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Finite Element Simulation for Determining the Optimum Blank Shape for Deep Drawing Process

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Abstract

Deep drawing is one of widely used sheet metal working process in industries to produce cup shaped components at a very high rate. The present study aims to determine the optimum shape of blank for deep drawing of cylindrical cup without ears. Earing is one of the major defects observed during deep drawing process due to anisotropic nature of sheet metal. Earing is defined as formation of waviness on uppermost portion of deep drawn cup. Earing defect occurs due to non-uniform material properties within plane of sheet (i.e. planar anisotropy). Knowledge about ear formation in deep drawing process allows a prior modification of process which can result in defect free final product with financial saving and time. In the present study efforts have been made to study the earing problem in deep drawing of cylindrical cups by finite element modeling software HYPERWORK-6.12. The blank material as EN10130Fe01 mild steel sheet of 1mm thickness has been considered as it has wide application a fabricating critical automobile parts. Mechanical parameters of mild steel are incorporated in finite element simulation of deep drawing process. Significant earing was observed at rolling and transverse direction on deformed cup form circular blank. Modification of initial blank is done to find the optimum blank to reduce the earing defect. Optimal blank shows significant reduction of % earing height, reduction in drawing load & improvement in maximum thickness variations.

Keywords: Deep drawing, Earing, Anisotropy, R-values.

I. Introduction

Sheet metal forming is one of the most widely used manufacturing processes for the fabrication of a wide range of products in many industries. The reason behind sheet metal industry gaining a lot of attention in modern technology is due to the ease with which metal may be formed into useful shapes by plastic deformation processes in which the mass and volume of metal are conserved and metal is displaced from one location to another. Deep drawing is a well establish process in industries to produce cup shaped components at very high rate. In deep drawing a metal sheet is used to form cylindrical components by a processed into die opening to draw the metal into desired shape without folding corners [1]. In deep drawing the metal is subjected to biaxial tensile stress due to action of punch and thinned down metal in outermost section of the block is subjected to compressive strain in circumferential direction and tensile strain in radial direction. As results of these two principal strains there is a continual increase in the thickness as the metal moves inwards [2]. This process usually has several interrelated variables include blank (geometry and material), the tools (geometry and material), the conditions at the tool–material interface, mechanics of plastic deformation, the characteristics of production and the plant environment in which process is being conducted [2]. Among these variables the material properties of the blank and initial blank shape have a significant effect not only on the quality of formed part but also the determination of process parameters [3].

Material properties play an important role in metal forming process. The formability is dependent upon the material properties such as strain hardening exponent (n), strain rate sensitivity parameter (m), anisotropy parameter (R). Anisotropy behavior of materials has most significant effect on deep drawability of sheet. The workpiece used in deep drawing process is anisotropic in nature due to the result of a large deformation during initial processing operations such a rolling, extrusion, etc. This anisotropy prevalent in the pre-processed sheet segment influences subsequent deformation, such as deep-drawing. Earing is major defect due observed due to anisotropic nature of sheet material i.e. the material properties are different in different directions. Four ears are formed usually at the top of the wall of the cup when a cylindrical cup is drawn from a circular blank. Earing occurs in the drawn cup due to anisotropy in sheet metal which comes due to preferred crystallographic texture developed during rolling process. Anisotropy is measured in terms of Lankford anisotropy parameters (R) which is defined as:

$$R = \frac{\varepsilon_w}{\varepsilon_t} = -\left(\frac{\varepsilon_w}{\varepsilon_w + \varepsilon_l}\right) = \ln\left(\frac{\left(\frac{w_f}{w_0}\right)}{\left(\frac{l_o w_o}{l_f w_f}\right)}\right) \qquad (1)$$

Where ε_w is true width strain, ε_t is true thickness strain and ε_t is true longitudinal strain and w_0, l_0 are Initial width and length and w_f, l_f are final width and length of the specimen. Plastic anisotropy can be classified into two types: normal and planar anisotropy. In normal anisotropy the properties differ in the thickness direction; in planar anisotropy however the properties vary with the orientation in the plane of the sheet. The drawability of sheets increases with normal anisotropy and planar anisotropy leads to formation of ears in the cup [4]. The average of the *R*-values obtained for different directions in the plane of the sheet metal represents the so-called coefficient of normal anisotropy R_n

$$R_n = \left(\frac{R_0 + 2R_{45} + R_{90}}{4}\right) \qquad (2)$$

Higher R_n means higher resistance to thinning, i.e. deeper cup can be drawn. Hence, a high value of *R* denotes that the material has a very good drawability, i.e. high LDR, which is desirable property for the deep drawing operation [5]. A measure of the variation of normal anisotropy with the angle to the rolling direction is given by the quantity known as planar anisotropy. Planar anisotropy causes earing defect in deep drawing and height and angular position of the ears completely relates to angular changing of *R* value. Earing can be defined as the formation of waviness on the top of the drawn cup. Ears are formed due to uneven metal flow in different direction and are directly related to planar anisotropy.

$$R_n = \left(\frac{R_0 - 2R_{45} + R_{90}}{2}\right) \qquad (3)$$

Where R_0, R_{45} and R_{90} are Lankford anisotropic coefficients along rolling direction (0^0), diagonal direction (45^0) and transverse direction (90^0). Earing is undesirable since it requires an additional processing step where excess metal must be trimmed causing wastage of material. Also, the metal representing the ear will be deformed into the cylindrical cup, and this will demand extra load and power. Forming without ears is difficult but not impossible. In case of isotropic material where planar anisotropy ΔR is zero, no ears will form. If the ΔR is positive, ears form at 0^0 and 90^0 to rolling direction and ears form at $+45^0$ direction if R is negative. Ideally sheet with high R_n and zero ΔR is good for deep drawing to draw deeper cups. But it is impossible to manufacture the sheets with the high normal anisotropy and zero planar anisotropy.

One of the approaches to prevent ear formation is to find an initial blank shape, referred to the optimal blank shape. Several researchers had carried out investigation to modify the initial blank to minimize the earing and adopted different approaches. Kishore and Ravi Kumar [6] modified initial blank by reducing material from 0^0 and 90^0 for EDD steel and found significant reduction in earing. Shim [7] modified the blank using sensitivity analysis and initial nodal velocity. Chung and Richmond [8] proposed a direct design method and its theoretical basis, called ideal forming theory, to get an initial blank shape. However, real forming conditions such as blank holder force, friction force, tool geometry, etc. are not considerd so the calculated blank shape had some shape error. No effort was made to address the earing issue.

Chung et al. [9] developed a sequential design procedure to optimize sheet-forming processes based on ideal forming theory, FE analysis and experimental trials. They used this procedure to design a blank shape for a highly anisotropic aluminum alloy sheet that resulted in a deep draw circular cup with minimum earing. Agrawal et al. [10] used upper bound method to model deep drawing and calculate cup height around the cup opening. The blank geometry was optimized based on the cup height variation. Due to the multiple unknowns in the complex velocity fields, thinning effect was not studied. Kim and Kobayashi [11] proposed a method to determine blank geometry for rectangular cup drawing operations. By calculating the flow line of the material point, the blank optimization is achieved. The present study aims to determine the optimal shape of blank using reduction of material using FE Modeling to obtain a cylindrical cup without ears.

II. Methodology

As mentioned earlier the presence of earing is more in drawn cup from sheet with of high planar anisotropy. The methodology used in present work for finding earing height and optimization of initial blank shape to minimize the earing is presented in the following sections.

2.1 Finite Element Modeling and Simulation

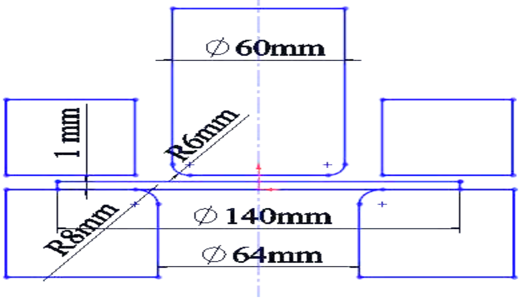


Fig.1 Schematic view of tooling used in deep drawing process

An FEM based software *Altair* HYPERWORKS is used in present work to simulate the deep drawing process. It is non linear dynamic simulation software which can simulate different types of sheet metal forming process such stretch forming, bending, deep drawing etc. In the present study, the model is constructed using the CAD software **PRO-E** and then converted into a finite element mesh using the preprocessor *Altair* **HYPERMESH.** Cylindrical cup drawing process was modeled using a die of Ø64.0 mm with corner radius of 8.0 mm and a cylindrical punch of Ø60.0 mm with a corner radius of 6.0 mm as schematically shown in Fig.1. Finite element modeling was done using HYPERFORM where the complete set-up of deep drawing was first created. All tooling surfaces were modeled using four-node shellelements. The blanks were modeled using four noded quadrilateral Belytschko-Tsay shells (Fig.2). Punch, die and binder were assigned as rigid entity (Master Surfaces) and Blank was assigned as deformable entity (Slave Surface). Die was fixed, however both punch and binder were allowed to move only in the z direction which was coinciding with the punch-axis. Adequate blank holding force (binder force) was applied to avoid flange wrinkling. Numerical calculations of the deep drawing process were performed using Incremental RADIOSS as non-linear solver.

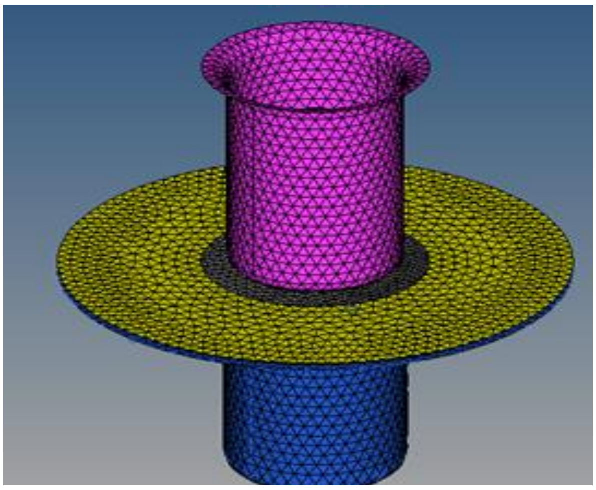


Fig.2. Meshed cylindrical cup deep drawing set up

The different boundary conditions which have been applied into finite element modeling are as follows:

Table 1. Process Parameters used for simulations.

Process Parameter	**Value**
Blank holder force	12 KN
Punch velocity	83.33 mm/s
Punch displacement	100 mm
Initial blank thickness (*t*)	1mm
Coefficient of friction	0.125

2.2 Selection of material and material model

The material is taken for simulation study is mild steel EN10130FeP01. It is selected for the present study because it has huge application due to its material properties. Mild steel is a type of steel alloy that contains a high amount of carbon as a major constituent. It has a relatively low tensile strength, but it is cheap and malleable. To get accurate results, the selection of an appropriate material model is considered as the most important part of the simulation.

Table 2. Mechanical properties of mild steel [12]

Material Parameter	**Value**
Young modulus of elasticity (*E*) (Gpa)	210
Initial yield stress(Mpa)	123
Poisson’s ratio (v)	0.3
Strength coefficient (*K*) (Mpa)	529.5
Strain hardening exponent (*n*)	0.268
R_0	2.53
R_{45}	1.84
R_{90}	2.72

The selected material model should have the capability to take care of the deformation process considering each and every material property as per the requirement. In the present study, the anisotropic plastic material model Hill orthotropic power law is used. It requires the input of various material properties Poisson’s ratio, initial yield stress, Young modulus of elasticity, R_0, R_{45} and R_{90}. The detailed material properties are given in Table. 1

2.3 Earing height Measurement

Earing height was predicted for several blanks of different diameter using FE modeling by following procedure [6]:

1. Circular blank was divided into 8 equal parts by drawing lines at 45^0 intervals from center to the circumference of the blank with respect to rolling direction.
2. The node numbers at the circumference of the blank were found corresponding to the points where the above lines intersect the circumference.
3. The differences were measured between the displacements (z-coordinate) at those particular nodes with the node (at bottom) of the cup. These differences (Fig.4.5) showed the heights of the cup at those particular nodes mentioned earlier or the position at deformed nodes in z direction also represent the cup height at those nodes in the rolling direction.

2.4 optimization of initial blank shape to minimize the earing

To minimize earing following procedure [6] was adopted to modify or optimize the initial blank shape:

1. In the present study ears were found at 0^0 and 90^0 to rolling direction, due to positive ΔR Value. The blank shape has been modified by removing the material the 0^0 and 90^0 to rolling direction. This is done by PRO-E modeling software.
2. The Δr_1 and Δr_2 values were found out as:
   $\Delta r_1 = R_0 - R_{45}$
   $\Delta r_2 = R_0 - R_{90}$
3. For modifying Circular blank, it is divided into 8 equal parts by drawing lines at 45^0 intervals from center to the circumference of the blank with respect to rolling direction. The co-ordinates (x, y) points were noted at those points. These points are numbered 1-8 as shown in Fig.3.
4. To remove material, four new points was determined (two each on X-axis and Y-axis). These points were numbered as 1', 3', 5' and 7' (Fig.3).
   The X- and Y- coordinates of these four points were determined as follows:
   Modified X-coordinate = $R - \beta\, \Delta r_1$
   Modified Y-coordinate = $R - \beta\, \Delta r_2$
   Where, R is the radius of circular blank and β is the ratio of the two plane-strain strengths. β= 4, 6, 8.

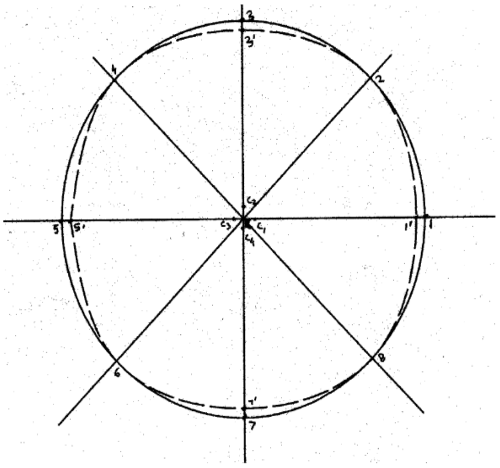
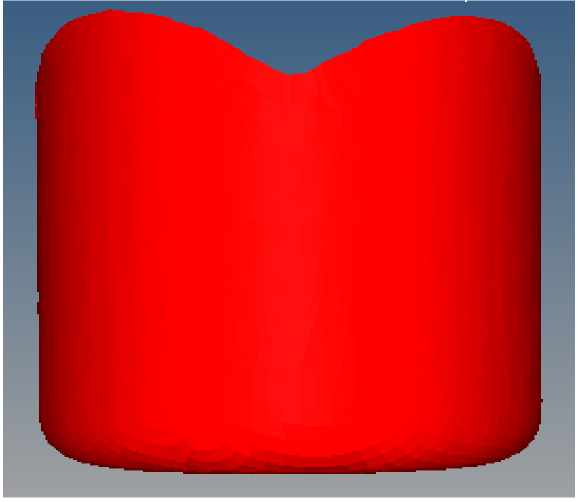


Fig.3 Method of drawing/sketching a modified blank [6]

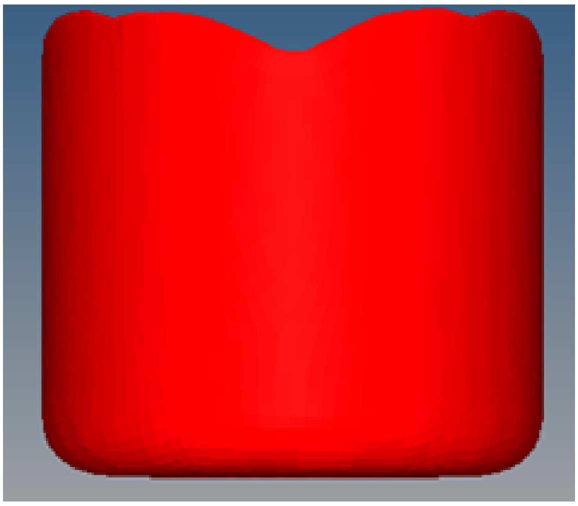
5. Earing height= max. cup height-min. cup height

3. Results and Discussions

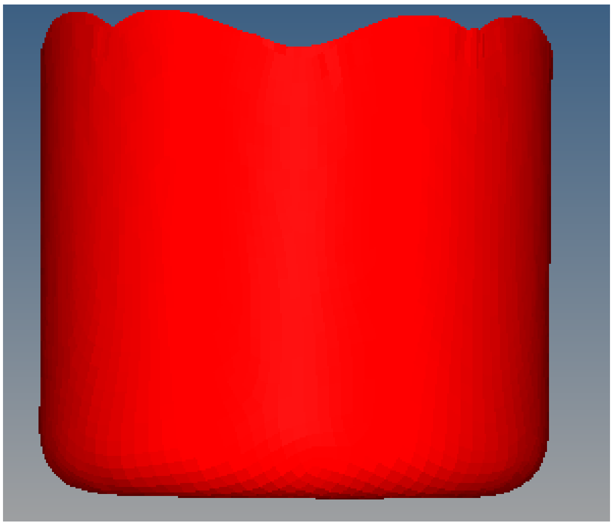
The below discussion compares results about effect on the cup height and % earing height and contact force for initial and optimal blanks.



Initial blank



Modified blank -1



Modified blank -2

3.1 Effect on cup height and % ear height

The use of modified blank has significantly reduces the variation in cup height. Among all three modifications, the cup height was more uniform using the 2^{nd} modification with β=6 where the variation of cup height is less. The cup heights were measured at different points with respect to rolling direction and plotted as shown in Fig.4 for different initial blank shape using the procedure discuss in the section 2.3. variation of the cup height is better observed through % ear height as shown in Fig.5, where % ear height is defined as:

$$\%\ \text{ear height} = \frac{max.cup\ height - min.cup\ height}{min.cup\ height} * 100$$

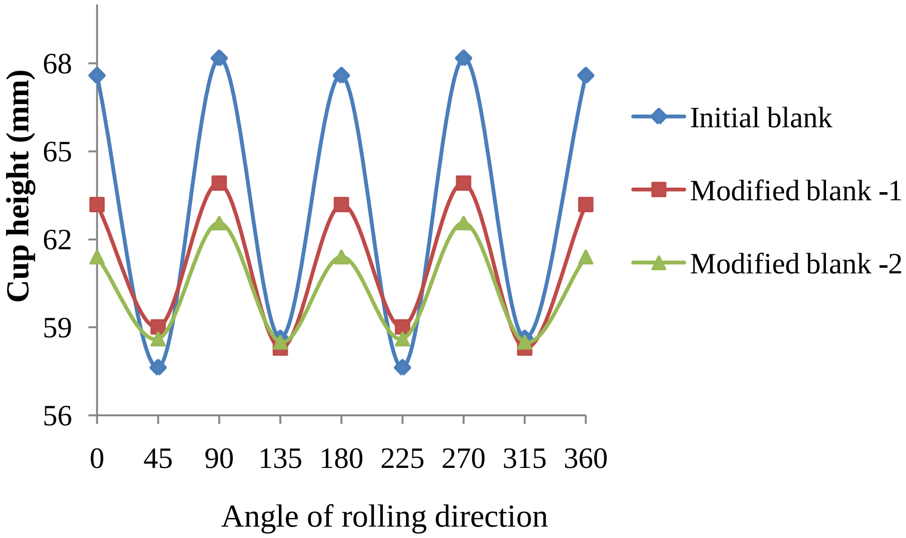


Fig.4 Comparison of cup height by initial and modified blank

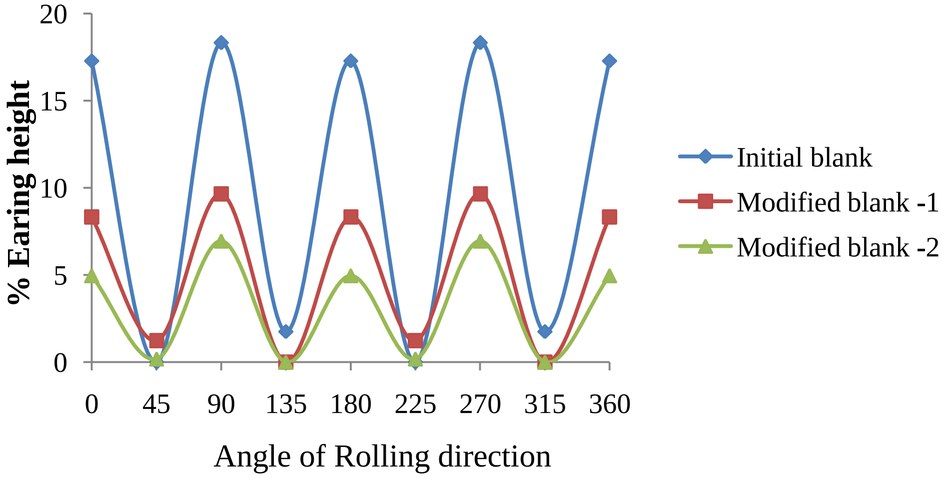


Fig.5 Comparison of earing cup profile of initial & modified blanks in terms of % ear height

Fig.5 compares the % ear height before and after the modification of initial blank. It can be observed that % ear height for the initial blank is around 17%, which reduces to 8-9.8% after the first modification and further reduces by 5-7% after the second modification. Hence, second modification of initial blank gives the least % earing height or more uniform earing profile than other blank, it is considered to be an optimal blank. The earing is reduced by using the modified blank due to material is removed where the metal flow is low to modify the blank further.

3.2 Effect on contact force

Contact force is force which is devolped with the contact of punch with blank; it is increases as contact of area of blank with punch increase. It is fact that contact force is of smaller value at the beginning of stroke because of smaller value of blank with the punch. But, as the punch advances into the die cavity resulting into larger contact resulting in increase in force. The contact force is directly related to forming load to form the component. With the use of modified blank, there is considered reduction in material of blank. So, the lesser area of blank is contact with punch displacement. Hence, lesser forming load is required with modified blank than the initial blank as shown in Fig.6.

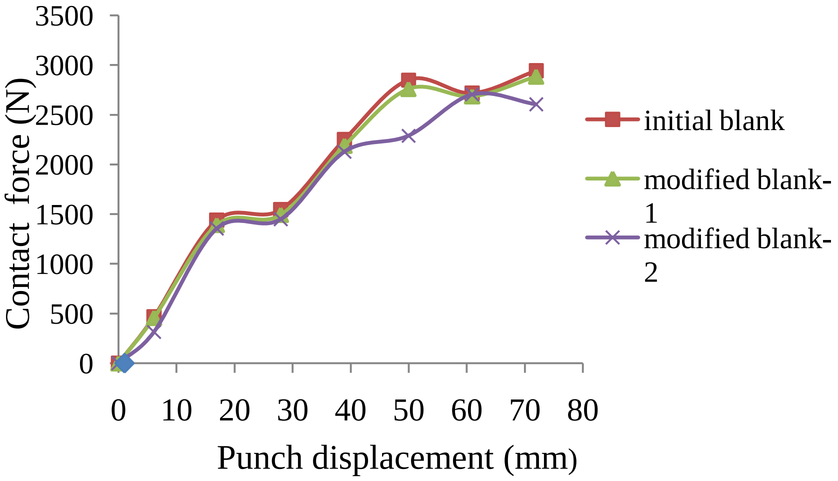


Fig.6 Comparison of contact force for initial & modified blanks with punch displacement

III. Conclusions

In the present work an attempt has been made to simulate deep drawing process, using FEM software HYPERFORM to study earing defect in EN10130Fe01 mild steel as material. The reduction of earing defect can be reduced by use of optimal blank i.e. non circular blank as initial blank for deep drawing process and use of optimal material which favors the reduction in earing defect. The derived conclusions are reported in brief as follows:

(1) The initial blank as circular blank produces more % earing height. Since it has higher planar anisotropy. So, modification is done for the initial blank to reduce the % earing height.
(2) The use of optimal blank i.e. non circular blank produce considerable reduction in % earing height, contact force hence improves the formability compared to initial blank.

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