Journal of Mechanical Engineering Research and Developments
ISSN: 1024-1752
CODEN: JERDFO
Vol. 43, No. 7, pp. 374-382
Published Year 2020

Analysis of the process parameters effect on the thickness distribution and thinning ratio in single point incremental forming process

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ABSTRACT: Incremental forming is a rather innovative process in which sheet metal is formed into complex shapes by stretching the sheet with forming tool whose path is controlled by a computer numerical control machine, this kind of process is suitable for low patch production and customized parts. The blank is fully clamped at its perimeter, so there is no any drawing operation occurs to sheet blank during forming process, therefore an excessive thinning would appear along the wall of the formed parts. Study the influence of some process parameters on the thinning ratio, find suitable parameters to minimize the thinning in single point incremental forming and find some methods to reduce it that is the aim of this research. Ansys workbench software based on finite element method is used to simulate the forming process and analyze the thickness reduction along the wall parts, numerical results are verified experimentally. The results showed the forming angle has great effect while the feed speed has the little effect on the thinning ratio on the formed parts.

KEYWORDS: incremental forming, thickness distribution, thinning, finite element method

INTRODUCTION

Incremental sheet forming (ISF) is a relatively new sheet metal forming process which is utilized to produce complex 3D products by using computer numerical control (CNC). The process is performed on CNC milling machine with using simple forming tool and fixtures. In the forming process, the geometry of the part to be manufactured is modeled as a surface model in CAD software which used to generate a tool path with a series of NC codes, and theses codes fed to the CNC machine so the forming tool subsequently follows the tool path generated and gradually deforms the sheet in small increments, accumulating plastic deformation between the tool and material that can result in obtaining the target as seen in figure (1). The main advantage of this process is that doesn't need the dedicated dies and moulds so parts can be formed directly from CAD data therefore this process is economical because less equipment’s is required and shorter production time is spent on. The formability of material in ISF is also better than the conventional processes. The process can be utilized for aluminum, magnesium, steel, and titanium alloys. These special characterizes make it suitable in rapid prototyping, small patch production, automotive and bio-medical industries. ISF also have different limits such as a low geometric accuracy, limited surface quality and high processing times but, by an accurate selection of process parameters and providing compensation for deviation, reasonable accuracy and quality can be produced [1,2]. Single point incremental forming (SPIF) is one of the incremental forming processes which uses one tool to form the sheet metal without any supports and dies in another side of the sheet.

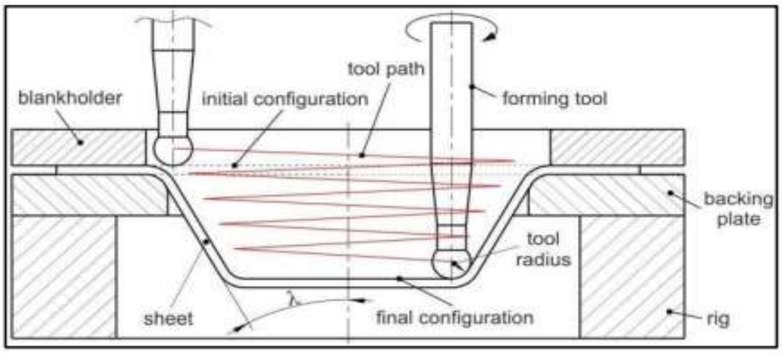

Figure 1. Single Point Incremental Forming [1].

Forming quality, including the excessive thinning rate of wall thickness is still one of the greatest challenges for the development of single point incremental forming. The thickness thinning ratio is directly related to the formability of the forming parts; thus, there different studies from researchers all over the world on the thickness distribution of forming parts [1]. E. Salem et.al investigated the thickness distribution along the wall of the formed parts in the single point incremental forming experimentally and numerically for AA7075-O sheets [3].

They determined the location of thinning on wall and showed the history of the evolution of the thickness reduction at this location during the whole tool path to form the products. G. Ambrogio showed the suitability of numerical analysis to predict the thickness distribution in single point incremental forming, they applied two numerical analysis strategies, implicit and explicit approaches and explained the differences between them and their potentials for simulating incremental forming process [4]. in order to valid of these simulation results, experimental work done to verify the accuracy of these two numerical strategies. D. Young and J. Jeswiet used double pass tool path technique to change the final thickness profiles along the wall of the parts with steeper angles [5]. it is concluded that this technique has the ability to reduce the thinning in the critical areas along the wall. J. C. Li et.al studied the effect of forming stages and angle intervals on the value of minimum thickness and on variance of thickness along the steeper walled part in multi-stage incremental forming [6].

Finite element method was done and experimentally verified to produce frustum cone of 30°. It is shown that the increasing of forming stages would increase the minimum thickness and improve the thickness variation along the parts. Finally, an expression was deduced to estimate the thickness in multi-stage incremental forming. Study the effect of some process parameters in SPIF on the thickness reduction, temperature and strain were presented by S. Khan and S. K. Pradhan, design of experiments and optimization were conducted by TAGUCHI and ANOVA [7].

Numerical simulation was done by ANSYS workbench and verified experimentally. Results showed a good agreement between them. M. Yang et.al presented study on the influence of some parameters on the thinning ratio on the deformation zones of the formed parts by SPIF numerically, the numerical results obtained of thickness used in fitted formula to predict the wall thickness [8]. Numerical and fitted formula results were verified experimentally. Different forming trajectories were used to reduce the thinning ratio along the wall parts. A. Shbeeb analyzed the role of the multi stage forming to reduce the thickness reduction in incremental forming process and showed using different trajectory techniques of the forming tool to produce parts with steeper wall [9]. Effect of anisotropy property on the thinning and spring back by forming conical cone by SPIF is studied by R. Lingam et.al [10]. The current study focused on the influence of some process parameters such as feed rate, spindle speed, step size, forming angle on the thickness distribution profiles along the wall of the formed parts and used some methods to reduce the thinning ratio on the wall numerically and experimentally.

EXPERIMENTAL WORK

The sheet material used in these experiments is Al1050 which has been gaining interest due to its low weight, high strength, high corrosion resistance, availability, and low fabricating costs. Tensile test was conducted to find out mechanical properties of the used material, standard tensile specimen was cut by using wire electrical discharge machining (EDM) which fixed on and made the test on a tensile testing machine model (WDW-200E) as shown in figure (2), the mechanical properties obtained from this test of the Al1050 as follows, the measured offset yield stress of 93MPa, coefficient of elasticity of 70GPa, and ultimate tensile strength of 113Mpa. and the relation between stress and strain is given by $\sigma = 143\epsilon^{0.21} MPa$.

Figure 2. Tensile specimen fixed on universal testing machine.

In order to implement the single point incremental forming process tests, sheet blanks were cut into square blanks with dimensions (250mm X 250mm) and of thickness 0.9mm, 9 holes distributed with circular pattern along blank perimeter were drilled, the blank was clamped through obtained holes by using nine studs M8 between a hollow circular frame and blank holder which both have outer diameter 200mm and inner diameter 170mm therefore forming area would be within 170mm. the above assembly was fixed on a three-axis CNC milling machine C-tek model KM-80D by screws and nuts. forming tools 12mm of diameter and 110mm of length with different tip shapes, sphere head, hemisphere head, and flat head have used in these experiments, this forming tool rotates and moves linearly with feed rate in accordance to predefined trajectory which programmed by G-codes by using UGS-NX10 CAD/CAM software which was fed to the CNC machine. Iso-planar tool path has utilized in this experiment which characterized by constant down back increments between consecutive contours, start point of the tool path has located close to the edge of the sheet and the tool progressed from out- to- in. The forming equipment and machine for carrying out the SPIF as shown in figure (3).

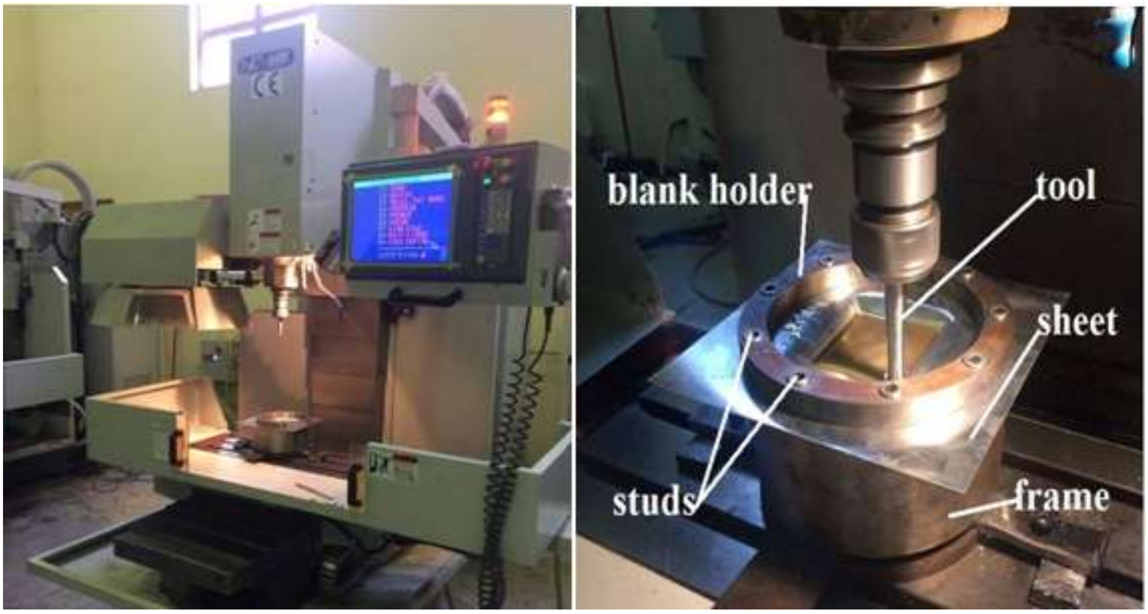

Figure 3. The forming equipments and CNC machine.

The geometry of the formed parts was produced by SPIF are the truncated pyramid with dimensions 110mm X 110mm and depth 38mm and each opposite sides of the formed part have the same angle therefore there are two angles have produced in one product 48°, 58°, the dimensions details of the geometrical shape of the product is given in the figure (4). It is worth pointing out that in order to minimize the friction between the sheet and the forming tool, fair amount of gear oil GL-4 was added before the forming operation begins. All detail of experimental work and process parameters for the experiment tests of single point incremental forming are mentioned in table (1).

Accurate thickness measurements carried out once the parts were formed , the formed part was cut along the wall thickness direction and then thickness values were calculated by using a micrometer with tapered tip which having 0.001 mm least reading, and the normality between part and micrometer tips took in account during measurements, points at the deformation zone along the radial direction of the wall from the clamping region toward the bottom base of part were selected to analyze the part thickness, furthermore the measurements were repeated many times and at different sections on the wall to get the average value to minimize the errors for each formed parts. It is worth mentioning that following formulas used in our experiments to predict the thickness and thinning calculations theoretically as follows.

$$t = t_{\circ}\ \sin(90-\alpha) \tag{1}$$

$$\varphi = \frac{t_{\circ}-t}{t_{\circ}} \times 100\% \tag{2}$$

Being $t_{\circ}$ the initial sheet thickness, t the current thickness, α = forming angle, and φ the thinning ratio along the wall parts [8].

Table 1. Details of experimental work.

material	AL1050	Thickness (mm)	0.9
Tool shape	Spherical, hemispherical, toroidal	Tool path	contour
Feed rate (mm/min)	800, 1000, 1200	Step size (mm)	0.3, 0.5, 0.7
Forming angle (degree)	48, 58	Spindle speed (RPM)	1000

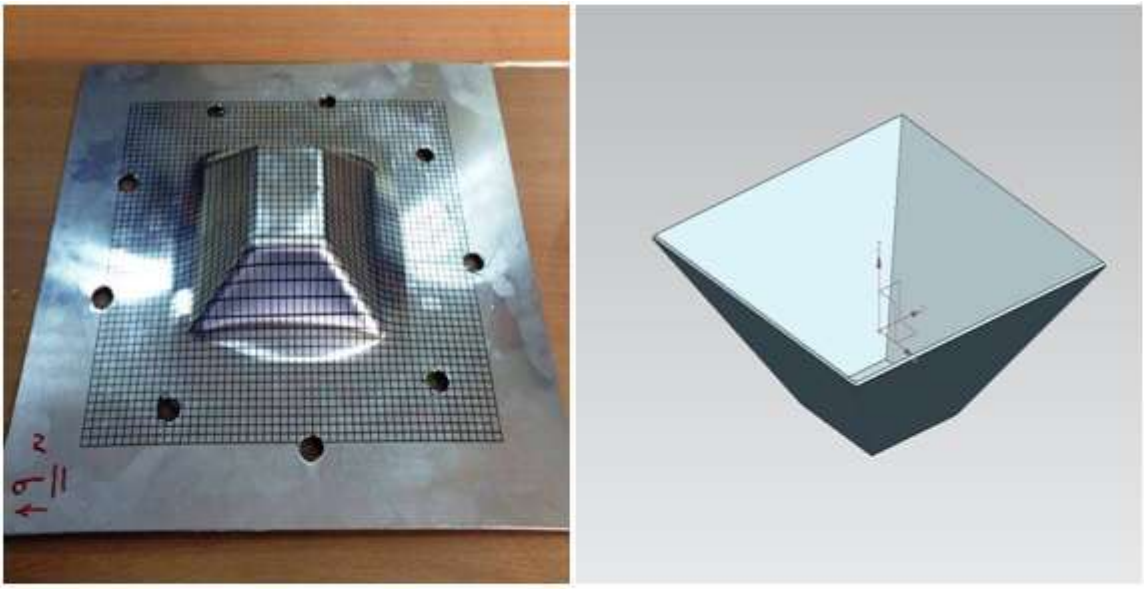

Figure 4. Experimental products and 3D CAD model.

NUMERICAL WORKS

The single point incremental forming SPIF is a tremendously complicated metal forming process. Since all modeling nonlinearities (geometric nonlinear, material nonlinear, and contact nonlinear) arise in this process. The best solving technique to model this process and based on some literature is the explicit solving approach. ABAQUS/CAE software package was used to carried out modelling of SPIF, as the explicit dynamic module could be used to simulate is suitable to simulate nonlinear analysis accompanied with long forming path.

Geometry Description

In order to reduce processing in term of consuming time and memory only two geometrical parts are conducted in numerical simulation, where the others auxiliary part was compensated with appropriate boundary condition

1. The tool was modelled as a discrete rigid body, 3-dimensional shell.
2. The workpiece was modelled as deformable body, 3-dimensional planar shell. While the sheet thickness was defined in the section properties of workpiece.

Meshing

The S4R shell purpose element with four nodes and 6 degrees of freedom in each node was used in meshing of workpiece geometry. While the R3D4, A rigid element of 4-node, bilinear quadrilateral behavior used to define mesh in tool geometry. A mapped mesh was adopted in workpiece, while a sweep edges mesh was adopted in tool as demonstrated in figure (5).

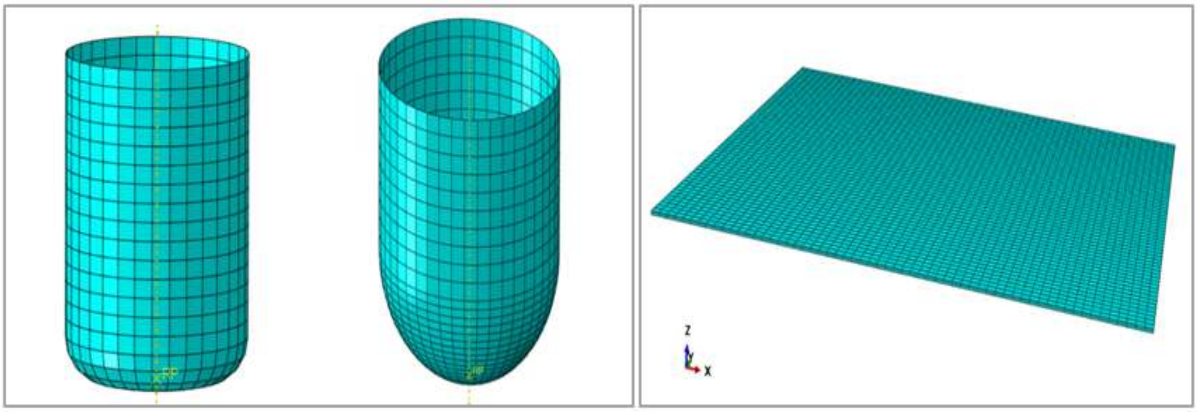

Figure 5. Meshing of some types used of tools and workpiece in SPIF.

Body interaction and boundary condition

In order to define the interaction between the tool and the workpiece the contact interaction property was used, also the contact features were set to be tangential behavior of 0.1 coefficient of friction. The penalty formulation is adopted to maintain surface to surface contact feature throughout solution. But regarding to the boundary conditions applied to SPIF numerical model they were as following:

1. A rotational velocity about Z-axis was applied on the tool.

2. A linear displacement in X, Y and Z axes according to experimental tool path was applied to the tool.

3. A fixed support was applied on the external four edges of workpiece.

The sequence of formation of pyramid shape throughout the SPIF simulation is introduce in figure (6).

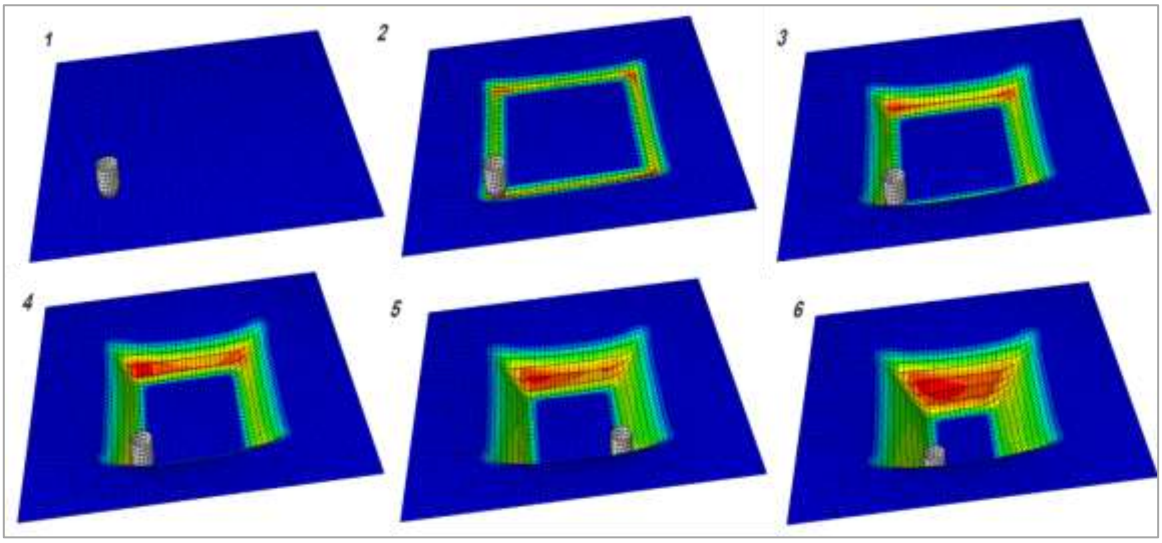

Figure 6. The sequence of forming process during numerical modelling.

RESULT AND DISCUSSION

The sheet thinning is a critical factor in the incremental forming processes, particularly when it comes to SPIF because it has a strongly related with the formability (and failure) of the products, especially with steep walled parts, meanwhile the process parameters have significant effects of the thinning at the part wall, so this study focus on the investigation the effect of some parameters such as forming angle, incremental step size, feed rate, and forming tool shape on the thickness distribution profile and thinning rate along the wall of the forming parts. SPIF was done to perform asymmetric truncated pyramid which has geometry shape with two angles in same formed part to reduce the number of experiments. The thickness variation along the wall were analyzed through numerical and experimental measurements from the clamped edge to the base of the pyramid.

Three different feed rates (800, 1000, 1200) mm/min were used to study the effect of this parameter on the thickness distribution along the wall theoretically, numerically and experimentally as shown in figure (7). This figure reports the thickness values remains without significant changes when the feed rates changing and it is concluded this parameter has a little effect the measured thickness values, therefore the highest feed rate (1200 mm/min) would being choose in the rest of the experiments in this study to reduce the machining time. Additionally, it is noted that the theoretical law (sine law) predicted average thickness values while, in fact there are a very complex distribution of the thickness along the wall, where observe near the blank holder the thickness begins decreasing gradually and continue the decreasing until reach the maximum thinning at about 17mm depth and then thickness returns increasing gradually at near the base.

Figure (8) shows simulation results of the thickness distribution and experimental results at varying incremental step sizes (0.3, 0.5, 0.7) mm. It is found that the lowest step size increase the minimum thickness and lead to a more homogenous thickness distribution, and in the same time there are no significantly obvious change occurs in thickness measured with step size changing from 0.3 mm to 0.7 mm. In the mean time, the relationship between forming tool shape and thickness distribution are established by experimental and FEM results are shown in the figure (9), three different shapes of spherical tip, toroidal tip (flat ended with fillet 2.25 mm), and hemispherical tip which all have the same diameter 12 mm were selected to analyze the effect of this parameter on the final thickness along the wall parts. Since the tool is responsibly on the deformation occurs in the sheet therefore the contact area between them would play the basically role in determine the amount of deformation occurs under the tool throughout the forming. The thickness distribution is found to be the most homogenous under the tool with hemispherical tip while the toroidal tip tool is the worst.

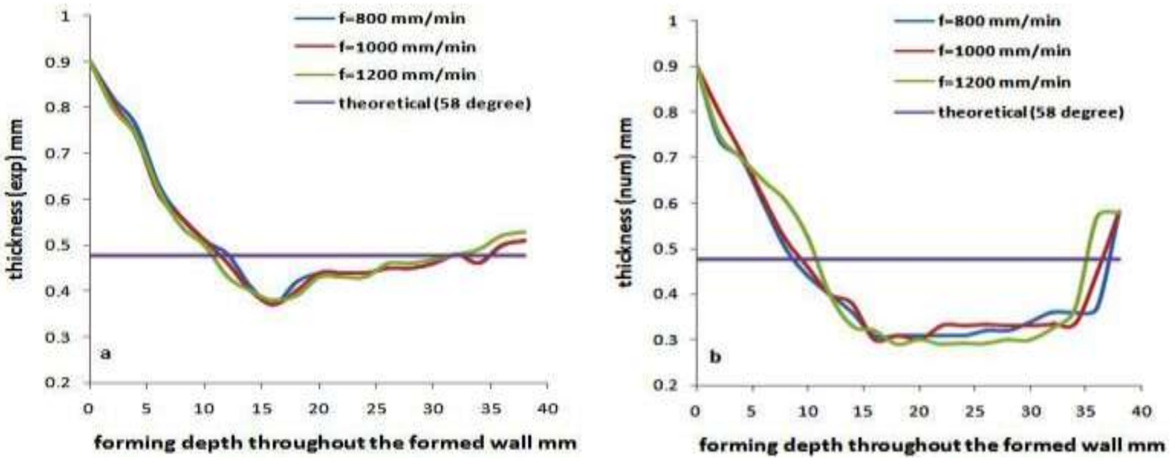

Figure 7. Thickness distribution with different feed rates, a: experimental works, b: numerical works.

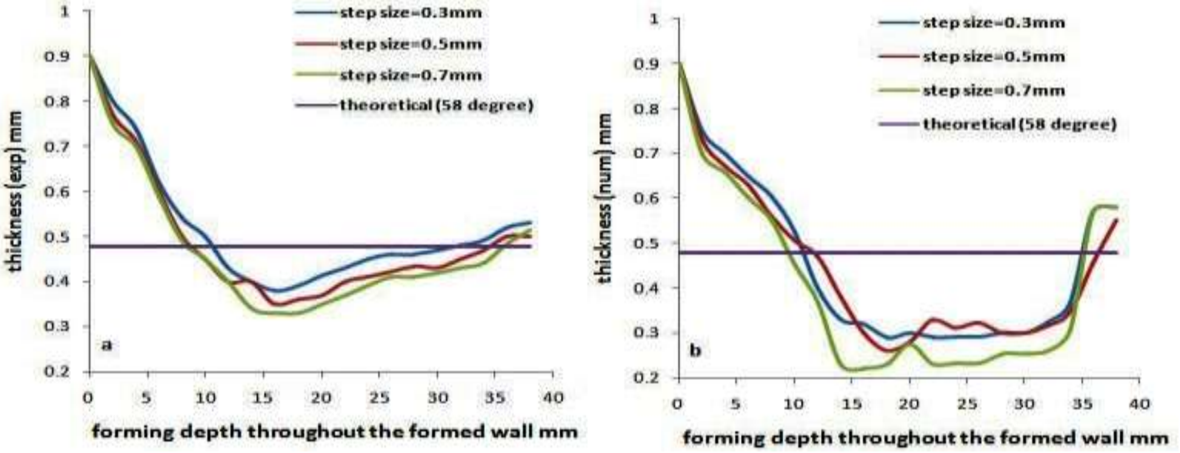

Figure 8. Thickness distribution with different step sizes, a: experimental results, b: numerical results.

It is worth mentioning that experiments were carried out with safe forming angles (48°, 58°) which according to pervious researches would not lead to failure, so in this way it is possible to focus the study on thickness distribution, localized thinning, and thinning values at the walls. Figure (10) shows the effect of forming angles on the thickness distribution profile. It is found that the significant thickness reduction along the wall at increasing of the forming angle due to increase of plastic deformation which occurred in the sheet and the process conditions becomes heavier at the larger angle.

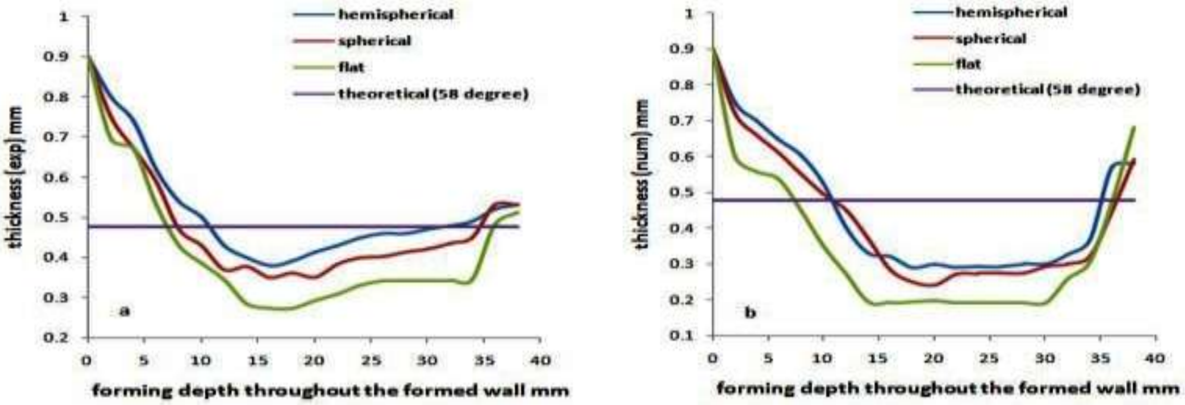

Figure 9. Thickness distribution with different tool shapes, a: experimental results, b: numerical results.

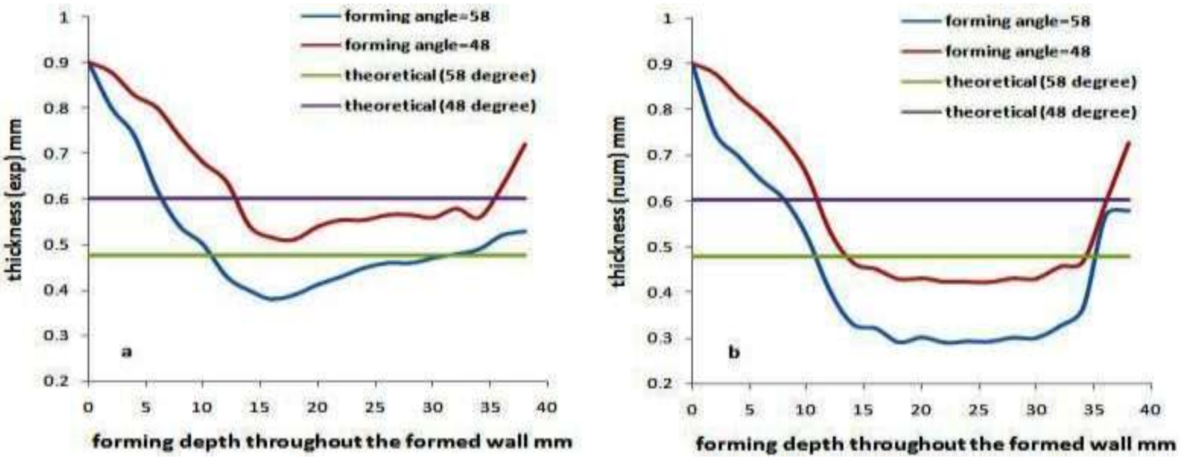

Figure 10. Thickness distribution with different forming angles, a: experimental results, b: numerical results.

It could note from all curves mentioned above the experimental results confirmed that the theoretical results obtained by sine law presented just an average approximation value of thickness according to equation (1) for the wall of formed part while in fact there are some areas subject to excessive deformation and other ones to less deformation along the wall part. Additionally, the predicted thickness value theoretically is higher than the measured thickness on most of the deformation areas. Meanwhile, although the numerical results influenced by different simplifications such as the tool is assumed to be rigid body, no temperature assumed, no heat transfers, the friction between tool and sheet assumed constant throughout the forming process and so on, the trend of thickness distribution behavior and the thickness values were predicted with a significant accuracy though the thickness measured in the experiments are higher than that of the numerical values with acceptable variations.

As far as thinning ratio are concerned the relationship details between the thinning ratio values obtained from the equation (2) and the parameters which have largest effect as described before in this study are the forming angle and the tool shape, the discussion would focused on the experimental results to easy the analysis. It is seen that as expected, the thinning ratio obviously increases from 28.5% to 42.2% when the forming angle increases from 48° to 58° this means the forming angle has the most effect on the thickness thinning ratio, the wall thinning ratio under three shapes of tool tip of hemisphere, sphere, and flat are 42.2%, 46.7%, and 53.2% respectively, the best result in according to thinning and more uniform thickness distribution when use the tool with hemisphere tip as the tool shape. Figure (11) explain the experimental and numerical product

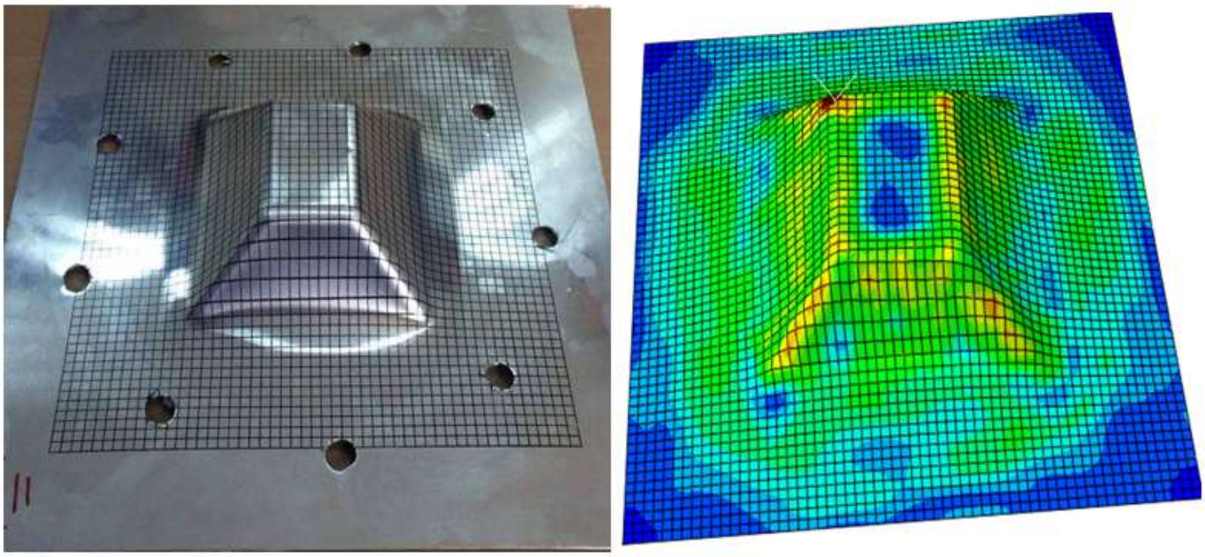

Figure 11. An experimental and numerical product.

CONCLUSION

Thickness thinning is the significant major factor in the SPIF process because it determines the forming limits of the sheet, meanwhile process parameters affect the measured thickness and thinning, therefore affect the final product quality. The theoretical model (sine law) uses to give average approximation values of the thickness and don't provide the sufficient information about the thickness distribution and localized thinning on the deformation areas in the same time don't take parameter effects into account. So, studying the relationship between these parameters and thickness distribution along the wall has established numerically by ANSYS workbench and experimentally validated. It is been seen the environment simulated is very agreement with experimental works, thus the numerical simulation can be considering a suitable tool for predicting the thickness distribution and thinning ratios. In the process of SPIF, the feed rate doesn't have a clear effect on the measured thickness. The thickness reduction along the wall increase when the step size increase but this increasing is no obvious. The best result in according to more homogenous thickness distribution and the less thinning ratio could get when use the forming tool with hemispherical tip and the worst when use the tool with flat tip. The forming angles has the largest effect on the thinning ratio along the wall, the thinning ratio increases rapidly when the forming angle increases. In the experiment, the process parameters were chosen with larger feed rate, smaller step size, smaller forming angle, and hemisphere forming tool to obtain the lower thinning ratio in order to improve the forming limits of the sheet.

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