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Wrinkling Defect in Sheet Metal Process using Finite Element Analysis

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Abstract: Deep drawing is popular sheet metal forming process. Deep drawing process is the most common metal forming process frequently used in automobile industry, the packaging industry and the house hold appliances industry to manufacture products with more complicated shapes and curvatures. Any metal that can be processed into sheet form by a rolling process should be sufficiently ductile to be capable of deep drawing. Both hot and cold rolled sheet products are used in deep drawing processes.

The basic theories governing the deep drawing are based on application of theory of plasticity to the deep drawing process. It is very difficult to apply these theories and arrive at a general solution which can handle any arbitrary geometry. The idea of finite element analysis is to find the solution of complicated problem in relatively easy way. The finite element analysis has been a powerful tool for the numerical solution of a wide range of engineering problem.

There are some possible failures likely occur during the process, like wrinkling, necking, scratching and surface defects. As thinner materials tend to be used in automotive industry, wrinkling has become the most important problem among the other defects. The study also aims to investigate wrinkling and its prevention. For this purpose, the commercial finite element analysis code Explicit Dynamic FEM model will be used.

Keywords: Deep Drawing, Finite Element Analysis, Optimum Sheet Thickness, ANSYS, Limiting Drawing Ratio (LDR)

I. INTRODUCTION

Deep drawing process is the most common metal forming process frequently used in automobile industry, the packaging industry and the house hold appliances industry to manufacture products with more complicated shapes and curvatures. In this process shown in Fig. 1 a blank usually controlled by a blank holder, is forced into a die by means of a punch to form a hollow component in which the thickness is substantially the same as that of the original material.

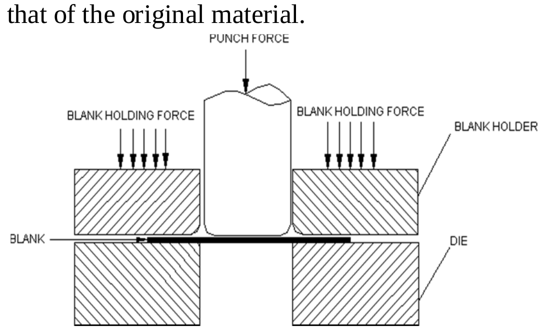

Fig. 1 Conventional deep drawing process

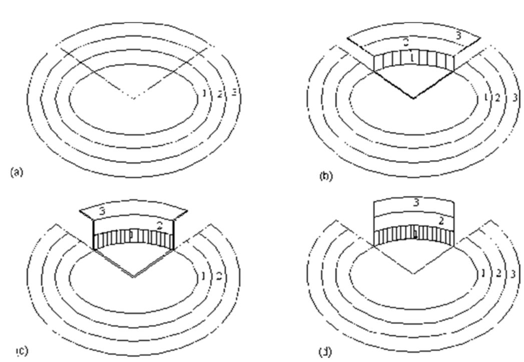

Fig. 2 Stages of deep drawing process

In a deep drawing process, flat sheet of metal, called blank, is placed over a die, and with the help of a punch, blank is pressed into the die cavity. Blank holder applies on the blank in the flange region during the deep drawing process.

The various stages of metal flow in drawing a cup from a flat blank are shown in Fig. 2. During the first stage, the punch contacts the blank and the metal section 1 is bent and wrapped around the punch nose. Simultaneously in sequence, the outer surfaces of the blank 2 and 3 moves radially towards the center of the blank until the rest of the blank has bent around the punch nose and a straight wall cup is formed.

There are two important regions in the drawn component, the flange where most of the deformation occurs and the wall must support a sufficient force to cause the deformation in the flange. If the blank diameter is too large, the force that must be transmitted by the wall will be excessive, thereby causing it to yield and fail.

The draw ability in deep drawing may be expressed as a limiting drawing ratio (LDR) which is the largest ratio of blank to cup diameters that may be drawn successfully. The draw ability of the process is governed by a number of material and process variables and is briefed in the section below.

The main aim of this study is to investigate the deep drawing process systematically. Deep drawing is one of the most important sheet metal forming process. The process includes many aspects that affect the final product. In order to understand Deep Drawing one must investigate all these variables and their effect on the process. Without extensive knowledge of all these variables, achieving a defect free deep drawn product is hardly possible.

There are some possible failures likely occur during the process, like wrinkling, necking, scratching and surface defects. As thinner materials tend to be used in automotive industry, wrinkling has become the most important problem among the other defects. The study also aims to investigate wrinkling and its prevention. For this purpose, the commercial finite element analysis code Explicit Dynamic FEM model will be used. The program is a nonlinear transient dynamic finite element method with both explicit and implicit solvers. ANSYS is widely used in applications of sheet metal forming (as metal stamping, hydro forming, forging, deep drawing, multi-scale processes) predicting the level of stresses and deformations in the metallic material and determine if the metal will fail. The elasto-plastic material model is utilized in the program in order to achieve accurate deformation behaviour of the material.

II. BACKGROUND

A. *Material Variables in Deep Drawing Process*

Any metal that can be processed into sheet form by a rolling process should be sufficiently ductile to be capable of deep drawing. Both hot and cold rolled sheet products are used in deep drawing processes.

For optimal draw ability in a wide range of applications, the material should

- Distribute the strain uniformly
- Reach high strain levels without necking or fracturing
- Withstand in-plane compressive stresses without wrinkling.

1) *Material Variables that Influences the Draw Ability:* Plastic Strain Ratio (r) - The plastic strain ratio also known as the anisotropic factor is defined as the ratio of the true width strain to the true thickness strain in the uniform elongation region in a tensile test. It is a measure of the ability of a material to resist thinning. In drawing material in the flange is stretched in the radial direction and compressed in the circumferential direction. A high plastic strain ratio indicates a material with good drawing properties. The plastic strain ratio frequently changes with the direction in the sheet. In a cylindrical cup drawing operation, this variation leads to cups with a wall that varies in height; this phenomenon is known as earing. It is therefore common to measure the average value, or average normal anisotropy and the planar anisotropy. Strain-Hardening Co-efficient (n) - The ability to distribute strain evenly depends on the strain hardening co-efficient (n). The strain hardening coefficient is determined by the dependence of the flow (yield) stress on the level of strain. In materials with high n value, the flow stress increases rapidly with strain. This tends to distribute further strain to regions of lower strain. Strain Rate Sensitivity (m) - Positive strain rate sensitivity indicates that the flow stress increases with the rate of deformation. This has two consequences. First, higher stresses are required to form parts at higher rates. Second at a given forming rate, the material resists further deformation in regions that are being strained more rapidly than adjacent regions by increasing the flow stresses in these regions. This helps to distribute the strain more uniformly. In a drawing operation, metal in the flange must be drawn in without causing fracture in the wall. In this case, high and values strengthen the wall, which is beneficial, but also strengthens the flange and make it harder to draw in, which is detrimental.

B. Process Variables in Deep Drawing

The process variables that influence the deep drawing process include punch and die radii, punch to die clearance, press speed, lubrication and type of restraint to material flow.

1) *Punch and Die Corner Radii:* At the start of drawing, when the punch struck the blank, it is wrapped around the punch and die radii, the stress and strain that develop in the work piece are similar to those developed in bending, with an added stretching component. The bends once formed have the radii of the punch and shell wall. The bend over the die radius, however is continuously displaced with reference to both the punch radius and the blank, and it also undergoes a gradual thickening as the cup is drawn. During drawing, the cup bottom is subjected to tensile stress in all directions, while the lower portion of the wall, particularly the corner portion connecting the bottom of the wall, and are primarily subjected to the longitudinal tension. The stress in the material drawn into the die consists of combined tensile and compressive stresses. The cup bottom tears from the side wall if a reduction is made that require a force greater than the strength of the cup bottom. Drawing is encouraged by increasing the punch and die radii. For the given condition, the punch force needed to move the metal into the die decreases as the die radius increases. If the punch corner radius is increased from one to five times the metal thickness, the load in the side wall is decreased so that the draw ratio is increased and therefore the cup can be drawn deeper before the side wall fails. However, the punch corner radius cannot be increased beyond ten times the metal thickness
2) *Punch to Die Clearance:* The selection of punch to die clearance depends on the requirements of the drawn part and on the work metal. As there is a decrease and then a gradual increase in the thickness of the metal as it is drawn over the die radius, clearance per side of 7%to 15% greater than stock thickness helps to prevent burnishing of the side wall and tearing out of cup bottom. The drawing force is reduced when the clearance is15% to 20% greater than that of the stock thickness and the cupped portions are not in contact with the punch and die. The force increases as the clearance decreases, the secondary peak occurs in the punch force curve when the metal thickness is slightly greater than the punch-die clearance where ironing starts.
3) *Press Speed:* Press speed depends mainly on the required rate of production. Under the cupping of drawing-quality work material with adequate lubrication and with controlled blank holding pressure using the presses maintained at a high level of accuracy, press speeds as high as 23m/min are used for deep drawing low carbon steel cups. If the above conditions are less than ideal the drawing speed is usually reduced to 7.6m/min. Press speed is of greater significance in drawing stainless steels and heat resistant alloys than in drawing softer, more ductile materials. Excessive press speed causes cracking and excessive thinning in drawing these stronger and less ductile materials.
4) *Lubrication:* The presence of an effective lubrication between the contact surfaces *i.e.* blank-die interface, blank-blank holder interface reduces friction thereby increasing the drawability, product quality and decreasing the tool wear. Further, when two metals are in sliding contact under pressure, as with the dies and the work metal in the drawing, pressure welding of the tools and the work metal is likely. This increases the drawing force and makes metal unevenly distributed causing tear in the work piece. Introducing a fluid film between the contact surfaces greatly reduces the chances of pressure welding and facilitates a free flow of metal between the surfaces. Selection of lubricant is primarily based on its ability to prevent tearing, wrinkling, galling and easy removal of lubricant after the process.
5) *Blank Holding Force:* Even in the simplest drawing operation, i.e. without any external restraint the thickness of the work material and the die corner radius offers some restraint to the metal flow. However, during drawing an added restraint is needed to control the metal flow. This additional restraint is usually obtained by applying blank holder force. The purpose of this force is to suppress wrinkling and control the flow of metal into the die. Compressive forces on the metal in the flange portion of the cup cause the work metal to wrinkle. If this wrinkled metal is pulled into the die during the drawing operation, it will increase the strain in the area of the punch nose and the work metal would tear soon after the beginning of the draw. Blank holding force is used to prevent this wrinkle and subsequent failure. The amount of blank holder force required is usually about one-third that required for drawing. Thickness of the work metal must also be considered when simple shapes are being drawn. The thinner the work metal, the more blank holding force is required. Blank holding force should be just sufficient to prevent wrinkling. Too high a blank holding force increases frictional resistance which hinders the material flow. This increases the load transferred by the cup wall there by inducing failure. Hence optimum blank holding force must be applied for the given material thickness and given draw ratio. There are no absolute rules for calculating the blank holding force, most holding force values are found empirically and by trial and error method.

C. *Defects in the Deep Drawn Parts*

1) *Bottom Fracture:* This is the most common failure often encountered during deep drawing process. Bottom fracture occurs due to excessive thinning near the punch corner radius. This effect can be minimized by increasing the punch corner radius and decreasing the punch load required for the drawing operation.
2) *Wrinkling:* This is a result of the high compressive circumferential stresses. When the blank diameter is high, the punch load rises to high value which may exceed the critical buckling load of the column. Since column stability decreases with an increasing slenderness ratio, the critical buckling load can be achieved at lower loads for thin sheet. To prevent this defect, it is necessary to use sufficient hold down force.
3) *Orange Peeling:* Orange peel effect occurs in sheet metal of relatively large grain size. The individual grains tend to deform independently of each other and leads to the surface roughness during drawing operation. This can be corrected by using finer size sheet metal. In this case, grains deform more nearly as a whole and the individual grains are difficult to distinguish with the eye.
4) *Earing:* It is the formation of a wavy edge on the top of the drawn cup. The wavy edge is usually trimmed to produce a uniform top. This formation is due to directional property of the sheet metal. Usually two, four or six ears will be formed, depending on the preferred orientation in the plane of the sheet.
5) *Spring Back:* Spring back is the geometric difference between the drawn component in its fully loaded condition, i.e., conforming to the tooling geometry, and when the component is in its unloaded, free state. The uneven distribution of stress through the sheet thickness direction and across the stamping in the loaded condition relaxes during unloading, thus producing the spring back. Factors that affect the amount of spring back include variations in both process and material variables, such as friction condition, tooling geometry, material properties, sheet thickness and die temperature.

III. SIMULATION AND ANALYSIS

A. *Design of Deep Drawing Process using Finite Element Method*

The main aim of this study is to investigate the deep drawing process systematically. Deep drawing is one of the most important sheet metal forming process. The process includes many aspects that affect the final product. In order to understand Deep Drawing one must investigate all these variables and their effect on the process. Without extensive knowledge of all these variables, achieving a defect free deep drawn product is hardly possible.

A time integration method used in Explicit Dynamics analysis system. It is so named because the method calculates the response at the current time using explicit information once the body is meshed properly, the next step is to define initial conditions or boundary conditions. At least one initial condition is required to complete the setup.

After defining the initial conditions (initial velocity, Angular velocity), the analysis setting has to be maintained as per the problem requirement. In the analysis setting, time steps have to be defined explicitly. The solution time depends on the time steps.

Time steps include;

1) *Initial time step*
2) *Minimum time step*
3) *Maximum time step*
4) *Time step safety factor*

In case of drop test the standard earth gravity is also taken into account

ANSYS Explicit Dynamics is included in the ANSYS Mechanical Enterprise-level license and is not available as a product by itself It utilises the Autodyn solver within the standard ANSYS Mechanical interface to analyse transient structural events. It is used for simulating fracture, cutting, failure, buckling, impact, drop as well as highly nonlinear quasi-static simulations that the implicit APDL-based solvers would struggle to converge. Users with an Autodyn level license have access to the Explicit Dynamics interface in Mechanical as a method to pre-process their structural geometry

a) Study of deep drawing system for stress reduction in sheet.
b) Prepare the different 2D CAD model of tool, die and sheet.
c) Perform the finite element analysis for all above models with same operating conditions.
d) Compare the results and present the best thickness for the sheet in different models.
e) Avoid the deep drawing defects

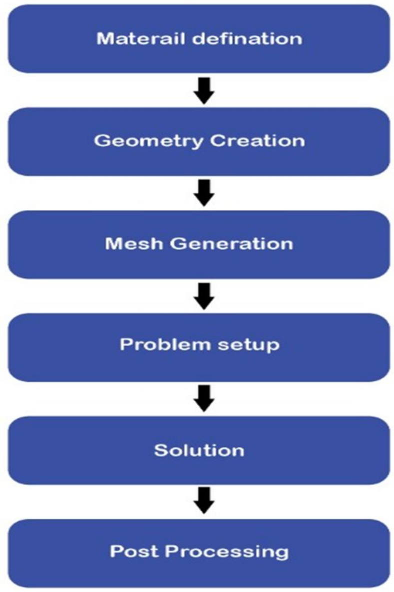

Fig. 3 Flowchart for the analysis of the forming process

B. Material Properties

Carbon steel plate material SAE-AISI 1008 for sheet metal blank stamping is used. The mechanical properties are summarized in Table 1, where σ_y is the yield stress, σ_u is the ultimate tensile strength and K the strength coefficient.

From an analysis of the forces in equilibrium during the formation of a deep-drawn cup, the use of an approximate equation for the total punch force as a function of the diameter of the blank at any stage in the process. An approximate equation of the maximum drawing force F (in N) or punch load has been developed

$$F = \pi D_p t \sigma_u (D_b/D_p - C)$$

C is a constant between 0.6 to 0.7. The drawing force F varies throughout the downward movement of the punch, usually reaching its maximum value at about one-third the length of the punch stroke. A factor of safety should be taken. In the study case the draw force was equal to 80.8kN (=67.4kN x 1.2).

A holding force was applied directly on the blank holder, usually represents 33% of the drawing force (F_h=33%x80.8= 26kN). According the dimensions and the material, the calculated holding force was equal to 26kN. The holding force F_h (in N) is an important factor in drawing operation.

In the case of low blank holder force there is wrinkle usually in the flange of the drawn part, when increasing wrinkle is reducing. But large value of the blank holder force will cause fracture in the material. The press force capacity can be calculated by using the adding between the draw force using a safety factor and the blank holding force.

In the study case the value is equal 108kN (or 11 ton). Other considerations should be considered in deep drawing to control the sheet metal fracture, as excessive friction between blank and punch, insufficient clearance between punch and die and insufficient punch or die corner radius.

Table I:
Material Properties for Steel Alloy (AISI 1008)

Properties	Sheet metal blank
Density (kg/m3)	7850
Young’s Modulus (GPa)	210
Poisson’s Ratio	0.3
Yield Stress σ_y (MPa)	180 (180 to 310)
Ultimate Stress σ_u (MPa)	330 (330 to 370)
Bulk Modulus K (MPa)	660

C. Geometry Creation

Drawing is a sheet metal forming operation used to make cup shaped, box shaped, or other parts. Fig. 4 represents the basic drawing operation with the main dimensions and parameters.

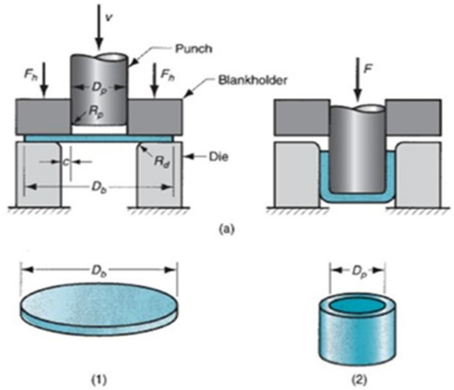

Fig. 4 Schematics diagram Deep drawing process & various parameters of deep drawing (Not to scale)

Table II:
Details of Various Parameters of Models

Parameters	Dimensions in mm
Punch diameter, Dp	50
Punch nose radius, Rp = 4 t (as a start)	4
Punch thickness	4
Cup height of the first draw	25
Cup total height, h	29
Clearance between punch radius and die radius, C ± ≥ 1,1 t	1.5
Sheet metal blank diameter, Db	100
Sheet metal blank thickness, t	1, 1.2, 1.35, 1.5
Die profile radius	26.5
Die shoulder radius, Rd (4 t ≤ Rd ≤ 8 t)	8
Die cavity height	29
Blank holder radius	36.5
Blank holder thickness	2

D. Meshing

In the numerical model, the Ramburgh-Osgood law is applied through the ANSYS material library. The punch, binder and die were modelled as a rigid body in order to reduce the computing time and resources.

1) *Meshing of Model 1 (Blank Sheet Thickness = 1 mm)*: Meshing of domain is done and total number of nodes and elements were found to be 9754 and 20040 respectively.

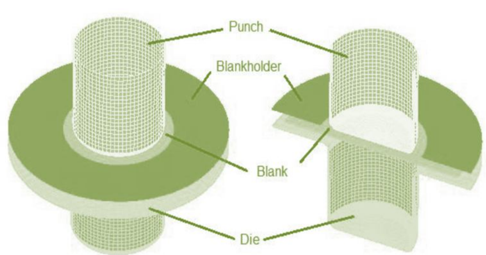

Fig. 5 Different meshing of die assembly

2) *Meshing o Model 2 (Blank Sheet Thickness = 1.2 mm):* Meshing of domain is done and total number of nodes and elements were found to be 9755 and 20048 respectively.
3) *Meshing of Model 3 (Blank Sheet Thickness = 1.35 mm):* Meshing of domain is done and total number of nodes and elements were found to be 9727 and 19900 respectively.
4) *Meshing of Model 4 (Blank Sheet Thickness = 1.5 mm):* Meshing of domain is done and total number of nodes and elements were found to be 9742 and 20006 respectively.

To define the material model of the metal should be taken in consideration the strain-rate with dependency of the isotropic material plastic curve. The rate sensitive power law plasticity model is a strain rate dependent plasticity model typically used for superplastic forming analysis. The sheet metal blank is made of a steel alloy material that is assumed to satisfy the stress-strain curve Ramburgh-Osgood as constitutive relationship:

$$\sigma = K\, \varepsilon^{m}\, \grave{\varepsilon}^{n} \quad (3)$$

where σ is the stress; K is the reference stress value or strength coefficient; m the hardening coefficient equal to 0.012; n is thestrain rate sensitivity coefficient considered 0.19; ε the true strain and $\grave{\varepsilon}$ the initial strain rate considered equal to 30. All these parameters permit to identify the correspondent plastic flow curve.
In ANSYS contact interaction between all components in die assembly was formulated using the CONTACT AUTOMATIC SURFACE TO SURFACE, generally recommended for this type of process. Thus, by choosing automatic surface to surface contact, the program will automatically adjust for the changes which occur during this simulation.
Contact assuming Coulomb friction between the blank, punch, die surface and the blank holder was modelled. In ANSYS its behavior can be controlled with the parameters on the CONTACT_... card: static and dynamic friction coefficients, exponential decay coefficient and coefficient for viscous friction. It is required the definition of the frictional coefficients.

IV. RESULTS AND DISCUSSION

In the present work finite element analysis have been performed for deep drawing process using ANSYS to study the effects of better stress reduction in sheet metal. For that four cases of deep drawing setup is created using the design modular software with dimension presented in methodology. All the four cases are enlisted below:

A. *Model 1 with 1 mm blank sheet thickness*
B. *Model 2 with 1.2 mm blank sheet thickness*
C. *Model3 with 1.35 mm blank sheet thickness*
D. *Model 4 with 1.5 mm blank sheet thickness*

The details are given for Model 2

1) *Observations for Model 2:* After performing finite element analysis using dynamic explicit formulation, total deformation, equivalent stress & equivalent strain distribution in sheet with 1.2 mm thickness has been analyzed. It has been observed that max deformation in sheet/ blank is 20.285 (mm), equivalent stress in blank is 520.34 (MPa) and equivalent plastic strain in blank is 0.7986 (mm/mm) directional deformation, equivalent stress & equivalent plastic strain contour diagram is presented in Fig.s.

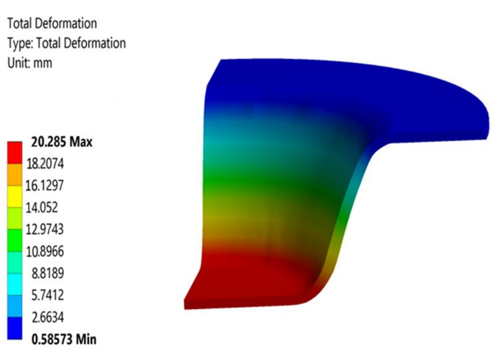

Fig. 6: Total Deformation contour model

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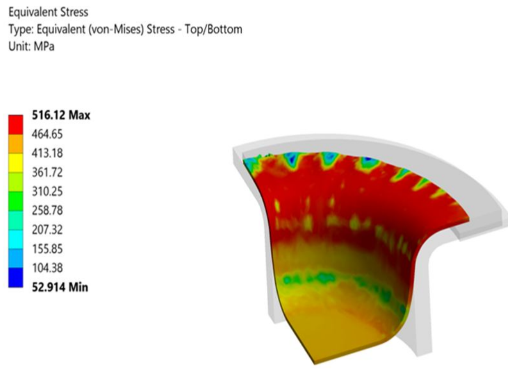

Fig. 7: Equivalent Stress contour of model 2

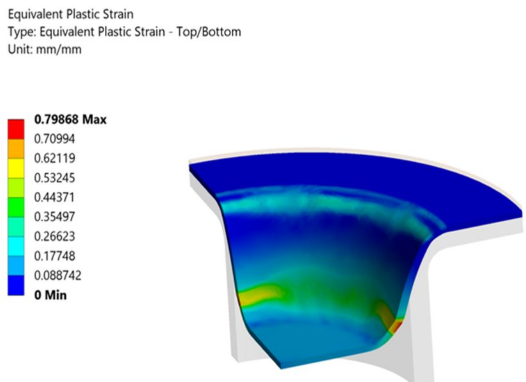

Fig. 8: Equivalent Plastic strain contour model 2

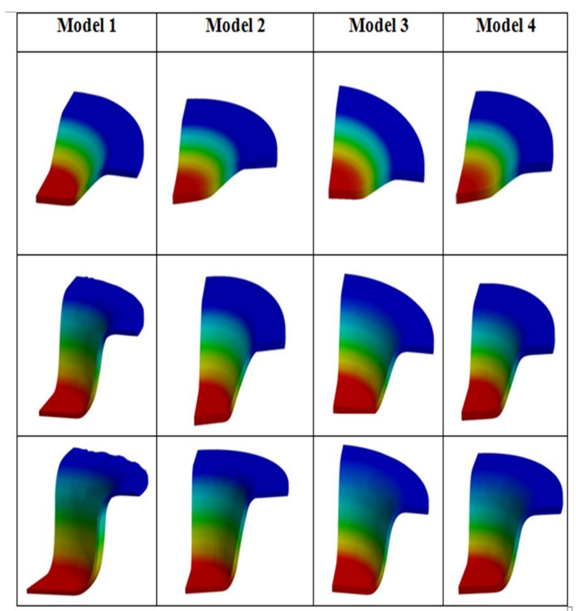

Fig. 9: Different deformed shapes of the blank

1) Comparison of the Deformed Shapes

Considering the results at different time instants and considering all die assembly, it is observed that the model 1 represents the total depth circular cup drawing with wrinkle defect. With model 2 only 20.285mm in depth is obtained with negligible defect. 3D Axisymmetric Model 3 permits to calculate the cup depth of 17.762 mm, however the deformed thickness sheet metal decrease significantly.

V. CONCLUSIONS

This study shows the finite element procedures for the sheet metal forming process and presents the performance of the use of axisymmetric conditions in the balance of the computational requirements against the desired accuracy of the results.

With numerical simulations it is possible to observe the quality of the piece according the thickness distribution and some defects like wrinkling, crushing and tearing material. So as per our FEA results observation we conclude to following points:

1) After many simulation runs, the optimal blank metal can be decided, and the deformed shape also can be predicted.
2) It is observed that at model 3 & 4 the part manufactured is wrinkle free but wrinkling shown in model 1 & 2.
3) Determining the expected tearing and wrinkling zones before the experimental part and improve the product quality.
4) It's important to say that the effect of blank holder force is remarkable due to the direct effect on the product quality.
5) Increase the fillets radius in both of punch and die will help to decrease the crack and wrinkling in the product.

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