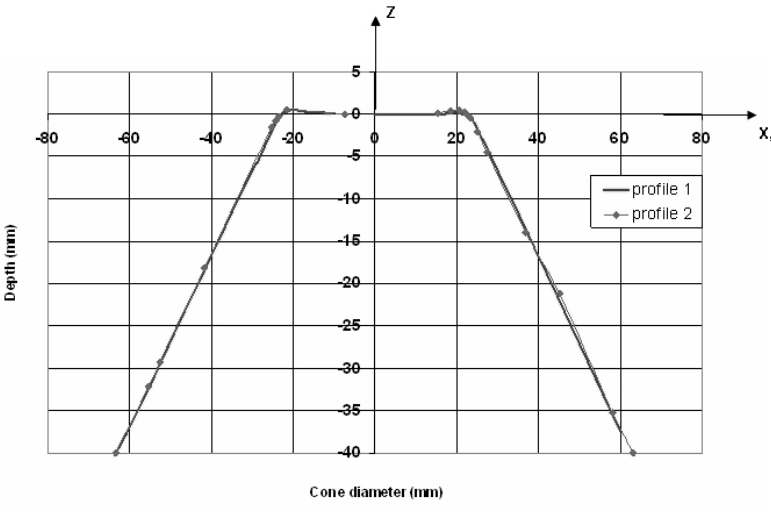

Figure 6. Comparison of geometrical profiles obtained on the conical shape for 2 axis sections

Figure 7 relates the comparison between experimental, numerical and theoretical measurements by focusing on profile 1. Theoretical profile corresponds to the CAM design. The profile measurements indicate classical defects resulting from ISF. First of all, a relevant sheet bending close to the major base is detected. Indeed, in this case, as the sheet is simply clamped around its contour, it remains free to bend during the tool action. Micari and al. have shown that such defect can be normally corrected through the use of a backing plate [13]. Then, when the punch action is relaxed, a concave curvature can be highlighted on the minor base of the part determining a concave curvature of the undeformed material, and the final depth of the part is lower than the desired one.

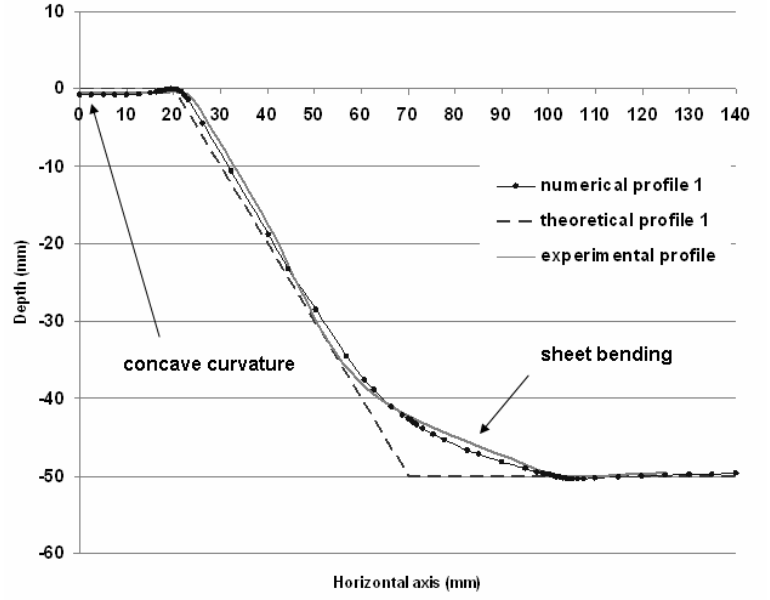

Figure 7. Comparison between numerical, theoretical and experimental profile measurement

To conclude about comparison between numerical and experimental results, a good correlation is observed. If geometrical error is defined by the difference between two curves, the maximum error

reaches 3%. In this sense, the modelling used is suitable to simulate the manufacturing of simple workpiece geometries, like truncated cones.

Springback analysis

One of the main accuracy problems resulting from ISF is due to elastic springback effects that are well known. The following analysis deals with an original way to analyze the springback effects by focusing on the influence of geometry variations of a truncated ring cut in the wall of the cone [13]. So the elastic springback analysis is carried from rings cut from the formed part as shown in Figure 8.

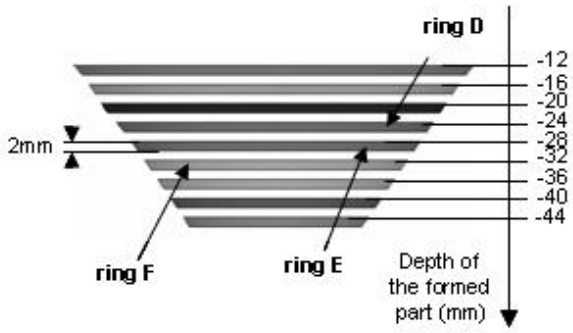

Figure 8. Location of rings cut from the formed part

From this modelling, a numerical study was performed to observe the potential relationship between the tool path and geometric defects due to springback. The first incremental forming strategy (strategy 1) used to performed simulation is the same as described above (Figure 2). The second strategy (strategy 2) adopted is similar to the first one, but in this case the digital tool path alternates in clockwise and counterclockwise direction at the end of each revolution (Figure 9).

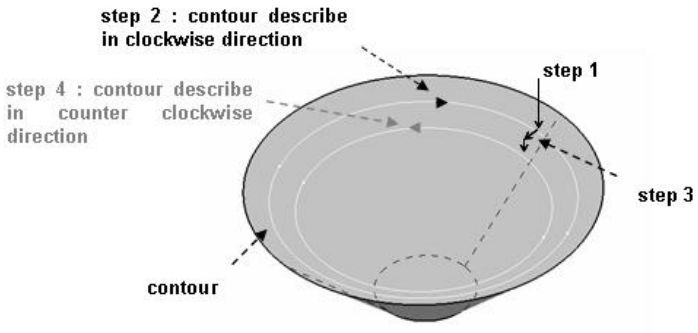

Figure 9. Schematic description of the tooling path – strategy 2

The trimming operation consists in "digital" cutting sheet metal rings resulting from numerical results obtained after incremental sheet forming simulation stage. This step do not led to more mechanical constraints into the rings but allows to obtain a new mesh adapted to the geometry of the each considered rings. Then, the principle consists in cutting rings along a circumferential line in perpendicular plane to the vertical Z axis. This step is led by doubling nodes localized along the circumferential line and creating new elements which allow to relax the structure. The nodes that are localized on the opposite axis are rigidly fixed to allow the prediction of elastic springback and to avoid rigid movement in the simulation phase (Figure 10).

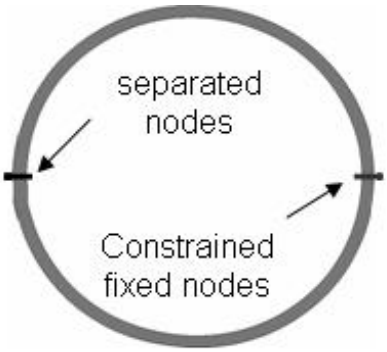

Figure 10. Model used for the simulation of the elastic springback obtained by cutting and relaxing rings in the wall of the conical part obtained by ISF

The closing of each ring (negative elastic springback) can be noticed in figure 11-a. Figure 11-b indicates a bigger gap in the horizontal plan for rings D, E and F (see Figure 8) corresponding to the middle of the wall.

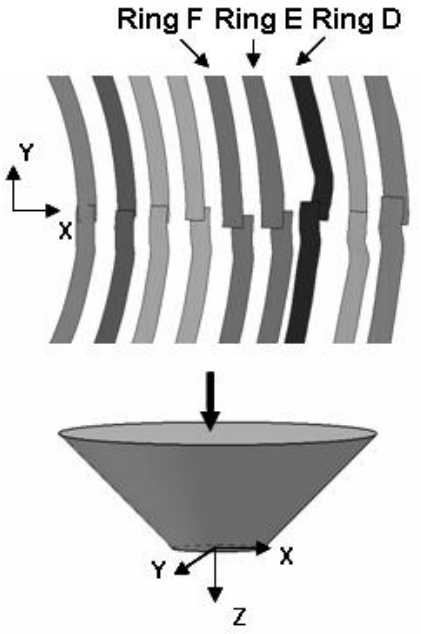

Figure 11-a. Results of elastic springback simulation of tronconical rings taken from the truncated cone – Top view

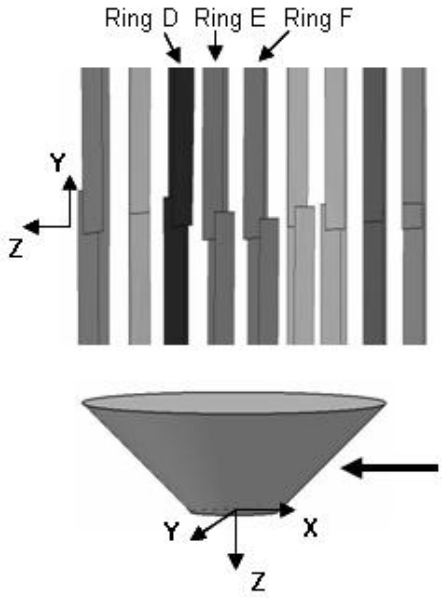

Figure 11-b. Results of elastic springback simulation of tronconical rings taken from the truncated cone – Right View.

In order to analyse the potential influence of tool path on the formed parts, the next analysis is focused on rings D, E and F that are localized in the middle of the wall. Figure 12 indicates numerical elastic springback in the horizontal plane XY measurements obtained from both forming strategies 1 and 2. In each case, negative elastic springback can be noticed. Nodes which are initially joined deviate from each other in X direction with a larger opening in the case of strategy 1 than in strategy 2. In contrary the deviation in Y direction presents a bigger closing in the case of strategy 2.

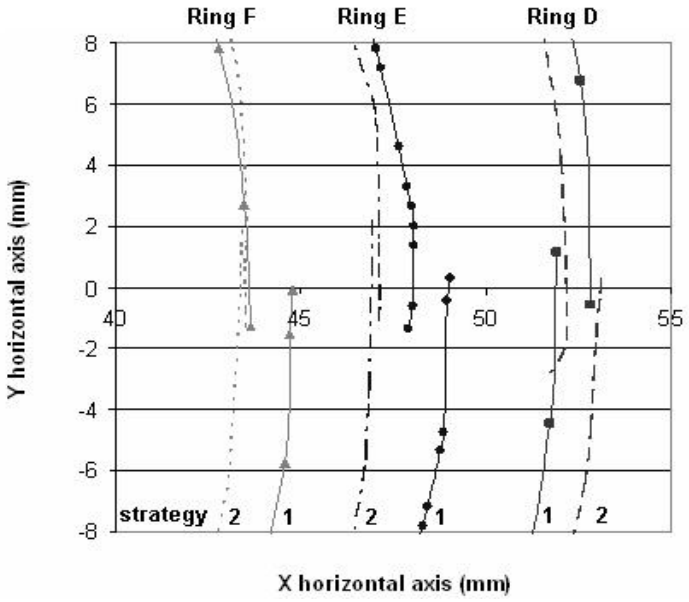

Figure 12. Tool path influence on elastic springback of rings localized in the middle of the wall of the formed part

Similar observations can be made for the other rings where the values of deviation in X direction and closing in Y direction are decreasing with the ring diameters.
These results were confirmed by an experimental analysis performed on sheet metal part. In this case, rings were cut by means of wire electrical discharge machining equipment (WEDM). Figure 13 shows the negative elastic springback observed on the experimental part.

Figure 13. Negative elastic springback of rings cutting in experimental part

The previous springback analysis has pointed out a homogenous material behaviour along the depth of formed part. Indeed, each ring is characterized by negative elastic springback. This behaviour can be explained through deformation mechanism encountered in SPIF. Indeed apart some bending effects close to the clamping area, the local action of the punch gives rise to an almost pure stretching deformation mechanism for axisymmetric parts.
In order to emphasize the relationship between sheet metal deformation mechanism and elastic springback, results were compared with these obtained using a conventional stamping process. So a stamping model has been built in order to get the same part geometry (apart from the bending zone noticed in SPIF) and to obtain a complex deformation mechanism along the depth of the part. It means that the sheet is under different deformation modes that classically occur during stamping process. Figure 14 indicates geometry and finite element model used for the simulation.

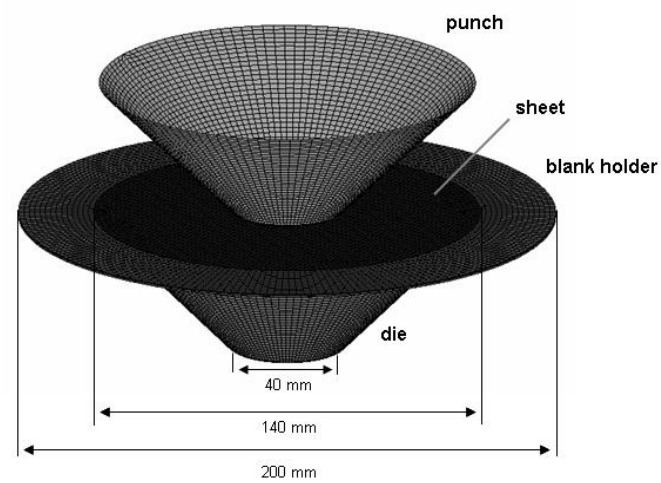

Figure 14. Stamping of a circular plate in a tronconical die with a tronconical punch

In conventional stamping process, a positive elastic springback of rings localized from the major base to the middle of the wall is observed, with a large opening near the major base and a smaller opening near the middle of the wall. This behaviour corresponds to a transition from tube thickening mode to stretching mode. From the middle of the wall to the minor base, negative elastic springback is observed in the same time as sheet thickness decreases. Figure 15 relates a comparison between elastic springback obtained by both forming processes for rings localized in

the middle of the wall (rings D, E and F). The numerical results exhibit the same tendencies than the experimental ones.

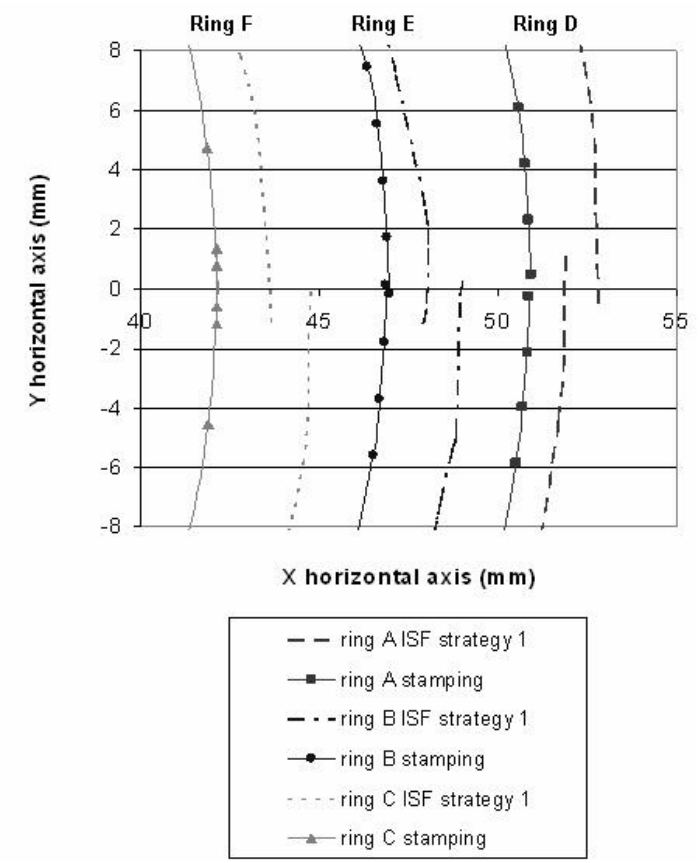

Figure 15. Comparison of elastic springback of rings localized in the middle of the wall of the formed part obtained by both stamping process and SPIF

To conclude with this section, although conventional forming processes are more accurate than SPIF, incremental sheet forming process leads to a more homogeneous material behaviour of formed parts than these obtained by stamping process. This characteristic is due to a homogeneous mechanism of deformation for simple shapes manufactured by SPIF differently than in stamping process where the mechanism of deformation evolves along the depth.

Conclusions

Incremental sheet forming process is a very promising sheet forming process which still requires further analyses and developments. Numerous studies have demonstrated the effect of process parameters like forming speed, forming force, tool shape and displacements, on the characteristics of the formed parts. The previous analyse emphasizes the necessity to control all process parameters by focusing on the influence of forming strategy on the formed part through an original way to investigate elastic springback along the depth of sheet metal part.

The development of a better knowledge of experimental variations of the characteristics of formed parts during the process becomes necessary to go further with the aim to make an industrially suitable technology. In this sense, a new study is carried out in our lab to develop a smart forming tool able to perform “on-line” sheet thickness measurements. The principle is based on the use of an ultrasonic transducer integrated into the tool in which a wave guide developed in order to transmit ultrasounds from the sensor to the blank.

Acknowledgments

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