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FINITE ELEMENT SIMULATION OF THE TWO POINT MULTISTAGE INCREMENTAL SHEET METAL FORMING PROCESS

Adil Shbeeb Jaber*

Asst. Lect., Production Engineering and Metallurgy, University of Technology, Baghdad, Iraq.

Abstract: Incremental sheet forming (ISF) is a novel technology to takes part in solving a lot of problems from classical sheet forming operation in terms of more flexibility, cheap, low production time, convenient for small batches and particularly rapid prototype production. This paper aims to provide enough information for understanding of the incremental forming process, especially focusing on numerical two point incremental sheet forming mechanism and multi stages incremental forming. The influence of some process parameters such as incremental step size and forming tool radius, on thickness distribution across the wall of the part is studied, as well as, studying the thickness distribution and strain analyses for three stages in multi stages incremental forming during forming the product with vertical angle.2-D model of cone shaped part with right forming angle has been developed in the three stages from sheet with thickness (1mm) of the aluminum alloy (AA1070). A commercial available finite element program code (ANSYS 11), is used to carry out the numerical simulation of the multistage incremental sheet forming. The results show that, when considering multi-stage incremental sheet forming, the task is even more difficult because the strain and thickness distribution resulting from the first stage will influence the subsequent results. Decreasing in the forming tool radius will increase in the thinning of the wall product due to excessive stretch will occurs, while the incremental step size is not significant effect on the numerical results (thickness, strain) distribution of the product. Finally, the goal to attain a vertical wall angle and equally maintain wall thickness and strain over the wall part is pursued. Mechanical tests, computer programming, geometry and design were required.

Key words: *Multistage forming, two point incremental forming, Process limits, Finite element method.*

محاكاة لعملية التشكيل ألتزايدي ثنائي التماس متعدد المراحل لشرائح المعدنية باستخدام طريقة العناصر المحددة

الخلاصة: تشكيل ألتزايدي لصفائح معدنية هو تكنولوجيا مبتكرة تشارك في حل العديد من المشاكل الكثيرة المصاحبة لعمليات التقليدية لتشكيل صفائح معدنية، حيث يمتاز هذا النوع بالمرونة ألعالية، كلفة قليلة، قلة وقت الإنتاج، وملائمة لدفع الانتاج الصغيرة وخصوصا إنتاج النماذج الأولية السريعة. حيث يهدف هذا البحث إلى تزويد معلومات كافية لفهم عملية التشكيل ألتزايدي والتركيز على المحاكاة العددية لإلية التشكيل ألتزايدي وبالخصوص التشكيل ألتزايدي ثنائي التماس متعدد المراحل. ودراسة تأثير بعض من متغيرات العملية مثل حجم الخطوة التزايديه و نصف قطر أداة التشكيل على توزيع السمك في جدار المنتج، إضافة إلى دراسة توزيع السمك وتحليل الانفعالات خلال ثلاث مراحل للمنتج خلال عملية التشكيل ألتزايدي متعدد المراحل ثنائية التماس لصفائح المعدنية للحصول على منتج ذات جدران قائمة الزاوية. تمت المحاكاة باستخدام نموذج ثنائي الإبعاد (2- Dimensional) لجزء اسطواني الشكل ذو زاوية تشكيل عاموديه في ثلاث مراحل من صفيحة الألمنيوم (AA 1070) بسمك (1mm)، وذلك باستخدام طريقة العناصر المحددة التي تم تنفيذها باستخدام برنامج (ANSYS11) لإظهار المحاكاة العددية لعملية التشكيل ألتزايدي متعدد المراحل، وقد أظهرت النتائج، إن عملية التشكيل متعددة المراحل تزداد صعوبة إثناء تقدم العملية ولذلك لان الانفعالات والترقق في السمك للمنتج في المرحلة الأولى سوف يوثر على النتائج في المراحل التالية، وكما تبين أن التقليل من نص قطر أداة التشكيل سوف يودي إلى زيارة الترقق في السمك على جدار المنتج نتيجة المط العالي الذي يحدث في العملية، بينما لا يوجد تأثير مهم لحجم الخطوة على النتائج العددية (توزيع السمك والانفعالات) على المنتج. وأخيرا إنتاج منتج ذو جدران عمودية مع المحافظة على توزيع منتظم لسمك والانفعالات على طول جدار المنتج باستخدام اختبارات ميكانيكية وبرامج حاسوبية وتصاميم الهندسية هو الهدف الذي تم تحقيقه.

* totelife@yahoo.com

1. Introduction

In machine design, products made of sheet metal are extensively used. For manufacturing of parts with traditional sheet metal forming mechanism, for instance deep drawing, dedicated tools are needed. They are highly specialized, costly and time consuming to manufacture. Newly novel sheet metal forming technique, incremental forming, have been introduced. It is based on utilizing of simple spherical tool, which is moved over CNC controlled tool path. The product is manufactured by deforming the sheet locally. The edges of blank sheet are fixed in sheet holder. The tool deforms the sheet blank drawing a contour on horizontal plane, then makes step downwards and draws next contour and so on until process is accomplished. For the operation universal three or more axis CNC machining centre can be utilized. To prepare the numerical control code general purpose Computer Automated Manufacturing (CAM) software can be used[1].

Equation (1) which is named sine law formula used to evaluate the thickness of formed part in the single point incremental forming operation. This is usually used for the shear forming operation.

$$T_f = T_o \sin(\pi/2 - \psi) \tag{1}$$

Where, (T_f) is final thickness, (T_o) is initial thickness and (ψ) is wall angle. Regarding to Sine law (1), it is hard to get bigger angle while having the same thickness throughout the product. It is complex to have big and deep drawing product without fracture because the more the forming angle the less the thickness distribution. Vertical wall or right wall angle leads wall thickness to reach zero regarding sine law. Increasing the ultimate wall angle can be promoted by many ways such as increasing thickness of sheet, changing diameter of tool and step down also have an influence on maximum forming angle. Multi-stage is other strategy to obtain large wall angle by redistribute material or shift the material with multi-stages. There are a lot of tries to carry out incremental forming which tool moves several times through same area through the geometry profile to increase wall angle with support. The idea of incremental forming technology were initially introduced in the patent at 1976 but the foregoing tool was not attainable in that time [2].

Experimentally, theoretically and numerically investigation was conducted by Pohlak et al. [3] to estimate the limit factors such as forming force components and material formability in the incremental sheet forming operation, a numerical analysis is modeled by using LS_DYNA (FEA) software, a simplified theoretical model was proposed to estimate the forming force compounds in the incremental sheet forming in the three directions. It is concluded experimentally, theoretically and numerical results in perfect harmony for estimation in forming force and forming limit diagram in ISF process. Radu [4], have investigated the impact of four parameters process (radius of the tool, incremental step down sizes, feed rate and spindle speed) on the dimensional accuracy and surface roughness. The performed analysis shows that the vertical step and tool radius are most important influence on quality of parts processed by single point incremental forming, both in terms of accuracy of the dimensions and surface roughness, it has been found that an increase in tool radius and tool speed (both spindle speed and feed rate) leads to better surface of the formed parts. On the contrary, an increase in step size shows an increase in surface roughness.

An overall review of the incremental sheet forming (ISF) technology was presented by Nimbalkar and Mandedkar [5]. A paper summarizes a technological review of the art of incremental forming process on various topics such as types of incremental sheet forming and differences between the (SPIF) and (DPIF) technology, equipment used in this process, described the solid forming tools, effect of diameter, material and shape of forming tool on the dimensional accuracy and surface roughness and time production , discussed the tool path generation and effect of different types of tool paths on the formability characterizations, the study deal with in material process parameters, formability incremental forming, forces and deformation mechanism in incremental sheet forming. Illustration for the thickness distribution along the wall products formed by single point incremental forming by using (ANSYS) program which based on finite element method was made by Qasim [6], as well as prediction of the limits of process as regards as the geometry final product, then the results were found in the method compared with the experimental work to validate this method, the selected material is an aluminum with 0.9 mm thickness , different products with cone like shape were simulated with various depth and angle forming. Two types of analysis were conducted to investigate the effect of angle forming on thinning wall of product and determine the effect of depth parameter on the thickness distribution over the wall product. it is concluded from this research the numerical results was very good agreement with experimental ones and theoretical analysis (sin law) for determining the thickness at different depths and angles forming and the variations in results don't exceed 6%. The thinning in the products increased with increased in angle and depth forming.

Hamdan et al. [7] presented combined Influence of some process parameters on the surface roughness of surfaces produced by incremental sheet metal, five forming parameters (number of forming stages, tool overlapping, feed rate, rotational speeds and state of initial blank) were investigated their influences on the surface roughness and dimensional accuracy of the products. The analysis of variance (ANOVA) results show the tool overlapping and number of forming stages have largest effects while the rotational speeds and state of initial blank have smallest effects on the surface roughness.

2. Experimental Procedures

The sheet metal utilized in this research is the Aluminum alloy (AA 1070) with thickness 1 mm, the chemical composition of the sheet materials is carried out by using spectrometer device to check the manufacture certificate of this materials as shown in Table 1. Mechanical properties for this material is very significant effect on the results, therefore, tensile test was conducted on specimens from this materials in order to obtain the important mechanical properties which used as input data to define the elastic – plastic response of the material used in the numerical simulation. The specimens for the tensile test were cut by wire-cutting machine according to ASTM EM8 standard as shown in Fig. 1, three specimens were tested to check the repeatability of the results and take the average values to reduce the error. Computerized universal testing machine (WDW-200EIII) with extensometer device were used to perform the tensile test as shown in Fig. 2. The specimens were loaded until fracture occurred, the tensile tests is carried out at cross head speed (0.5 mm/min) equal to initial strain rate of $(1.6*10^{-4})$ S^{-1}. Fig. 3, the true stress-strain curve was concluded from engineering stress-strain curve that obtained directly from testing machine. The slope of linear elastic region define the modulus of elasticity while the slope of the flow curve at specific level of stress (yield stress) is tangent modulus, the yield stress was evaluated by taking the 0.2% offset from this curve, mechanical properties for an Aluminum alloy (AA 1070) are shown in Table 1.

Table 1. The chemical composition of the Aluminum sheet AA 1070 (% of Mass).

element	Al	Fe	Si	Cu	V	Mg	Zn	Mn	Ti	other
Com.	99.72	0.24	0.19	0.05	0.05	0.03	0.03	0.03	0.03	0.03

Figure 1. The universal testing machine used to make tensile test.

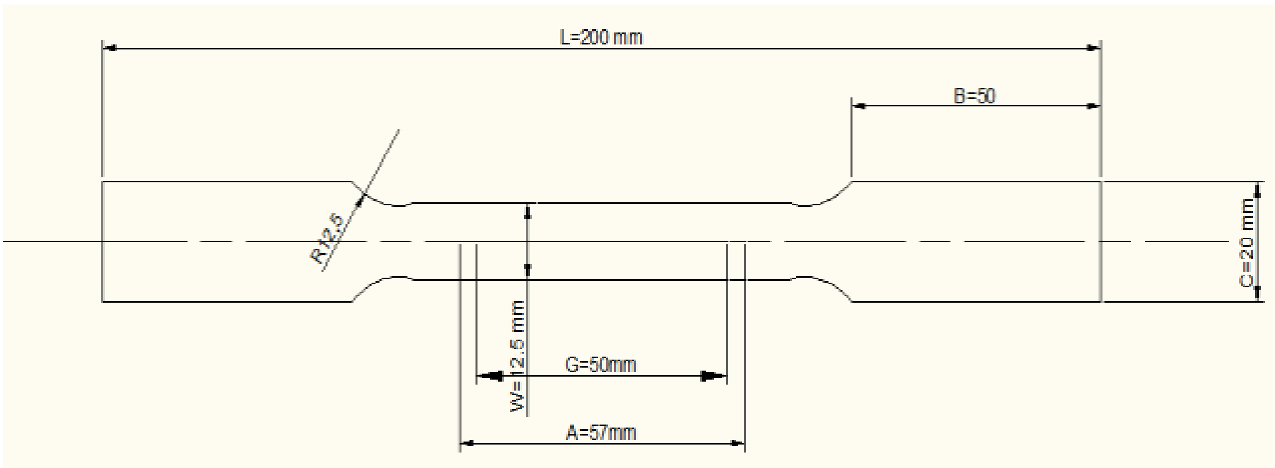

Figure 2. The dimensions of the tensile test specimen.

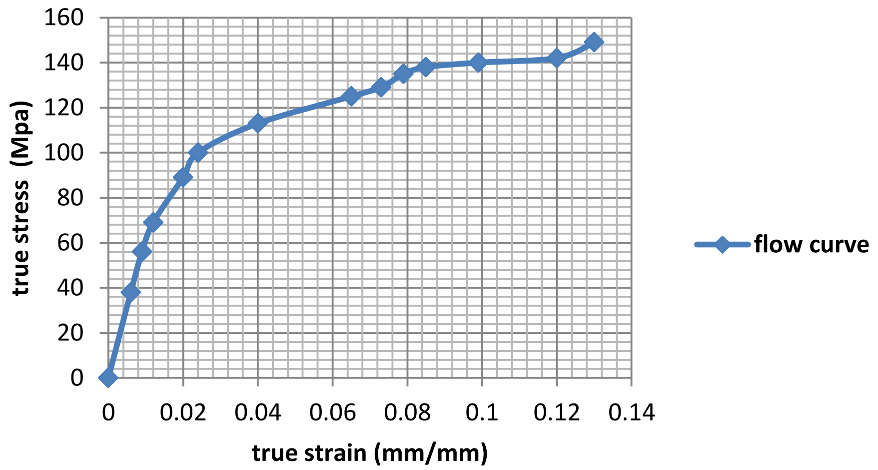

Figure 3. The true stress – true strain curve of the aluminum alloy (AA1070).

Table 2. The material properties for an Aluminum alloy (AA1070) used in numerical simulation.

symbol	parameters	value	unit
E	Young's modulus	75	Gpa
Ʊ	Passion ratio	0.33	_
σ_y	Yield stress	70	Mpa
E_t	Tangent modulus	0.2	Gpa

3. Finite Element Analyses

Numerical simulation using computers or computational simulation has increasingly become a very important approach for solving complex practical problem in engineering and science. Numerical simulation translate important aspect of a physical problem into a discrete form of a mathematical description, recreates and solves the problem on a computer, and reveals phenomena virtually according to the requirement of the analysis. It provides an alternative tool of scientific investigation, instead of carrying out expensive, time-consuming experiments in laboratories or on site [9].

3.1. Finite Element Program (ANSYS) Software

In current study, a commercial available finite element program code (ANSYS 11) is used to perform the numerical simulation of the incremental sheet forming process, with capability to analyze a wide range of different problems. Two ways were used in ANSYS namely; interactively through the graphical user interface GUI, and through the use of the batch files and ANSYS commands [9].

3.2. Numerical Modeling

Commercial finite element analyses code ANSYS11.0 was utilized, in which the "Newton-Raphson" implicit approach was used to resolve nonlinear issue. In this approach, the stroke steps on forming tool are defined explicitly by modeling the final shape (cone like shape) in the UG-NX9 (general purpose computer automated manufacturing (CAM) software and then generated the tool path (Iso-planar tool path), the tool path generation is not needed in simulation, however for simulation is used to make tool move along predefined trajectory, finally extracted the coordinates for tool paths of the product to define the stroke steps during the forming in the simulation by ANSYS software through a time extent. Within every step, some solutions (substepes or time steps) are carried out to apply the displacement gradually. At every substep, a number of equilibrium iterations are completed to get a converged solution. In this study, three stages were modeled during forming process, first forming produced cone like shape with forming angle 60° from sheet when the forming hemispherical head tool start forming from top to the down (performing stage), after the completion of the first stage, a second stage starts the forming from down and return to the top of product but with forming angle 80° (upward stage) and then followed the third stage repeat the first stage with forming angle 90° to produced final product with vertical angle walls (downward stage).

3.3. Element Types And Meshing Procedures

The 2-D 4-node structural solid axisymmetric element (PLANE42 2D LARGE STAIN SOILD) was used for work piece (blank). The tool set (forming tool, die and blank holder) was modeled as rigid bodies. Element sizes are controlled by controlling the division specification of lines. Mesh density of the blank and tools affect the accuracy of the results. So the meshes in the blank are finer. The most important portion of the tool whose mesh density affects the accuracy and reliability of the results is its arc segment and the meshes of this portion are finer than other portions, the shape of element adapts with suitable curve to fit the curvature part such as radius of the forming tool and entry die, the details of meshing described in Table 3. The movement of the punch was defined using a pilot node. The degrees of freedom of the pilot node represent the motion of the entire rigid surface.

Table 3. The description of meshing process .

Part name	Element shape	Element size	No. of element
Blank	rectangular	(1*0.5)	250
Blank holder and ring	square	(1.5*1.5)	20
Forming tool	square	(1*1)	35
Die	square	(1*1)	60

3.4. Contact

Automatic contact procedure in ANSYS11.0 was used to model the complex interaction between the blank and tooling. In studying the contact between two bodies, the surface of one body is conventionally taken as a contact surface and the surface of the other body as a target surface. The "contact-target" pair concept has been widely used in finite element simulations, which was used to represent contact and sliding between the surfaces of tool set and blank. For rigid-flexible contact, the contact surface is associated with deformable body, and the target surface must be the rigid surface. Therefore, rigid tool set-flexible blank contact, target elements of TARGE169 were used, to represent 2D target tool set surfaces which were associated with the deformable body blank represented by 2D 8-node contact elements of CONTA172. There are three contact pairs are constructed:

1. Contact pair between forming tool and blank.
2. Contact pair between blank holder, ring and blank.
3. Contact pair between die and blank.

3.5. Assumptions, Plastic Behavior Model

Because of the symmetry in the model geometry, constraints and boundary conditions, an axisymmetric model needed was analyzed. Description of the movement used in this study for the multistage incremental sheet forming process is shown in Fig. 4. For simplifying the simulation of this incremental operation, the following assumptions were made as follows.

1. Temperature of work piece (blank) remained constant, no heat transfers between work piece and tool set.
2. The die, forming tool, ring and blank holder were rigid.
3. The tool moved down at constant speed through the path predefined through the forming operation and the dies were fixed.
4. Bilinear Isotropic Hardening BISO option uses the von Mises yield criteria coupled with an isotropic work hardening assumption. This option is often preferred for large strain analyses.
5. The principal axes of anisotropy coincide with the material (or element) coordinate system.
6. Elasto-plastic constitutive model with isotropic strain hardening was used to simulate the sheet response. The elastic behavior was taken to be linear and the plastic response was modeled using von Mises yield criterion.
7. The friction coefficient is assumed to be uniform and constant for all contacting surfaces and equal to 0.1.

The (FE) model of the tools and blank sheet for multistage incremental sheet metal forming is shown in Fig. 5. The final product with vertical wall are shown in Fig. 6.

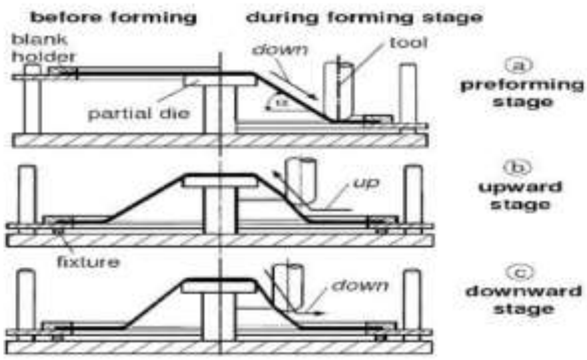

Figure 4. The multistage incremental sheet forming process.[2]

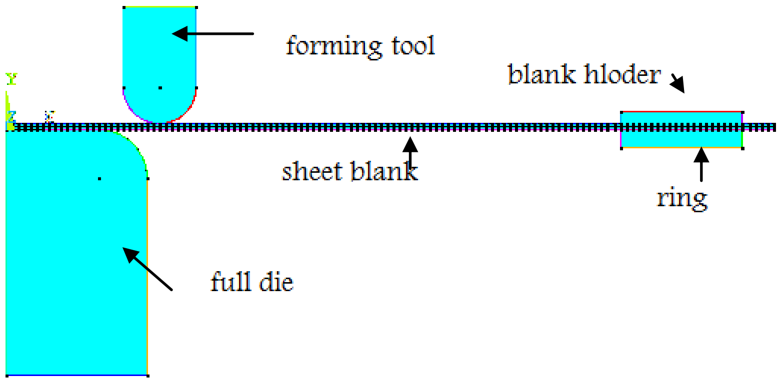

Figure 5. The finite element model of the two point incremental sheet metal forming .

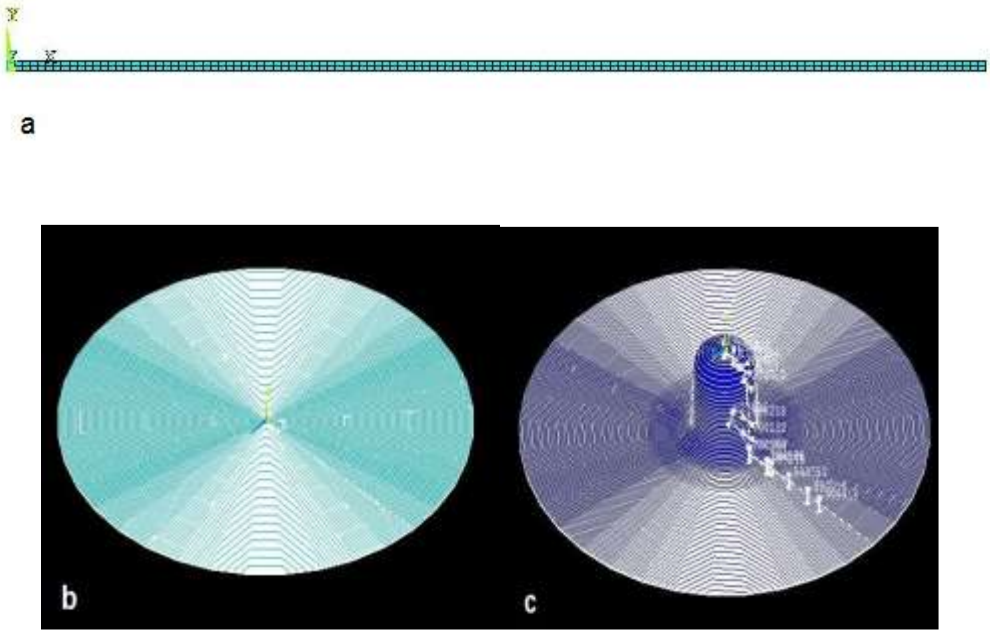

Figure 6. (a) The FEM of 2D axisymmetric blank used in this study. (b) the FEM of blank after full expansion. (c) FEM of final product with vertical angle in two point multistage incremental sheet metal forming .

4. Result and Discussion

In order to investigate the multi stages two point incremental sheet forming process. FE model simulated this process, these multistage two points incremental sheet metal forming were modeled as follow. The blank is a circular plate having a thickness 1 mm and a diameter 250 mm is placed over a moveable frame and the blank is held from its perimeters with a blank holder which applies the restraint force for preventing the flange movement. In this type of supporting, a cylindrical full die with entry radius 6 mm is used with vertical angle to produce the final product, while forming tool have (12,18) mm of diameter are used in these simulation.

Firstly, the influence of some process parameters such as (incremental step down size, radius of the forming tool) on the thickness distribution of the cone shape part with a wall angle of 60° is studied , and then especial focus of the mechanism of the multistage two point incremental forming to produce part with vertical walls were investigation in three stages. Finally, the simulation results including the thickness and strain distributions over the product walls throughout three stages were concluded.

The strategies of the movement of the forming tool to produce product with vertical angle as follows, first forming stage produced the cone like shape with forming angle 60° from sheet when the forming hemispherical head tool start forming from top to the down (performing stage), after the completion of the first stage, second stage of forming starting from down and return to the top of product but with forming angle is 80° (upward stage) to produce cone like shape with wall inclined 80°, finally the third stage. Repeat the first stage with forming angle 90° to produced final product with vertical angle walls (downward stage). Different shapes of material deformation during simulation in multistage incremental forming throughout the three stages are displayed in Fig. 7.

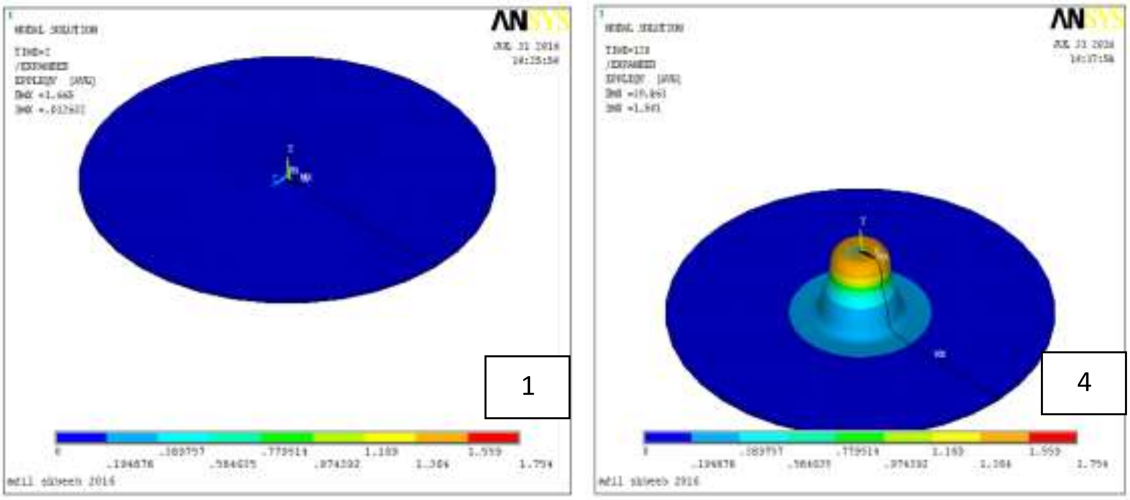

Figure 7. Different stages of material deformation during simulation in multistage two point incremental sheet metal forming.

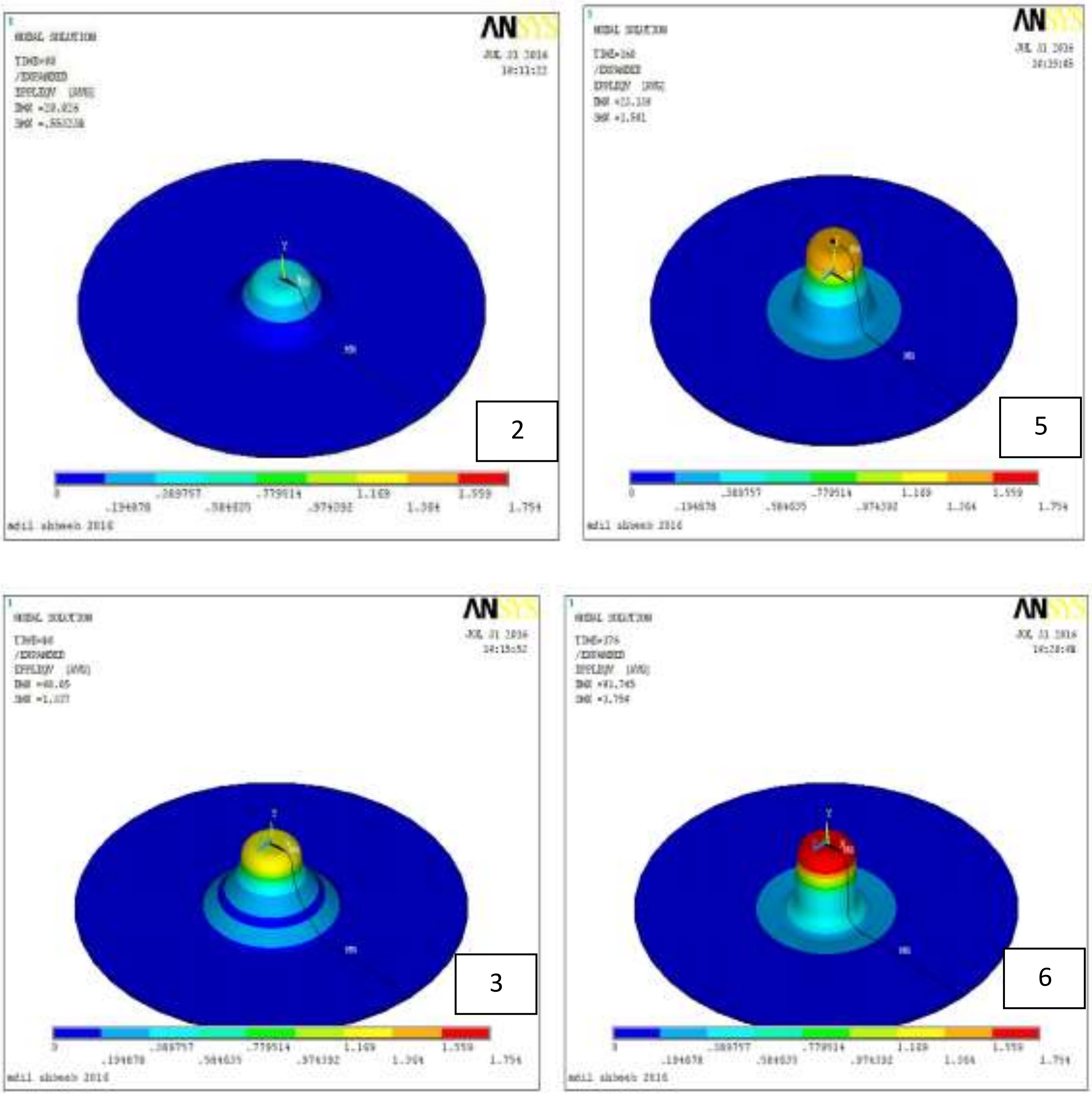

Figure 7. continued

To study the influence of incremental step size (ΔZ) in the two point incremental forming process to produce cone like shape with wall angle 60° on the thickness distribution of the product wall from the center to the rim of the product flange , three values of step size were chosen (0.5, 1, 1.5) mm with constant values for another parameters such as radius of the tool and entry die are 6 mm, thickness and diameter of the blank (1, 250) mm respectively and friction between tool and sheet is assumed (0.1). The numerical results of the thickness distribution of the product at different step size, there are no change in the thickness for three values of the incremental step size as shown in Fig. 8. The influence of tool radius on two point incremental forming, two models of the tool radius (6, 9) mm with constant entry radius of die and other process parameters have been made. Fig. 9 presents the influence of radius of tool on the thickness distribution throughout the wall product with wall angle 60°, it is seen from this figure the two curves have the same trend and increase the tool radius will lead to decrease the thinning on the wall product due to decrease in the amount of stretch occurs.

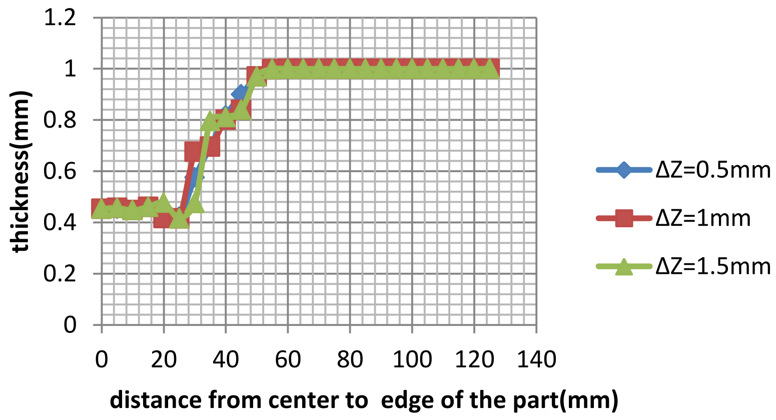

Figure 8. The thickness distribution for the final part at different step size of the process.

To produce product with steep wall on ISF in one stage is possible because its final thickness of sheet metal will reached zero according to (1), therefore one of strategies used to solve this problem and produce product with vertical wall is multistage incremental forming. In this study numerical simulation of the multistage incremental sheet forming have been made, three stages were used with angle forming (60°, 80°, 90°) respectively, the tool and die entry radius 6 mm, step size used 1 mm and thickness of the sheet metal 1 mm. Fig. 10 shows the distribution of equivalent (effective) strain over the part wall for three stages, it can see from the figure, maximum value at part base and entry die regions due to sever deformation (stretching, bending) in these regions, and then there is some decreasing in values in the part wall region when compared with entry die region, thinning in wall region due to tension stress in this region, afterward the value of equivalent strain is zero at product flange, no deformation occurs in this area. Also it is obvious clear the values of effective strain increase with progress of forming stages, because of its values in first stage will added to values in the next stage, therefore maximum values of equivalent strains appear in the third stage.

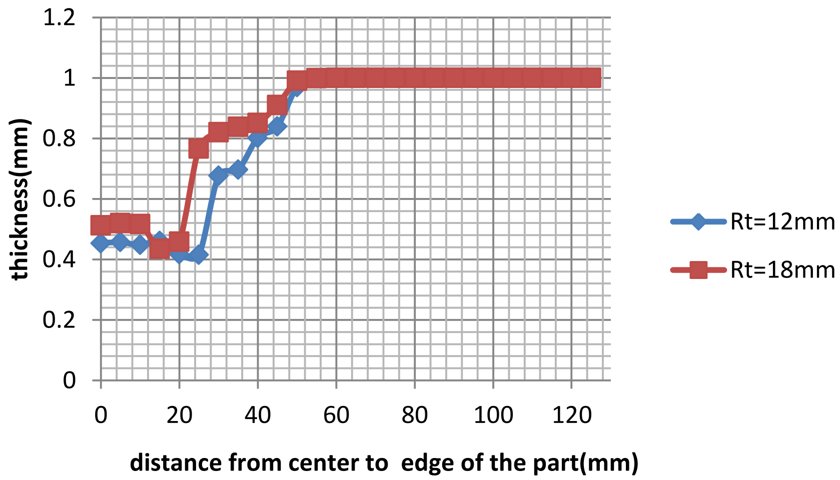

Figure 9. The thickness distribution for the final part at different tool radius of the process.

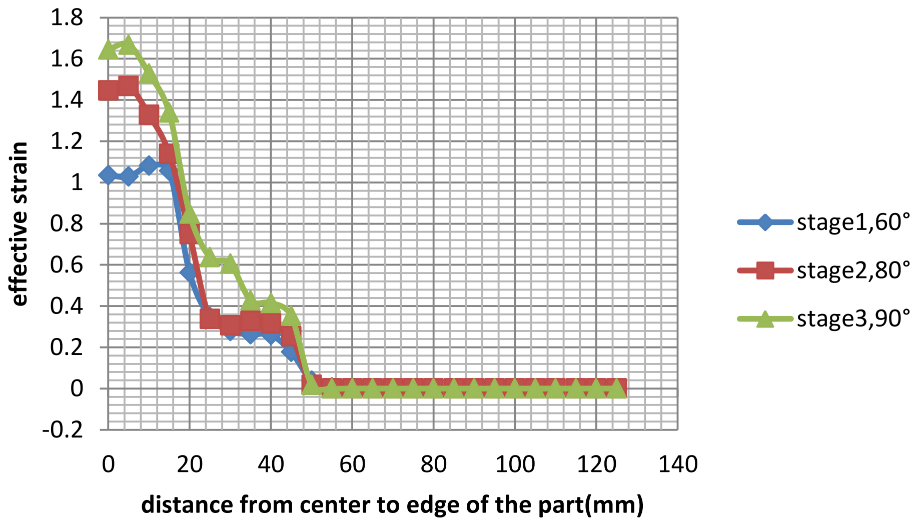

Figure 10. The equivalent strain distribution for three stages of the process.

Fig. 11 shows that the thickness distribution for the three stages of the process from center of product to the edge of product, it is obvious from figure three curves for three stages have the same trend, for three stages there are a lot of change in the thickness in the base of product because there are excessive deformation in this region, and in the die entry region the more thinning occur because of stretching produced from excessive bending in this region and then thickness begins to rise until reaching maximum value in the part rim due non deformation in this region, the thickness in this region approximately equal the initial thickness of the sheet, it is shown from the figure the thinning increases with progress of forming stages and the maximum value of thinning display in third stage due to accumulation of thickness decreasing from first and second stages.

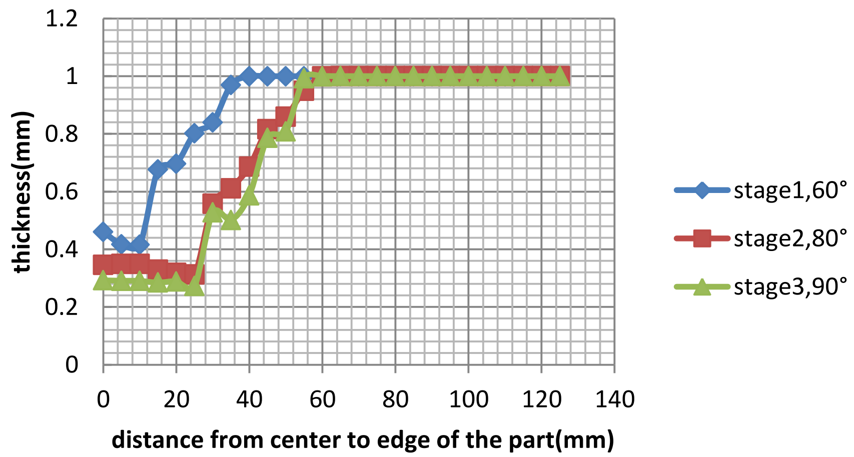

Figure 11. The thickness distribution for the products of the multistage incremental forming process.

5. Conclusions

Multistage incremental sheet forming is selected to produce the products which have steep angles and also vertical walls during incremental forming operation (ISF). The multi stages incremental sheet forming was simulated using FEM with implicit formulation and using von miss yield criteria. It is clear when considering multi-stage forming, the following important points are concluded .

1. The task is even more difficult during progress of the multistage process because the strain and thickness distribution resulting from the first stage will influence the subsequent stages.
2. With increasing the number of stage the values of equivalent stains at the part wall will increasing.
3. With increasing the number of stage the values of thinning at the part wall will increasing.
4. The incremental step size don't affect the numerical result (thickness distribution) may be due to the values of parameter chosen in this study are very close in values and their effect on the thickness distribution of the wall product are nearly similar, therefore there aren't change on the result.
5. Decreasing in tool forming radius will increase in thinning of the wall product due to excessive stretch will appear at smallest radius of forming tool.
6. Produce of the product with vertical wall by using multi stage two point incremental forming process in numerical simulation with acceptable values of thickness and strain can attained.

Abbreviations

A	length of reduced section of the tensile test specimen
AA	Aluminum alloy
Ansys	analysis system
B	length of grip section of tensile test specimen
C	width of grip section of tensile test specimen
CNC	computer numerical control
DPIF	double point incremental forming
FEA	finite element analysis
FEM	finite element method
G	gauge length of tensile test specimen
HV	Vickers hardness
R	radius of fillet of tensile test specimen
Rt	tool radius
SPIF	single point incremental forming
W	gauge width of tensile test specimen
2D	two dimension
ΔZ	incremental step size

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