Evaluation of square deep drawn AA6061-T6 blank based on thinning pattern

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Abstract. Deep drawing can be generally described as a process of converting a metal sheet into a desired shape and geometry. Material flow and formability of the blank depends on the die and the punch geometries and it is important to predict the material behavior during square deep drawing to reduce possibility of defect and part rejection. In this research, a 3D Finite Element (FE) model is developed to simulate the square deep drawing process of an AA6061-T6 material using ANSYS Explicit Dynamics. The developed model can be used to predict the thinning pattern of the blank especially at the corner area. This research focus on the effect of design parameters namely punch corner radius (R₁), punch nose radius (R₂), die corner radius (R₃) and die shoulder radius (R₄) towards thinning pattern.

Keywords: Punch radius, die radius, square deep drawing, thinning, FEA

1. Introduction

Deep drawing is one of the most important processes in the production of sheet metal parts. Automotive industry is one of the sectors that utilized this process to manufacture various parts such as structural and outer panels. Deep drawing is complex deformation affected by the geometrical and process parameters including blank holder force, blank thickness, friction, die radius and punch radius [1]. Typically thinning, tearing and wrinkling (flange and wall) are the most frequent defect can be found in deep drawn part [2]. The effects of all these parameters are not independent. According to Prasad and Rao, tearing effect will occur when lower the die corner radii and wrinkling will take part when die corner radii is higher [3]. Gowtham et al., also supported that, a decreased die radius created stretching marks and earring type quality problems [4]. Study on prediction of the forming results such as determination of the thickness distribution and the thinning of the sheet metal blank may increase the productivity through less defect and part rejection. It was first studied by Colgan and Monaghan using statistical analysis and design of experiments, they manage to determine the most important factors influencing a drawing process. It seems that the punch/die radii have the greatest effect on the thickness of the deformed mild steel cups compared to blank-holder force or friction [5]. Zein et al. also presented a Finite Element (FE) model for the 3-D numerical simulation of deep drawing process to predict the thickness distribution and thinning of the blank with the die design parameters (geometrical and physical parameters) [6]. The simulation was successful as the forming loads can be predicted to complete the drawing process. Hassan et al. have proposed a newly process to increase the formability of square cups using a flat headed square punch through a conical die with a square aperture. The effects of die fillet radius, die corner radius, die throat length, punch profile radius; punch corner radius, punch shape factor, relative die clearance and blank thickness on the draw ability
of square cup were mainly investigated using FEA [7]. Based on the predicted thickness distribution of the deep drawn circular cup and analysis of variance test, it is evident that die radius has the greatest influence on the deep drawing of stainless steel blank sheet followed by the blank holder force and the friction coefficient [8]. However, Venkateswarlu et al. using the combination of finite element method and Taguchi Analysis observed that blank temperature has greatest influence on the formability of aluminium material followed by punch velocity and die arc radius [9]. Material flow during the deep drawing process is differ between circular and square cups. Younis and Jaber using Low carbon steel AISI (1008) shows that excessive earing appears in the square cup. This is due to excessive material flow in the corner and minimum material flow at the flat area [10].

2. Methodology

The investigation will utilize the finite element analysis software namely Ansys to study the effect of few design parameters such as die profile radius and punch nose radius to thinning pattern. The finite element (FE) model is developed based on a quarter of 3-D square deep drawing of AA 6061-T6 using ANSYS18.2/Explicit dynamics. The modeling is as the following steps:

2.1 Basic configuration

For this study, the geometrical details of the punch, blank and die are schematically shown in Figure 1. The AA6061-T6 blank with thickness of 0.8 mm is prepared in 60 mm diameter size.

![Figure 1](image)

**Figure 1.** Varied geometrical features definition. (a) top view of a punch, (b) side view of a punch, (c) top view of a die and (d) side view of a die. (Note: \( R_1 = \) Punch corner radius, \( R_2 = \) Punch nose radius, \( R_3 = \) Die corner radius and \( R_4 = \) Die shoulder radius)

2.2 Numerical Model

**Material Properties**

The material is modeled as an elastic-plastic material with isotropic elasticity, using the Hill anisotropic yield criterion for the plasticity to describe the anisotropic characteristics of the blank. Table 1 shows the material properties of the blank.

| Physical and Mechanical Properties (Ramulu et al., 2013) |
|---------------------------------|----------------|
| Young modulus (E) | 66 G Pa |
| Poisson ratio (\( \nu \)) | 0.33 |
| Density (\( \rho \)) | \( 2.703 \times 10^6 \) kg mm\(^{-3}\) |
| Yield strength (\( \sigma \)) | 269 MPa |
| Friction coefficient (\( \mu \)) | 0.2 |
Boundary Condition
The quarter model of the deep drawing process is shown in Figure 2. For simplifying the simulation of the deep drawing processes, the following setup was made. The punch moved down at drawing force, $F = 21510$ N. No change in the temperature during the forming process, no heat transfer between tool and blank. Fixed support is provided to die and blank holder force. Blank is fully constrained along X and Z direction. Punch is fully constrained along X and Z direction.

Element Type and Meshing
The punch, blank holder and die were modeled as rigid bodies and blank was modeled as flexible body. Know that mesh density of the blank and other tools affects the accuracy of the result. Therefore, the meshes in the blank are finer than the mesh in punch and die to get the accurate results for deformation occurs in the blank. Mesh was generated by providing the following mesh parameters for blank is 1.0mm and for punch and die mesh size were set as default. Element type set was linear and default. Following boundary condition were applied in the Analysis Process using solver target AUTODYN.

Contact
Automatic contact procedures in ANSYS 18.2 were utilized to model complex interaction between the tooling and sheet and were set as frictional contact. The target and contact surfaces constitute contact pair which represents contact and sliding between the surfaces of blank with punch and die.

Figure 2. The developed model of the square deep drawing process components

2.3 Thickness Measurement
Figure 5(a) shows sectioning made on the drawn blank, while Figure 3(b) illustrate the locations with a distance 5mm of thickness measured on the drawn square cup from the center of the cup. For consistency of the location and to reduce error, the resulted profile will be exported to Space Claim Design Modeler available in Ansys Explicit Dynamics for thickness measurement and location plane was cut at the corner of the cup drawn.
Figure 3. (a) Sectioning of the drawn blank and (b) locations for the thickness measurement

3. RESULTS AND DISCUSSION

3.1 Effect of Punch Radius to Thinning
The geometry of punch corner and punch shoulder radius influences the thickness distribution and thinning in blank in the deep drawing processes. Figure 4(a) and 4(b) show the result of thickness distribution for different values of punch corner and nose radius. The thickness was measured at the corner side of square cup. From the results, the thinning start occurs at position 8 and 9 from the center of the cup. The more thinning occurs because of stretching in the punch radius region. Both graphs show the maximum thinning at position 9 and the blank start thickening gradually until at position 11 and 12. Figure 4(a) shows that the maximum thinning and thickening of the cup occurred when the value of punch corner radius is 3 mm. The thickness of the cup in base region is equal to initial thickness of the blank 0.8 mm and then start to be thinning and reach maximum value of thinning at position 9. The thinning at the wall cup is maximum due to stresses produced in this region. When punch corner radius is smallest the area at the corner side is the smallest, so thinning is maximum due to excessive bending and unbending at this area.

3.2 Effect of Die Radius to Thinning
The geometry of die corner and die shoulder radius influences the thickness distribution and thinning in blank in the deep drawing processes. Figure 4(a) and 4(b) show the graph of thickness distribution for different values of die corner and die shoulder radius. Figure 4(a) shows that thinning occurred at position 9 and 11. Then the blank start thickening at position 12. The maximum thinning occurred when the value of die corner radius is 6 mm. The more thinning occurs because of stress and
compressive force in the die corner region. Figure 8(b) shows thinning of the cup occurred at position 9 and 11 whereas the thickening occurred at position 12. The maximum thinning of cup occurred when the value of die shoulder radius is 6 mm and the maximum thickening occurred when the value of die shoulder radius is 3 mm. When die corner radius is highest the area at the corner side is smallest so thinning is maximum due to excessive bending and unbending at this area. When the die shoulder radius is smallest the area at the corner die is wider, so less material of blank will flow at that area and thus thickening happen.

![Figure 5](image.png)

**Figure 5.** (a) Effect of die corner radius ($R_3$) on blank thickness distribution and (b) effect of die shoulder radius ($R_4$) on blank thickness distribution.

3.3 Depth of the cup

Figure 6 shows the effect of punch and die radius to the depth of the drawn square cup. When all the radius of punch and die are 3 mm the height of the cup drawn are same 15.36 mm. The height of the cup drawn differ when the radius of punch and die changing. The maximum height of cup drawn is when the radius of punch corner, $R_2 = 6$ mm and minimum height of cup drawn occurred when punch nose radius, $R_1 = 4$ mm. When the punch corner radius increases the area in that region is bigger thus more material flow will be occurred as a result the height of the cup is maximum. When the punch nose radius smaller the area in that region is smaller thus less material flow will be occurred due to high compressive stress as a result the height of the cup is minimum.

![Figure 6](image.png)

**Figure 6.** Effect of punch and die radius on height of the square cup.

4. Validation

Figure 7 shows the validation graph of thickness distribution from the cup center of AA6061 between the experimental method and FE simulation. The result from the FE simulation was compared with
result from experiment conducted by Raju et al. (2010) for validation. From the result, it is observed that thinning is maximum at position 9 and 10 with the value 0.74mm. Thickness increases gradually, and both graphs show nearly depict similar pattern. The result shown that maximum percentage of thinning for experimental method is 7.34% while 7.50% for simulation. The pattern of both graphs is nearly same compared to each other but the percentage of thinning with simulation is less compared to experiment. Result showed a reasonable agreement with experimental work of some researchers with an average standard deviation of 1.86% for thickness location #1 to #8, 0.12% for location #9 to #10 and 1.11% for location #11 to #17.

Figure 7. Validation (measured at flat side with R₂ = 6mm)

5. Conclusions
A finite element analysis-based simulation has been done using ANSYS Explicit Dynamic for the square cup deep drawing process. The effects of die corner, die shoulder, punch corner and punch shoulder radii on the drawability and quality characteristics has been done. It has been found that when the die radius reduced the amount of force needed to draw the blank is increased by 0.57%. An optimum die and punch radius were an important parameter to obtain minimum thinning is 0.01mm.

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