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# Experimental Evaluation and Finite Element Simulation to Produce Square Cup by Deep Drawing Process

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## Abstract

Deep drawing process to produce square cup is very complex process due to a lot of process parameters which control on this process, therefore associated with it many of defects such as earing, wrinkling and fracture. Study of the effect of some process parameters to determine the values of these parameters which give the best result, the distributions for the thickness and depths of the cup were used to estimate the effect of the parameters on the cup numerically, in addition to experimental verification just to the conditions which give the best numerical predictions in order to reduce the time, efforts and costs for producing square cup with less defects experimentally is the aim of this study. The numerical analysis is used to study the effect of some parameters such as die profile radius, radial clearance between die and punch, blank diameter on the length and thickness distributions on the cup, dynamic-explicit (ANSYS11) code based on finite element method is utilized to simulate the square deep drawing operation. Experiments were done for comparison and verification the numerical predictions. effective square cup with less defects and acceptable thickness distributions were produced in this study. It is concluded the most thinning appear in the corner cup due to excessive stretching occur in this region and also it is found the cup thickness and height prediction by numerical analysis and in general in harmony with experimental analysis.

***Keywords***: *Square deep drawing, Finite element method, thickness distribution.*

## 1. Introduction

Sheet metal forming is one of the most widely used manufacturing processes for the fabrication with a wide range of products in various industries. Cylindrical, rectangular and some complex shaped parts can be produced with the help of process [1]. Deep drawing process is one of the important sheet metal forming processes, traditional deep drawing is a process by which a sheet of metal with certain thickness is converted to certain shape of geometry, the blank (undeformed sheet), is placed onto the die which have cavity, and it is pressed by punch into the die cavity, the schematic illustration of the deep drawing process and variables of it shown in the figure (1). Deep drawing of square cup is one of the most widely utilized operations in sheet metal forming technology, It has been widely used for hundreds of years.

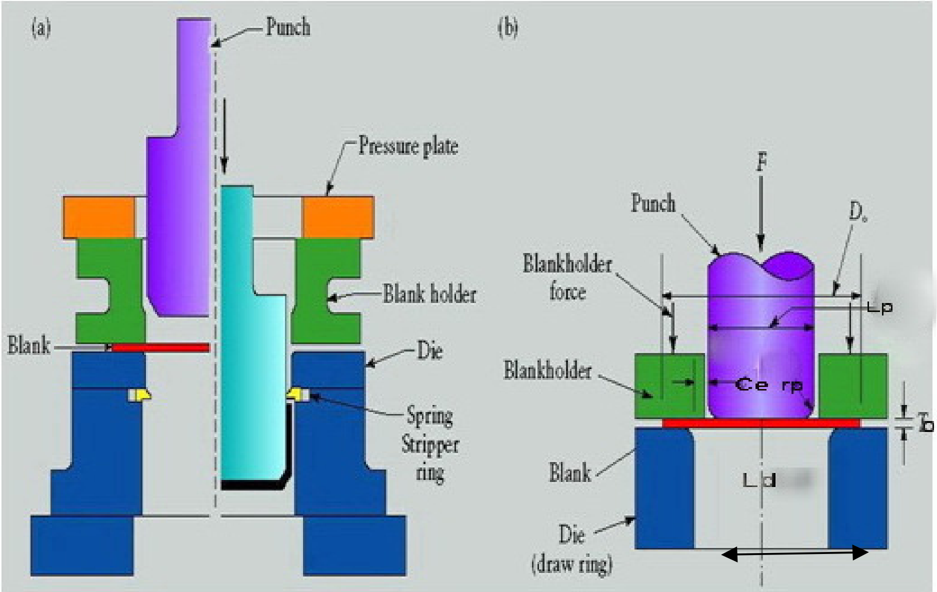



**Fig. 1. (a) Schematic illustration of the deep drawing process, (b) Variables in deep drawing process[2].**

For example, it is utilized to produce car parts in automotive manufacture, utilized in electrical power engineering and aerospace industries, also making domestic items like kitchen sinks, square shaped parts are very critical in deep drawing process as stresses induced are not same in all directions. Various factors affect this process like blank size, blank thickness, die fillet radius, punch profile radius, lubrication [1,3,4]. therefore modern researches focus on the optimum values of these process parameters for non-symmetrical deep drawing parts ( square, rectangular, triangular and hexagonal shapes), in the field of square deep drawing process more researches have been focused.

E. onder, A.E. tekkaya [5] reported that numerical analysis of different blank shape using various sheet metal forming processes such as conventional deep drawing, hydro-mechanical deep drawing and high pressure sheet metal process, the effect of some process parameters were studied for each cross section, two types of steel have been used as materials blank in the numerical analysis and on the experimental verification. Dynamic-explicit FE software and an elastic-plastic model was used in this numerical analysis. The analysis displayed that depending on the blank shape and dimensional setup certain process are preferable for obtaining more satisfactory products. It is concluded from this study the hydro-mechanical deep drawing can produce cup with less thinning while the high pressure sheet metal yields the largest thinning in the product with same geometry.

common conclusions derived out from the research carried out by Halil Uibranhim demirci, Cemal esner and Mustafa yaser [6] to investigate the effect of the blank holder force on wall thickness, cup depths, tearing and wrinkling in square deep drawing process experimentally and numerically via the LS-DYNA software are summarized as follows: the wall thickness distributions obtained by experimental and finite element method is seem to be showing generally errors of around 15%, it is observed that thickness of the cup wall gets thinner in the punch profile region and increased in thickness occur toward the edges of the cup section. K. youns, M. J. Abdrasul [7] study the effect of die and punch corner radii on the behavior and flow of metal and at the limit of fracture (failure is of any breaks in the square cup) in the process of deep drawing and compare the practical results with the theoretical results that we get by using the method of finite element analysis, the FEM code the commercially available software (ANSYS 11- 3D) used here. Moshen et al [8] have proposed a newly process to raise the formability for the square deep drawing process by using flat headed square punch to deformed the flat circular blank in to conical shaped die with square orifice at its end. FEA was utilized to investigate the effect of geometrical parameter such as die and punch profile radius, punch and die corner radius, die cone angle, relative clearance and initial thickness of the blank on the square cup formability in order that determine the optimal values of these parameters, the limit drawing ratios were utilized to estimate the impact of the parameters on the drawability of cup. Experiments with same conditions have been done to verify the FE predications. It is concluded the LDR obtained from this process is significant higher than that of the improved classical deep drawing ways.

U. pranavi et al evaluated the formability of AA 6061 aluminum alloy blank with thickness of 2mm by using deep drawing process to produce square cups, numerical simulation commercial FEM code in which Hollomom's power law and Hill's 1948 yield criterions are implemental to investigate the influence of blank holder force, punch and die profile radius, lubricating conditions and blank size [9]. The deep drawing of a rectangular cup from AISI 304 stainless steel sheet was investigated numerically and experimentally. The FEM was used for computer modeling of the deep-drawing process. The thickness distribution predicted from the FEA was compared with experimental measurements. It was observed that the numerical results agree well with the experimental values. The minimum thickness was observed at the punch radius in both the simulation and experiment were studied by B. Sener, H. Kurtaran [10]. H. Vairavan, A.B. Abdullah [11] study the mode of thinning in the square deep drawing process by focusing on the alignment between punch and die. The thickness measurements of the square cup are obtained by analyzing the images obtained from the Alicona Infinite System, a commercial 3D non-contact surface measurement system. The reduction in the thickness mode is then mapped on the basis of the measurements made on a few positions along the drawn blank cross-sectional profile. It concluded that misalignments increase the load required for the drawing process, therefore this high load will increasing the probability of occurs fracture in the square cup especially in the corner region. furthermore, misalignments also may cause non uniform distribution thickness, thus leading to the early failure of the blank. Modeling and the corresponding experimental validation of angular deep drawing parameters on the thickness of the wall, tensile strength and height of the square profile cups. The full factorial experimental method was used to collect the data. the results of finite element analysis were compared with measurements of experimental. As a consequence, it was showed that angular deep drawing dies gave best results with different angle values than conventional dies with higher drawing ratios. In general, the quality of the cup increased by an increase of the die/blank holder angle. Finite element method model results were in good agreement with experimental measurements [12]. Consequently, the present work focused on the main object is the avoiding the fracture and excessive wrinkling may occur in the square deep drawing process to achieve this objective must study the square deep drawing process and the parameters required for defect free finished part that requires a lot of trials to achieve this goal experimentally. Therefore, studied the effect of the some process parameters ( die profile radius, blank size and clearance) on the thickness distributions throughout the cup and lengths of the cups and then determine the optimum values of these parameters numerically by using ANSYS software to reduce the efforts, time and costs, finally the experimental verification can be done only for optimum values of the process parameters obtained from the numerical results.

## 2. Experimental Procedures

### 2.1 Material Selection

The properties of material to be drawn by square deep drawing have significant influence on the success of this drawing operation. Low carbon steel (1008-AISI) was used in this study. This material is selected because of its good formability, specification and widespread usage in the industry, with sheet thickness 0.7mm to reduce the possibility of wrinkles defects based on the results extracted from previous researches. Chemical composition test was carried out by using spectrometer device to verify the manufacturing certificate of (1008-AISI) low carbon steel. The composition studied in the state company for inspection and engineering Rehabilitation activities (S.I.E.R) as shown in Table (1).

**Table 1,**
**The chemical composition of the low carbon steel (1008AISI).**

| element | C% | Mn% | Si % | P% | S% |
|---|---|---|---|---|---|
| measured | 0.08 | 0.32 | 0.02 | 0.015 | 0.021 |
| AISI | =<0.1 | 0.3-0.5 | 0.01 | =<0.04 | =<0.05 |
| element | Cr% | Cu% | Al % | Mo% | Ni% |
| measured AISI | 0.03 | 0.09 | 0.05 | 0.002 | 0.03 |

### 2.2 material properties

To find out the mechanical properties of the sheet blank to be drawn, tensile test carried out for this purpose. Firstly specimens were cut from the sheet and tested according to ASTM (American society for testing of materials) standard E8M specification, the dimensions of tensile specimen as shown in figure (1), then the specimens were fixed carefully by the gripper on the universal testing machine type (WDW-200E), after that it loaded until fracture occurred under cross head speed 2mm/min at strain rate $6.6X10^{-4}$ $s^{-1}$. The tensile test has been done in the University of Technology-production engineering and metallurgy, strength of material laboratory, the universal testing machine used in this study as shown in figure (2).

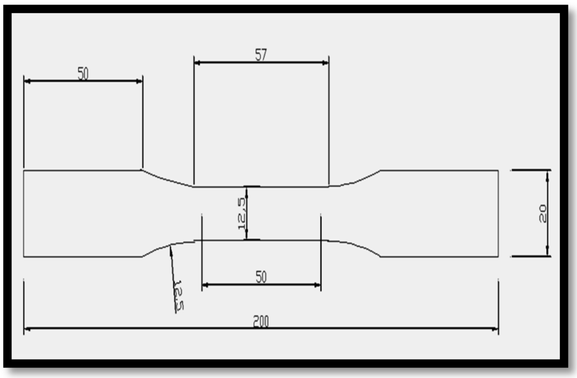



**Fig. 1. The dimensions of the tensile test specimen according to ASTM standard E8M specification.**


**Fig. 2. The tensile test machine type (WDW-200E).**

The tensile test machine directly gives the curves between load-deformation curve and engineering stress-engineering strain curve, and by using the equation (1) and (2) below can get the data for drawing the true stress- true strain curve . The relationship between true stress and true strain curve was described in figure (3).

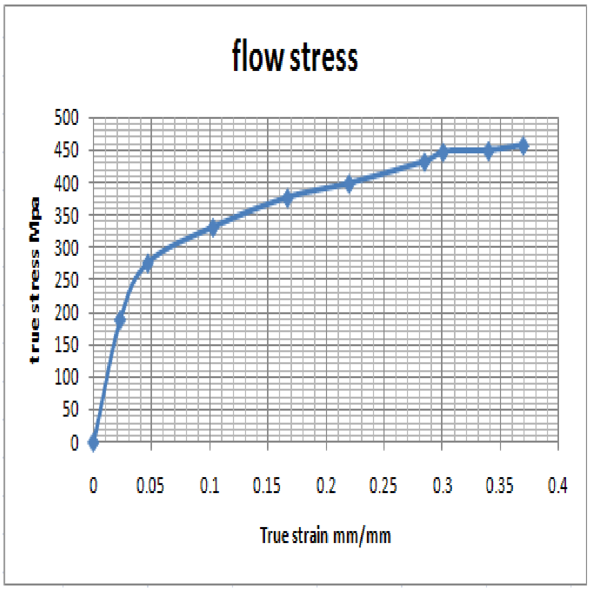



**Fig. 3. True stress and true strain curve.**

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, and determined the strength coefficient and strain hardening exponent by taking the logarithm true stress and true strain for data in the uniform plastic deformation region where the strain hardening exponent is the slope of the logarithmic curve and strength coefficient is the value of intersection this logarithmic curve with stress at true strain equal to 0.1.

The mechanical properties for low carbon steel blank as shown in table (2). Three tensile specimens were tested in order to take the average values to reduce the errors obtain from measurements.

$$\sigma = \sigma^{\circ}(1+e) \qquad \ldots(1)$$

$$\epsilon = \ln\left(\frac{l}{l^{\circ}}\right) \qquad \ldots(2)$$

Where $\sigma$ = true stress, $\sigma°$ = engineering stress, $\in$ = true strain, e = engineering strain, $\frac{l}{l°}$ = ratio between instantaneous length and original length of the gauge section of the tension test specimen.

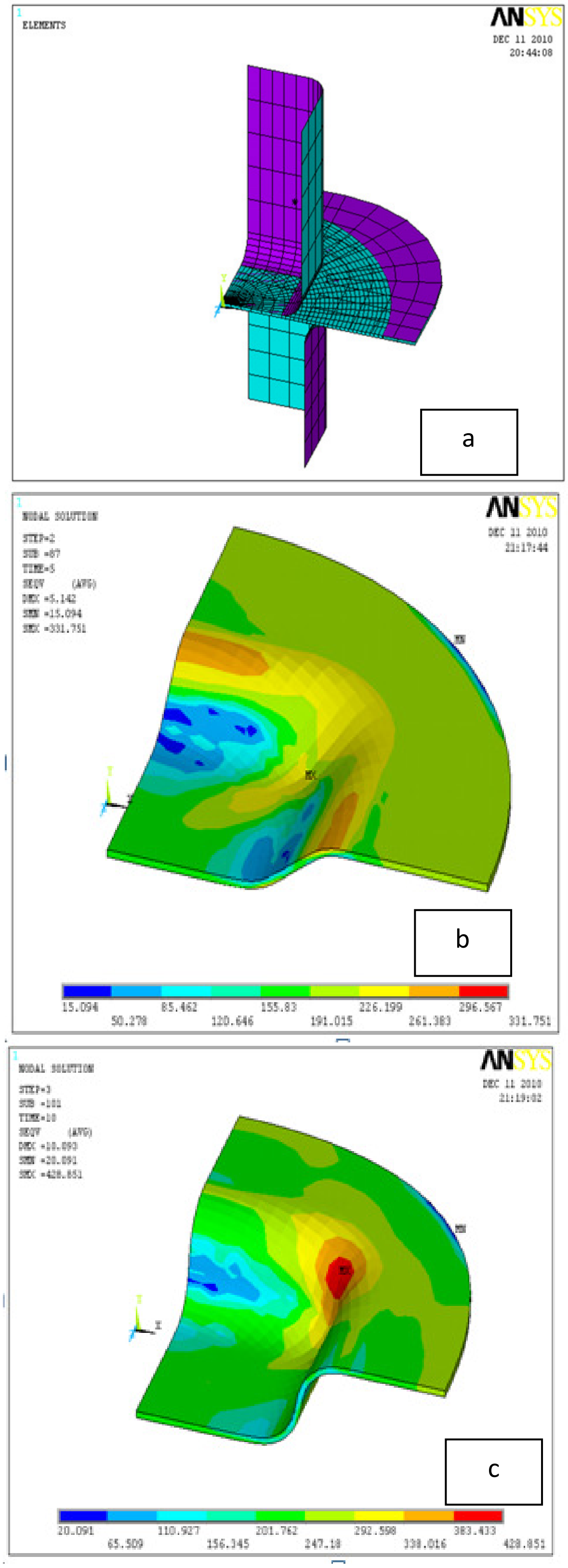
**Table 2,**
**The mechanical properties of the sheet used.**

| Property | Symbol | Value | Unit |
|---|---|---|---|
| Young modulus | E | 200 | Gpa |
| Poisson ratio | U | 0.3 (from the standard tables) | mm/mm |
| Offset yield stress | $\sigma_y$ | 203 | Mpa |
| Tangent modulus | $E_t$ | 0.5 | Gpa |
| Strain hardening exponent | n | 0.23 | --- |
| Strength coefficient | K | 548 | Mpa |

## 3. Numerical Simulation
### 3.1 Modeling

Commercial finite element analysis code ANSYS11.0 was utilized to model and analysis the deep drawing operation, in which the nonlinear issues are solved by using "implicit method "Newton-Raphson. In this method, the stroke of the punch is defined with steps throughout the forming process over the certain time range to adjust the velocity of the punch. Solutions (time steps or sub steps) are carried out in order to apply the movement on the punch gradually in each step. At each substep, a number of equilibrium iterations are carried out to get a converged solution.

Because the geometry of tool and sheet are longitudinal and lateral axial symmetry and also symmetry in the constraints and boundary conditions, the only a one fourth section of the model needed was analyzed. The FE model of the sheet material, drawing die and sequence of deformation mechanism throughout the square deep drawing process is shown in Figure (4).



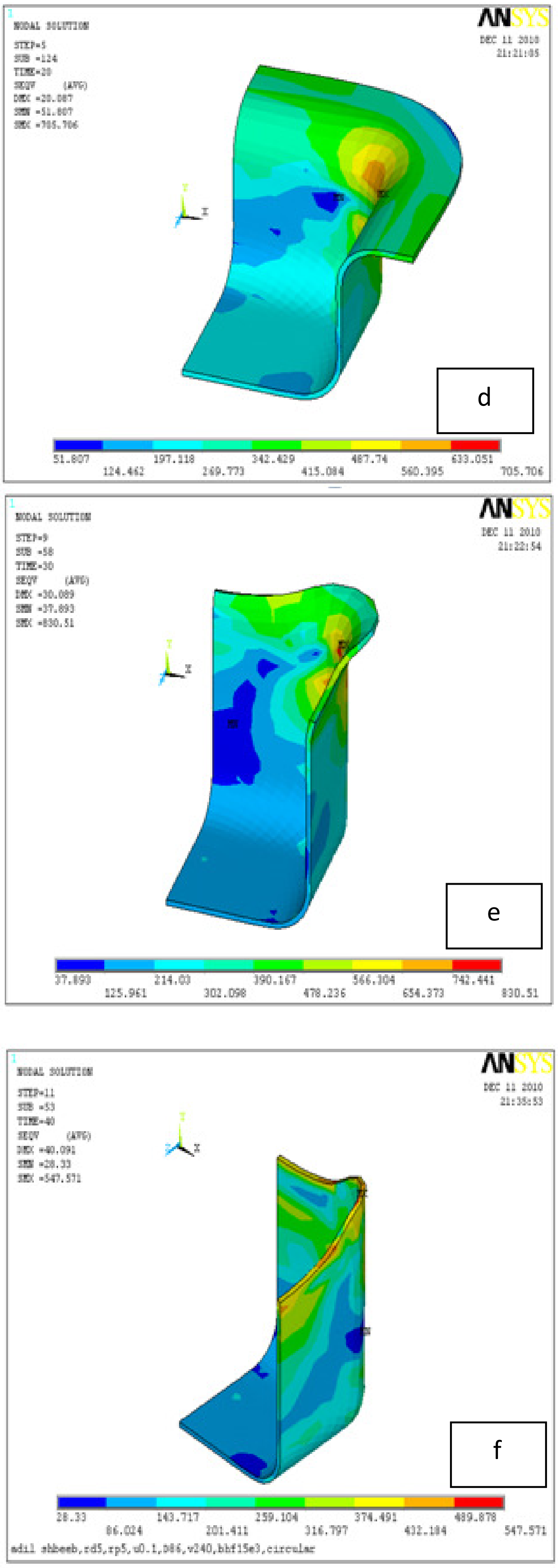



**Fig. 4. a) Finite element model of tools, b-f) sequence of the deep drawing deformation of the blank.**

Bilinear Isotropic Hardening option uses the von Mises yield criterion connected with an isotropic work hardening assumption. The principal axes of anisotropy coincide with the material (or element) coordinate system. Elasto-plastic constitutive model with isotropic strain hardening was utilized to simulate the sheet response. The elastic behavior was taken to be linear and the plastic response was modeled using Hill's 1948 yield criterion (anisotropic).

For simplifying the simulation of the deep drawing processes, the following assumptions were made:

1- The deformations in the tool are very small when compare it with the deformations in the sheet, therefore the dies were rigid assumed to reduction the solution time with acceptable accuracy.
2- The punch moved down at constant velocity (60mm/min) throughout the deep drawing process and the die was fix.
3- No change in the temperature during the forming process, no heat transfers between tool and sheet.

## 3.2 Element Type and Meshing

The 3-D 8-node structural solid element of SOLID45 was utilized for blank. The tool set (punch, die and blank holder) were 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 than the meshes in the tool in order to get the accurate results for large deformations which occurs in the blank. The most significant regions of the tool whose mesh density affects the accuracy and reliability of the results are its entry radius of the die and punch, the meshes of these regions are finer than other portions.

The pilot node was used to define the motion of the punch; the pilot node was used to gain the drawing force during the simulation. The pilot node has degrees of freedom which represent the motion of the entire rigid surface, including three translational and three rotational degrees of freedom in three dimensions, and two translational and one rotational degrees of freedom in two dimensions, and the boundary conditions (displacement), concentrated loads, rotations can be applied to the pilot node.

## 3.3. Contact

Automatic contact procedures in ANSYS11.0 were utilized to model the complex interaction between the tooling and sheet. For flexible (blank) and rigid (tool set) contact, target elements of TARGE170 were utilized, to act three dimensions target (punch, die, blank holder) surfaces which were associated with the deformable body (sheet) acted by three dimensions 8-node contact elements of CONTA174. The target and contact surfaces constitute a "contact pair", which were utilized to represent contact and sliding between the surfaces of blank and tool set. A Coulomb friction law was used to study the influence of friction at the materials and tool interface, the constant friction is assumed at the drawing sheet and tool interface.

**Table 3,**
**Main specification of the universal testing machine used in the deep drawing process.**

| aspects | specification |
|---|---|
| Model | WDW-200E |
| Capacity | 200KN |
| Range of speed | (0-500) mm/min |
| Possibility of testing | Tensile, compression, bending |
| Standard follow | ISO 6892- 1:2009 (E) |

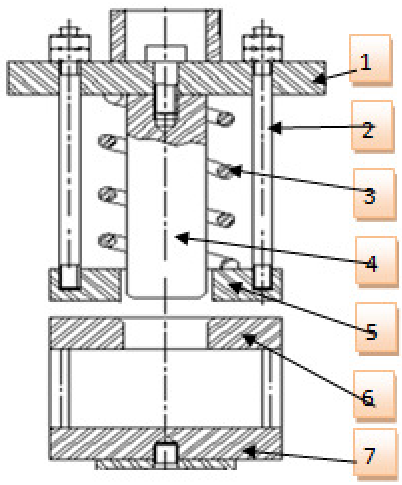
**Table 4,**
**Parameters process of square deep drawing.**

| parameter | Symbol | value | unit |
|---|---|---|---|
| length of square punch | Lp | 40 | mm |
| Punch profile radius | rp | 5 | mm |
| Punch corner radius | rc | 5 | mm |
| Length of square die | Ld | 41.55 | mm |
| Die fillet radius | rd | 5 | mm |
| Clearance | C | 0.77 | mm |

## 4. Deep Drawing Test

Experimental equipment were design and implemented to produce square cup, they are made from tool steel which were machined by wire cut machine and polished in order to obtain good surface finish, the operations of the manufacturing of equipments of deep drawing process were done in local market. These equipment were setup on the universal tensile machine, the specification of this tensile machine used to produce square cup by deep drawing process as shown in Table (3).The parameters of experimental tooling is described in Table (4). Circular blank with diameter of 80 mm and thickness of 0.7mm putted on the die surface and punch will drop toward the die in order to deform the blank. drawing speed used equal to 60 mm/min, the blank holder force was determined as the minimum value which prevent wrinkling by trial and error; it was 15KN-18KN. The deep drawing test has been done in the University of Technology-production engineering and metallurgy, strength of material laboratory, Schematic representation of rig deep drawing tooling as shown in figure (5), the tools of the deep drawing process and the universal testing machine used in this study as shown in figure (6).

In order to study the strain distribution within the cup during drawing process, a grid pattern of ( 5, 10, 15, 20, 25, 30, ….mm) radius circles was printed on undeformed blank by using mechanical grid marker (compasses), after deformation the change in the grid circles will occurs. Circular blank were drawn with different sizes to study the effect of some parameters on the length and thickness distribution in the square cup drawn.




| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Top plate | Guide | Spring | Punch | Plank holder | Die | Bottom plate |

**Fig. 5. Schematic representation of rig deep drawing tooling.**


**Fig. 6. The tools of deep drawing process.**

## 5. Results and Discussion

The result can be divided into three sections. First section covers the effect some parameters on the height of the square cup drawn by FEM, second section describes results of thickness distributions on the cup from center to the edge of cup in the rolling direction by FEM, and final section deals with comparison between experimental and numerical results to valid the numerical result.

### 5.1 Cup Heights

There are a lot of parameters effect on the square deep drawing process in order to produce product with acceptable defects, it must be study the effect of these parameters on the cup drawn. In this section effect of some parameters such as radial clearance and blank size on the height of the square cup are studied, as well as there are flat and corner sides in the square die cavity lead to different metal flow along the square die cavity, thus the process will be most difficult in this research. The numerical analysis were performed using ANSYS 11 commercial finite element code. Mild steel materials have the tool geometry with (punch and die profile radius in mm) [rp=5, rd=5], (blank diameter in mm) D=80, (blank holder force in KN) bhf=15, value of coefficient of friction μ=0.1, (punch speed in mm/min) v=60, and then the numerical results were compared with the experimental. The circular blank was placed onto the die with taking into consideration rolling direction of the sheet.

Figure (6) represents the effect of radial clearance on the cup height, four value of clearance are used with constant remaining parameters. It is noted that from the figure, the cup height increases with decreasing the radial clearance and reaches the maximum height at corner of the cup. It can be concluded that when the radial clearance (gap between punch and die) is less than or equal to the thickness of blank, accumulation of metal in some flange regions is obtained by compression stresses, this metal in this region will flow into die cavity and because it has thickness more than the gap between die and punch, it cannot flow into die cavity causing stretching deformation. Consequently, the height of the cup is increased. Sample with clearance equal to the thickness of sheet metal for example, it is noted the length of the cup in the flat side equal to 24.6 mm but it reach to the 28.8mm in the corner region due to excessive stretching occur in this region and then return deceases to the 24.9mm in the perpendicular direction on the rolling direction.

Figures (7) show the effect of the blank size on the cup height in the square deep drawing. Circular blanks with diameters (D=78, 80, 82, 84, and 86mm), and thickness of 0.7mm for all blanks used with keep constant remaining parameters. As expected the cup height increases as the blank size increases due to increase in the amount of metal sheet used to produce cup. The average length of the cup is 23mm when use blank diameter 78mm but the average length of cup reach to 31mm when use blank diameter 86mm.

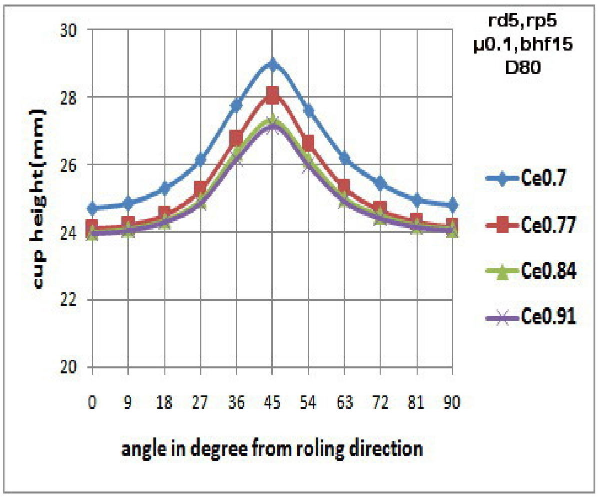



**Fig. 6. The effect of radial clearance on the cup height.**

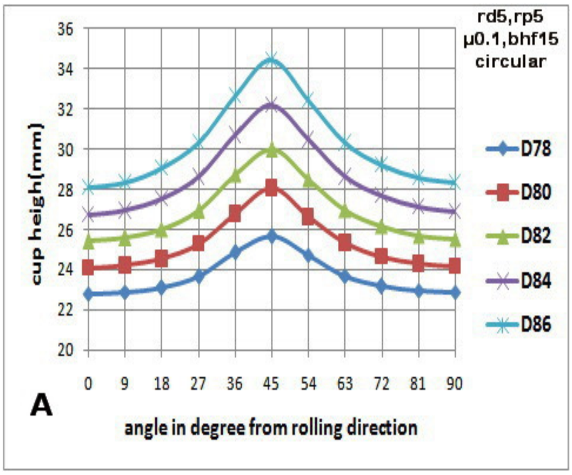



**Fig. 7. The effect of blank size on cup height.**

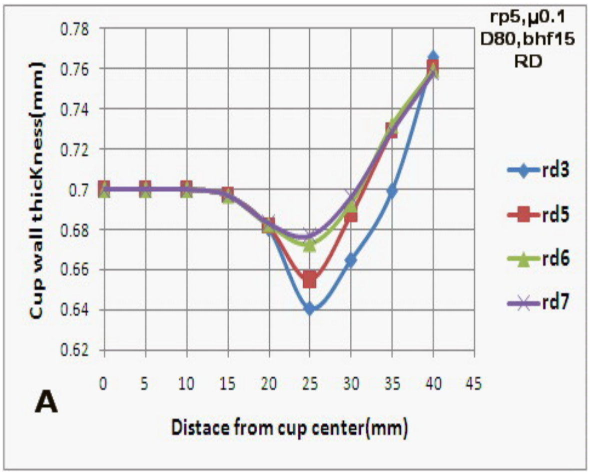



**Fig. 8. The effect of die profile radius on the cup wall thickness along rolling direction.**

### 5.2 Cup Thickness

This research shows the variations in the die profile radius have a great influence on the predicted thinning distribution on the cup drawn by deep drawing process. Four types of the die profile radius (3, 5, 6, and 7 mm), with punch profile radius (5 mm), (blank diameter in mm) D=80, (blank holder force in KN) bhf=15, (coefficient of friction) µ=0.1, (punch speed in mm/min) v=60 were chosen. Figure (8) shows the effect of die profile radius on cup wall thickness along $0^{\circ}$ with respect to rolling direction. It is obvious that the thickening increases with increasing die corner radius because the amount of stretching will reduce on the large profile radius, when in the smallest die profile radius the more thinning displayed in the cup drawing due to excessive bending and unbending occurs in small radius. In is noted more thinning occur in the punch profile region when use rd=3, the percentage of thinning reached to 5% while the maximum thickening occur in the cup edge when use rd=7, the percentage of thickening reached to 8%. These percentages are acceptable.

Figure (9) presentations the influence of blank size on the cup wall thickness distribution in the direction of the rolling. It is evident that the thickness remains constant under the punch face (cup bottom) for all blank sizes ( no deformation occurs in this region), and decreases with increasing the blank size at the punch corner region, the more thinning occurs because of stretching in the punch profile region and then begins to rise until reaching maximum value at the cup rim with increasing the blank size. It is obvious from the figure the thickness of the cup in the base region for all blank sizes used is equal to the initial thickness of the blank 0.7mm, while in the punch profile region the thickness decreased to the 0.65mm for all sizes ob blank used and then increased to reach maximum value of thickness at the rim of the cup 0.77mm.

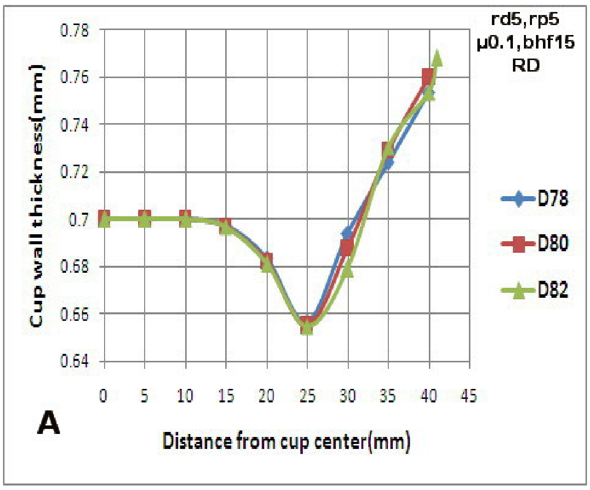



**Fig. 9. The effect of blank size on the cup wall thickness along rolling direction.**

### 5.3. Comparison Between Numerical and Experimental Result

The FEA was performed to investigate the effects of the process parameters on the square cup drawing. In order to validate the finite element simulation results, the actual square cup drawings for mild steel materials have tool geometry [rp=5, rd=5] (punch and die profile radius mm), in different blank sizes were conducted and the experimental results were compared with the FE simulation results. In order to measure the cup wall thickness, the drawn cup was divided into two parts by using a diamond saw as shown in Figure (10). Heights of cups can be measured by using simple devices such as vernier caliper or ruler as shown in figure (11).

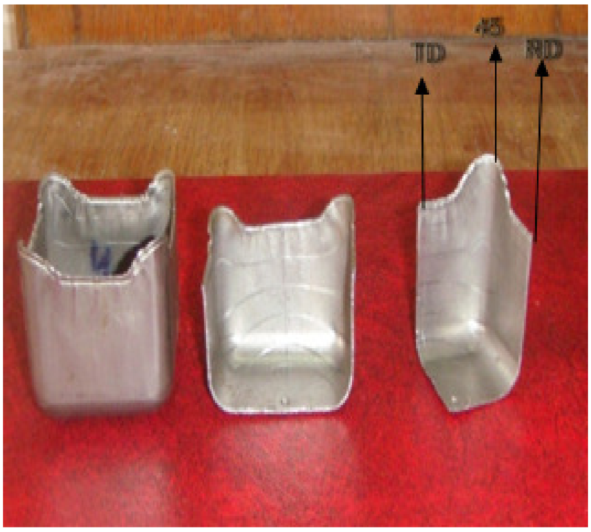



**Fig. 10. The sample of divided cup.**

**Fig. 11. The sample of cup.**

Figure (12) represents the cup height for different blank sizes theoretically and experimentally, it is noted from the figure there are low difference between lengths measured experimentally and numerically reached to 7% and this percentage of difference is acceptable value. Figure (13) represents the thickness distribution along $0^{\circ}$ with respect to rolling direction. It is evident from the figures that the predicted values and calculated values have the same trends, but they are different in values, the value of difference between them reached to 3%. This give indicator the numerical method used a powerful tool to simulate the sheet metal process to reduce the cost, time and effort.

The difference between the FE and experimental results can be accounted for by possible errors in both analyses and experimental. In analyses the possible errors are due to the lack in the exact information about material properties and friction condition, in experimental the possible errors are due to the blank thickness variation, also due to the misalignment of the blank over the ring die. The errors in measurement of the forming loads result from fluid pressure losses in the hydraulic systems.

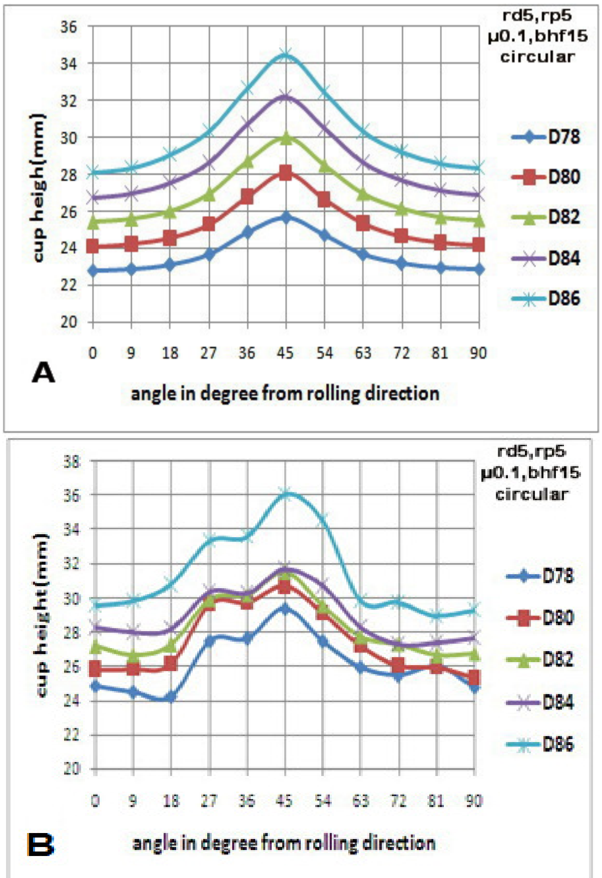



**Fig. 12. The heights of the cup versus angle in degree from RD, A) FEM and B)experimentally.**

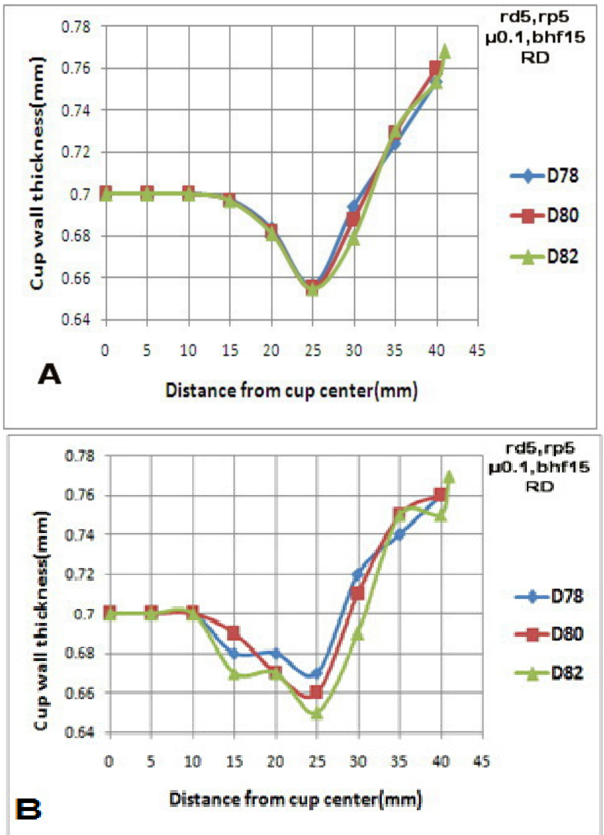



**Fig. 13. The distributions of the cup wall thickness experimentally and FEM along rolling direction, A)FEM, B)experimental.**

## 6. Conclusion

The following are specific conclusions of the current research.

1. The deformation states vary along the square die cavity, the flow of metal at the corner of the cup is less uniform and more complex than that in the cup side walls. Therefore square cup forming process experience very complicate.
2. The cup height is very affect by radial clearance between punch and die, decreasing in radial clearance will increasing the height of the cup.
3. Increasing in blank size will increasing in the height of the cup.
4. Most thinning appear in the corner cup due to excessive stretching occur in this region.
5. most thickening appear in the edge cup due to compressive stresses in this region.
6. Increasing in die profile radius and blank size will reduce the thinning in the cup square cup drawn.
7. possible errors in both numerical analyses and experimental can be explained the difference between the FE and experimental results.
8. The earing in square cup depending on the planar anisotropy of sheet and difference in flow through the die cavity.
9. Increased in the die profile radius increased to occur the wrinkling while decreased in the die profile radius increased the thinning in the cup.

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# بحث عملي و المحاكاة بالعناصر المحدد لإنتاج وعاء مربع بواسطة عملية السحب العميق

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**خلاصة**

عملية السحب العميق المستخدمة لإنتاج أوعية المربعة الشكل هو عملية جدا معقدة وتسيطر عليه الكثير من المتغيرات وبالتالي ترافقها الكثير من العيوب مثل التاذن والتجاعيد والكسر في الأواني الناتجة. دراسة تأثير بعض من هذه المتغيرات العملية لتحديد قيم هذه المتغيرات التي تعطي أفضل النتائج , حيث تم الاعتماد على توزيع السمك والأعماق لوعاء المنتج لغرض دراسة تأثير هذا المتغيرات عدديا, إضافة إلى الإثبات التجريبي الظروف التي تعطي أفضل التنبؤات العددية فقط لغرض تقليل الجهود والوقت والكلفة لإنتاج وعاء مربع خالي من العيوب تجريبيا هو هدف هذا البحث. دراسة عددية استخدمت لدراسة تأثير بعض المتغيرات من نص قطر تقوس القالب والخلوص بين القالب والخرامة و قطر الغفل على ارتفاع الوعاء و توزيع السمك على طول الوعاء المسحوب, برنامج Ansys المعتمد على طريقة العناصر المحددة استخدم لإجراء المحاكاة لعملية السحب العميق المربع. تجارب عملية استخدمت لمقارنة واثبات النتائج التي تم الحصول عليها من المحاكاة العددية. وعاء مربع خالي من العيوب تم إنتاجه مع توزيع مقبول السمك على طول الوعاء,وقد تم استنتاج ان الترقق غالبا ما يظهر عند زاوية الوعاء نتيجة للتشوهات القاسية في هذا المنطقة و وقد وجد أيضا توافق بين نتائج التنبؤات العددية لتوزيع السمك والارتفاعات والتجارب العملية.