Incremental Deep Forming Strategy to Overcome Depth Limitation Using SPIF

Dr. Salah Echrif
Dept. of Mechanical Engineering, Zawia University

Abstract:

In this paper, the main focus was on the development and enhancement of a non-conventional metal forming a process called dieless forming or incremental sheet forming (ISF) that needs further investigations. ISF is complex due to the number of variables involved. Thus, it is not possible to consider that the process has been well assessed; several remaining aspects need to be clarified. Before conducting the experiments, numerical simulation was done to test the capabilities and limitations of the finite element method at simulating the ISF process. The numerical simulations were carried out with regard to the overstretching in depth phenomena and the forming strategy. A deep forming strategy was *developed to enable ISF to form a cylindrical cup with a higher depth like in deep drawing. In this research, a cup with height more than half of its diameter has been formed.*

***Keywords**: SPIF, forming strategy, process simulation*

Introduction:

Nowadays, several industries use forming processes like deep drawing and stamping in order to manufacture sheet metal components with high productivity. These processes need large initial investments and long die-preparation times, with specific dies for each part, particularly when the parts have complex shapes or are only needed in small series, as is the case with unique aeronautic and automotive parts. Therefore, there is a need for a flexible technology that is also viable for small and medium-sized enterprises. Incremental sheet forming (ISF) is a new process for manufacturing sheet metal parts which is well suited for small batch production or prototyping (1, 2). ISF, also known as Die-less NC Forming, was introduced in Japan by Matsubara (3) as a method for prototyping and manufacturing sheet metal products in small series.

ISF versus deep drawing:

conventional metal forming methods like deep drawing is characterized by its unique technology. Deep drawing (Figure 1 (a)) and ISF (Figure 1 (b)) are compared to understand the capability of each process as listed in Table 1. ISF is considered a prospective manufacturing process because a comparatively small and light-weight machine can be utilized to form sheet metal without material expense of specialized dies. In addition, ISF can be employed as a local production process with advantages of avoiding long transportation distances. Re-work or re-forming of old products are further capabilities offered by ISF, which is less energy-intensive than re-melting the material.

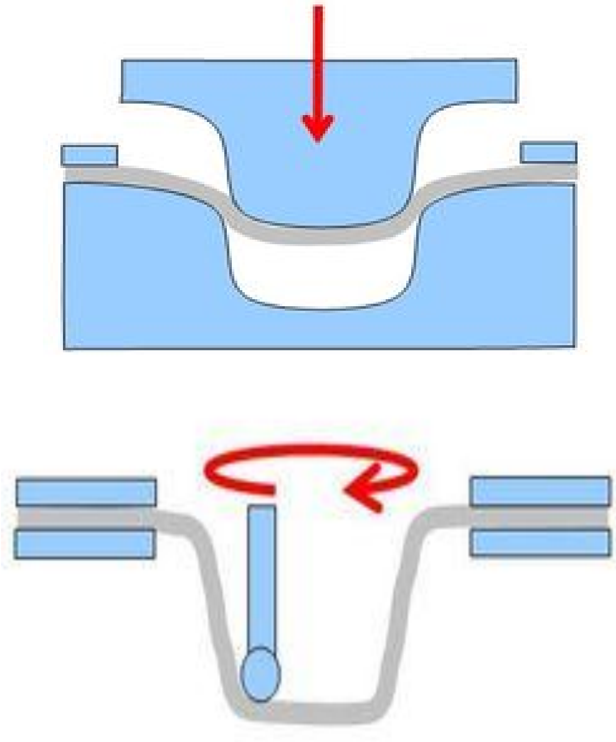

Figure 1 (a) Deep drawing with male and female dies (b) SPIF

Deep drawing is a process of forming sheet metal through a forming die with a punch. Metal in the area of the die shoulder undergoes a lot of stress, and will result in wrinkles if a blank holder is not used to control the flow of material into the die. Material is usually thickest in the area where the metal loses contact with the punch - the punch radius - and thinnest in the areas where stresses are greatest. The metal is stretched around a plug, and then moved into the die. Table 1 shows a comparison between the incremental forming process and deep drawing. Many researchers have been estimating the economic and ecological aspects of incremental forming and compared with deep drawing. From the comparison between ISF and deep drawing it is clear that ISF is suitable as prototype and it requires low power and small machines that are nowadays available almost in every workshop. Thus, it is better to find a way to produce parts by ISF that are able to be made by deep drawing.

Table 1: Comparison of single-point incremental forming (SPIF) and deep drawing

Properties	Drawing Type	
	Deep drawing	Incremental sheet forming
Tool required	Die	dieless
Formability	Good	better
Material strain	Normal	high
Required force	Large	small
Productivity	Mass production	Low volume production
Material flow	Very complicated	simple
Failure prediction by	FLD	FFD
Production time	Short	long
Work piece shape	Nearly any	Nearly any
Machine used	Hydraulic or mechanical presses	CNC
FE computing time	Short	long
Cost per unit	Profitable more than 1000 pcs	Profitable less than 1000 pcs

Incremental sheet forming (ISF) process is appropriate to form steep flanges, e.g. for parts designed for deep-drawing as shown in Figure 2. When parts are designed for deep-drawing, they usually contain steep or rectangular side walls that cannot be manufactured using the standard ISF strategies. This study will present a forming strategy that is able to form such parts.

Figure 2: Drawn cup with central hole

ISF forming methods:

Existing experimental configurations for incremental forming can be put into two general types: negative and positive incremental forming. Negative die-less incremental forming, also known as single point incremental forming (SPIF) as illustrated in Figure 3 (a), is the first form of incremental forming. Positive die-less incremental forming is also referred to as two point incremental sheet forming (TPIF). The TPIF equipment, shown in Figure 3 (c-d), consists of an apparatus that clamps the sheet metal (blank holder) and allows for downward movement with tool path increments in the z-axis direction. The blank is supported in the middle with a stationary post (a partial die or full die) and a clamped perimeter (blank holder) that moves down on bushings as deformation of the sheet progresses. Unlike the TPIF, the main tool in the SPIF forms a shape from its periphery towards the centre, and the blank remains fixed in the Z-direction. In this way, the main tool forms the shape by stretching.

The configurations shown in Figure 3 (a) and (b) have a stationary blank holder. The configurations shown in (Figure 3 (c) and (d)) have a blank holder that moves along a vertical axis, as the forming tool incrementally deforms the sheet. In this paper, the method of SPIF is used to form a cylindrical cup with specific steps of forming strategy. Using forming passes strategy (multi-stage) to form a cup is not a new idea in SPIF (4). In two point incremental forming (TPIF) a cylindrical shell with vertical wall has been achieved, [5, 6].

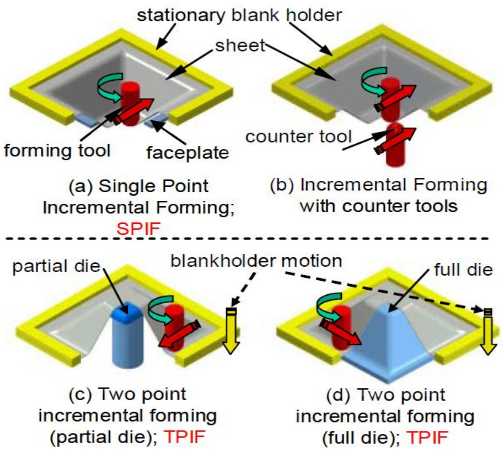

Figure 3: Types of forming methods (Jeswiet, 2005)

Simulating the process:

A numerical investigation method based on finite element method is presented using LS-DYNA software in order to establish the influence of the forming tool on the state of thinning. The numerical methodology of the solution is based on explicit time integration. The sheet material used is AA1100 with 2 mm thick and considered isotropic with a flow stress $\sigma_y = K*\varepsilon^n$

The material model used in the simulation is "power low plasticity". This model provides Elasto-plastic behaviour with isotropic hardening. After conducting the tensile test, the stress-strain curve data are determined by forming geometry (7) and the following data is input in the model: K Strength coefficient =111and n Hardening exponent = 0.14. Density = 2.710, E = Young's modulus = 6.89, Poisson's ratio = 0.33.

The desired formed part is consisting of several CAD models. Every CAD model represents an individual forming pass that together with the other forming passes will build the forming strategy to form a cylindrical cup. The geometry of the desired part is 60 mm radius and 60 mm depth for the last forming pass and the raduis R of 15 mm at every corner which makes the hight (h) to be equal to the radius (r). The contact between the rigid tool and the shell sheet is defined by the keyword "contact forming one way surface to surface". The key word "Define" is used to define the curves that represent the nodal point or X-Y-Z coordinates of a point which is generated from CATIA as G code. Under the key word "CONTROL" adaptive re-meshing is adopted when the contact surfaces approach or penetrate the tooling surface. The LS Pre-Post processing software is used to prepare for the K file. The K file is the extension of the pre-post processing software that will make file ready to run under LS-DYNA.

After running the K file, a phenomenon is observed that as the tool moves down during the second stage, a small plateau is formed beneath it. The geometry is formed during the second stage leaving a residual cone in the centre. This is because the depth of the part is increased in the second stage, whereas the tool path goes deeper as in the first stage. The simulated geometry is more pointed in the centre region and a little bit deeper after every forming stage.

Conducting the experimental part:

1. Experimental setup

The experiments were conducted utilizing the CNC GATE vertical turret milling machine connected to control panel of ANILAM 5000M. The G codes generated from CATIA software are transferred from the PC to the ANILAM controller. The forming tool used was a solid hard-steel hemispherical head mounted on a shaft. It was made from hard steel called HSS High Speed Steel. Aluminium alloy sheet AA-1100 with 2 mm thickness was used in the experiment conducted in the study.

2. Incremental deep forming strategy

Benefiting from the results obtained previously from the phenomenon of overstretching the bottom of the formed part, a forming strategy is performed to form a cylindrical cup with part depth more than its radius. The strategy basically consists from several forming passes or multi stage that attempts to form a cup. The strategy aims to deform the cup firstly by building the horizontal and vertical wall step by step until it comes to flat bottom and 90 drawing angle of the vertical wall as shown in Figure 4. The radius D/2 of all the parts formed is fixed by 60 mm whereas the depth (height) is changing according to the ratio. The figure illustrates an example of deforming a cup with H = D/2 where H is the height of the cup and D is the diameter. The forming depth should be equal to the radius which means height to radius ratio is equal.

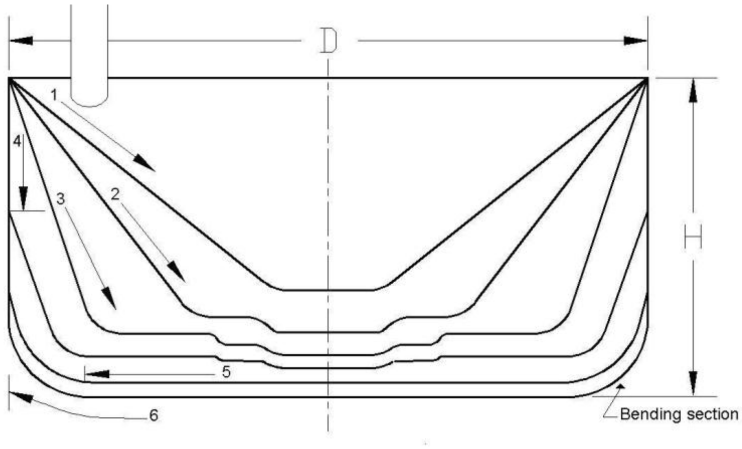

Figure 4: deep forming strategies to form a cylindrical cup

The depth is divided towards the 60 mm radius so that every part will be investigated individually starting from forming a cup with h/r 15/60 to check is it possible to form a cylindrical cup and with how many stages can be achieved.

Discussion the experimental and numerical Results:

The table 2 shows the experiments conducted to form different cups with different depths. The study is focused on the last formed cups simply because they represent deep forming and this is the subject of the present paper.

Table 2 different height/radius ratio of a cylindrical cup

h/r	Ratio	Number of forming passes	Depth reached
15/60	¼	2	15
30/60	½	4	30
45/60	¾	4	45
60/60	1	6	60
75/60	5/4	8	74

- Forming with h\r = 1   (60:60)

It can be done with 4 completed passes and 2 non completed passes. Benefiting from both pressing down and overstretching of the part bottom downwards, forming a cylindrical cup with a depth equal to the radius can be achieved. The strategy of the forming process is to preface building a horizontal and vertical wall step by step and to keep the dimensions of the previous pass and the next pass close to each other. In other words, avoiding high drawing angels and wrinkles with sharp edges is the most significant factor to complete the forming without fracture.

The first three passes aim to prepare for shaping the cup whereas the fourth pass forms the first step of the vertical wall of the cup until certain depth to avoid crack. At this point the downwards forming is no longer in process and the rest will be only upwards forming. The maximum vertical depth that can be reached is 25 mm. The forming tool in the fifth pass starts from the center moving in horizontal direction until it comes to the critical area (bending section) then the tool should stop forming. The last pass is the finishing stage that pushes the sheet down due to the phenomena of over stretching although the forming tool moves horizontally and at the same time finishes building the vertical wall of the cup as shown in figure(5).

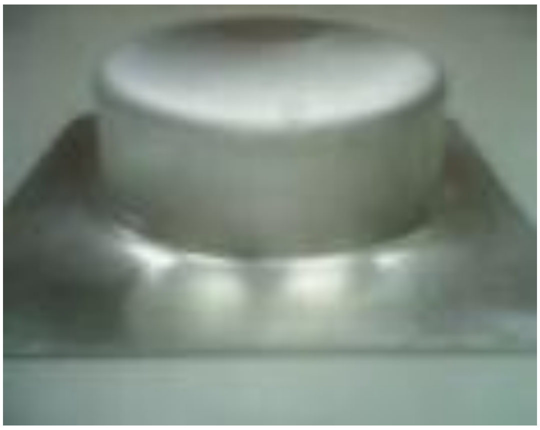

Figure 5: Cup with radius-height ratio equal to 1

- Forming with h/r=1.25 (75:60)

In this case, the number of forming passes exceeds two passes more than the previous one so that the forming depth reached 74 mm as shown in Figure 6, with a vertical wall drawing angle and the failure occurred at 75 mm. In the last two stages the forming tool started from the centre towards the edge and pressing downwards 35 mm to build the horizontal bottom. The forming tool ends forming in the bending Area. This section is the most critical area where the crack mostly occurs.

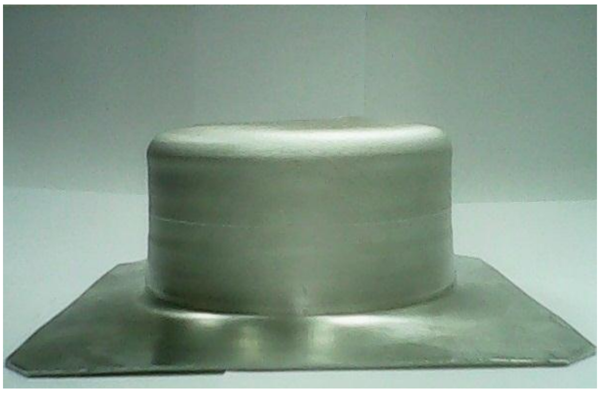

Figure 6: Cup with height-radius ratio more than one

The previously mentioned result in Table 2 for the case of height-radius ratio more than one is in close agreement with the analytical approach illustrated in Figure 7 in terms of thickness distribution. It is noticed after cutting the formed part that the thickness is distributed unevenly along the section as same as in the numerical part section Figure(7).

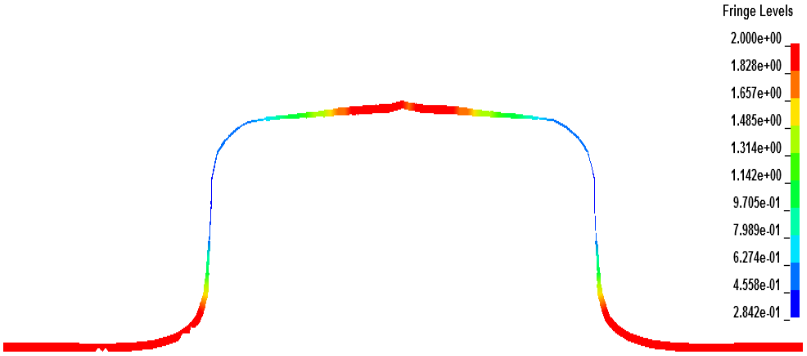

Figure 7: Part section in LS-DYNA

The cross section shows that the sheet thickness in the centre is much thicker than in the binding section. By pushing the metal from the centre to the edge after the fourth pass, deep forming can be achieved without fracture. In other words the thicker the sheet is the deeper it can be formed. It is also observed that wrinkles appear in the vertical wall by every forming step finish. This is because they represent the condition of the uniformly thinned sheet just before necking occurs.

The thinnest area in the numerical result is distributed in four regions on the vertical wall shortly before bending section. This is because of the high strain in some regions where the thickness gets less as shown in Figure 8 (a) in both numerical and experimental models. The square Grid analysis utilized for obtaining the strains with pattern of 2 mm x 2 mm and then each square's deformation is measured, Figure 8 (b). It is found that four regions around the vertical wall are more stretched. After the first forming pass, the deformation mode transfers from plane strain- stretching to biaxial-stretching. Based on theoretical background that states for plane strain are located on the vertical walls while strains close to equal bi-axial stretching are located at the corners, it can be derived that the fracture occurred due to maximum thickness strain on the corner.

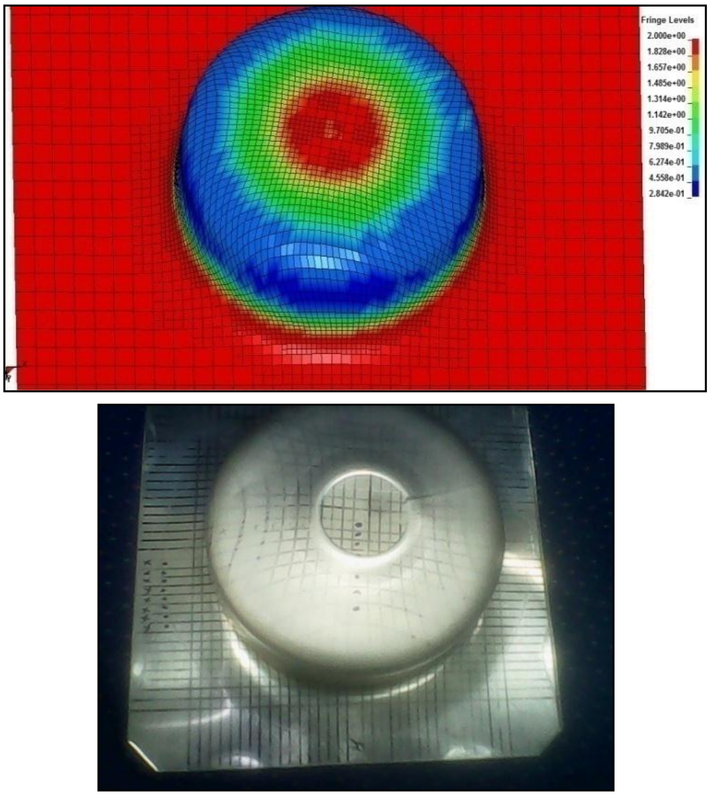

Figure 8: (a) thickness distribution (b) square Grid analysis

On the other hand, the experimental results show that the thinnest area is exactly in the bending section. The fracture appeared exactly in the corner in the bending section shortly before finishing the forming pass for radius-height ratio equal to 1 or radius-height ratio of 5/4. Because the thickness of the vertical wall is not evenly distributed, the formed part is cut into sections AA and BB so as to measure the thickness along the surface as shown in Figure 9 and 10 for both experimental and numerical results.

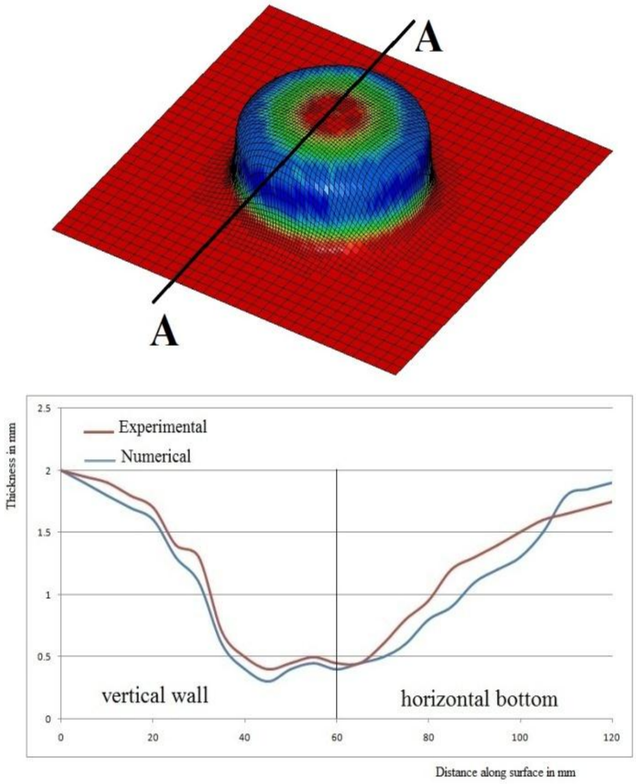

Figure 9: Thickness distribution along part with h = r section AA

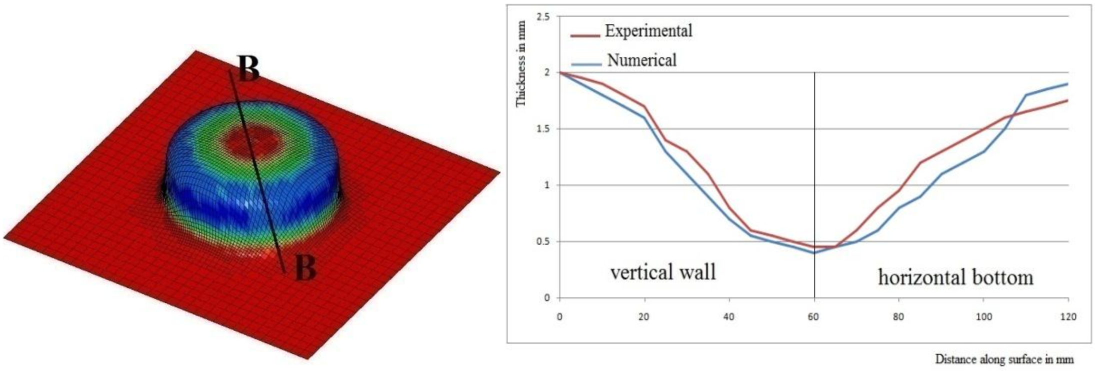

Figure 10: Thickness distribution along part with h = r section B

Conclusion:

In this investigation, several multi-stage forming strategies have been presented that are able to produce a cylindrical cup with different forming depths. Sheet thickness with 2 mm showed better possibility to form deep cups. The most significant forming strategy that aims to compete deep drawing is forming a cup with height more than its radius which has not been done before. The numerical results are in close agreement with the results gained experimentally in terms of thickness distribution and forming the cup. Sheet thickness has significant role in delaying fracture and increasing the depth of the formed part. It shows that the thicker the sheet is the more depth can be achieved. Finally many simulations were done to validate the results of the experiments. The numerical output shows that the thickness distribution along the vertical wall is not even.

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