A Spline Shape Deep Drawing using Finite Element Simulation and Experimental Work Test

Kadhim H Mukhirmesh and Waleed K Jawad
Dept. of Production Engineering and Metallurgy, University of Technology, Baghdad, Iraq
Email: 70081@uotechnology.edu.iq

Abstract. In the current research, an analysis study was conducted to process of design of spline cup drawing. Deep-drawing tools (dies and punches) were designed and manufactured to implement the experimental work required to produce a spline cup with inner dimensions are height h=3 mm, width W=9.64 mm, and diameter d=34 mm, drawn from a circular blank of a diameter D_b = 80 mm, and thickness t = 0.7 mm made of low carbon steel (1008-AISI). To simulate the spline shape deep-drawing process, a commercial finite element program code ANSYS 19.0 Workbench was employed. The research aims to produce the spline shape and study the effect of the punch wall curvature radius on the drawing force, thickness distribution, and effective strains across the sidewall, major and minor axis curvature of a completely drawn spline cup using experimental testing and finite element modeling. From the comparisons between the experimental and finite element results, it was shown that the numerical results of a spline cup deep-drawing are good agreement with the results of the experiment and lie within an average of (4% - 8%). The drawing force and thinning for the small punch wall curvature radius is higher than the large punch wall curvature radius. The maximum drawing force and maximum thinning with the smallest punch wall curvature radius (0.5) at the minor axis curvature of a completely drawn spline cup. The maximum effective strain with the smallest punch wall curvature radius (0.5) at the minor axis curvature region at the completely drawn spline cup rim.

Keywords. Spline shape, Deep drawing, Spline cup, The punch wall curvature radius.

1. Introduction
The deep-drawing operation is used in industrial sheet metal forming operations by which a blank metal sheet is drawn into a specific shape such as cylindrical, conical, box, and oval, or any other shapes. Deep-drawing is a very complicated process. It is affected by several factors like die radius, die fillet radius, punch profile radius, press speed, and material characteristics [1]. Common shapes produced by the deep-drawing process are cylinders for aluminum cans, enclosure covers for oil filters, cups for baking pans, and fire extinguishers. Industries benefited by the deep drawing process are beverages, lighting, dairy, automobile, aerospace, pharmaceuticals, plastics, etc. [2]. Many of various studies have been conducted with the deep-drawing process for both symmetric and axisymmetric shapes. These studies covered some parameters to obtain the final product without imperfections, such as wrinkling and thinning, in the deep drawing process. Parka et al. [3] carried out the deep drawing operation of an elliptical cup utilizing technologies, including experimental and FEM approaches. To get the optimal parts in the deep-drawing operation, elliptical deep-drawing
experiments were accomplished with various fillet radii of the punch and die. The optimal fillet radii of the punch and die in the deep-drawing operation with a non-axisymmetric blank sheet form are proposed. Jawed and Salman [4] developed a method to produce hexagonal cups from converting the cylindrical and compare them to hexagonal cups from a blank sheet in the deep-drawing process. From the results, the least excessive metals will appear in the wall curve radius of the primary diameter of hexagonal cup produce from converting the cylindrical cup compared to hexagonal cups produce from the circular blank sheet. The more lamination occurs at the region of the cup curve in hexagonal cups produce from the circular blank sheet compared to the hexagonal cup produce from converting the cylindrical cup. Mahida and Shah [5] introduced the deep-drawing process by FE analysis for producing elliptic shapes using the simple die set without draw beads or blank holder utilizing a conical die and simple die. Based on these results, the percentage lamination and stress distribution on elliptic shapes utilizing a conical die are less than simple die. The conical die gives a better product than the simple die. AL-Gharrawi and Tuaimah [6] studied the influence of the sheet thickness on a multi-stage deep-drawing operation for hexagonal shape using both experimental work and numerical simulation. The results appeared that the maximum drawing force decreases with the stages progress drawing, higher thinning take place in the shape profile region with the sheet thickness equal to (initial sheet thickness $t = 0.5 \text{ mm}$), and higher thickening takes place on the rim shape with the sheet thickness (initial sheet thickness $t = 1.2 \text{ mm}$). Waleed and Ali [7] investigated the influence of radial clearance of the distribution of stress and strain in the astral deep-drawing process. In this study, three types of radial clearance equal to (1.1, 1.2, and 1.3) are used; the results showed that the maximum drawing load value of 55kN was recorded with a radial clearance equal 1.1mm. The process of a squeeze in the wall that occurred with the radial clearance of 1.1mm is due to the difficulty of the metal flow to be exposed to maximum tensile stress. The maximum effective stress (674MPa) and strain (0.973) were recorded with the clearance of 1.1mm at the minor axis. Younis et al. [8] evaluated experimental work and FES to produce square cup deep drawing operation and study the effect corner radius of the die, the square cup depth, blank size, and radial clearance between the die and punch on the thickness distributions were evaluated. It was shown that the more thinning take place in the profile cup was attributed to more stretching observed in this zone. Jawad and Ikal [9] carried out work to study the drawing process, a star shape drawn from the flat circular blank and redrawing from cylindrical shape using experimental and FE analysis. The finite element analysis results were compared with the experimental results, and it was found that the maximum punch force of 39.12kN was recorded with the production of a star shape drawn from the flat circular blank sheet when comparing the punch force (32.33 KN) recorded when redrawing the cylindrical shape into a star shape. This is due to the exposure of the cup produced drawn from the blank to the highest tensile stress. Hassan et al. [10] proposed processes based on using conical dies to increase the deep drawability of asymmetric cups with rose, clover, star, and triangular cross-sections. From the results, it was expected that this proposed technique could produce shape cups of elliptic, trapezoidal, cocoon-shaped, rhombic, rectangular, and L-shape cross-sections.

2. Finite Element model

To model and simulate the deep drawing operation, commercial finite element analysis code based on ANSYS 19.0 workbench was used, the procedure of FE simulation to design and model a spline cup of deep-drawing process and analysis under the effect of the various wall curvature radius of the punch on the drawing force, thickness distribution, and effective strain across the wall spline cup. The spline cup (Figure 1), with inner dimensions of height $h = 3 \text{ mm}$, width $W = 9.64 \text{ mm}$, diameter $d = 34 \text{ mm}$, and length 32.25mm, is produced from a flat circular blank with dimensions of $D_b = 30 \text{ mm}$ and $t = 0.7\text{mm}$ of low carbon steel (1008-AISI). The mechanical properties of the flat circular blank that is used in this FES as listed in Table 1.
Table 1. The mechanical properties of the unformed flat circular blank

| Property                  | Unformed blank value |
|---------------------------|-----------------------|
| Yield Stress (MPa)        | 220                   |
| Ultimate Stress (MPa)     | 378                   |
| Young Modulus (GPa)       | 200                   |
| Tangent Modulus (GPa)     | 0.5                   |
| Mass Density (gm/cm³)     | 7.8                   |
| Poissons Ratio            | 0.31                  |

The static structural analysis was used to perform the geometry and modeling of all parts of a deep-drawing operation. Using the design modeler, all parts (blank, punch, blank holder, and die) were designed and modeled, as shown in Figure 2. For toolset – blank stiffness behavior is flexible. The assignment is low carbon steel, while the stiffness behavior of other tools (die, blank holder, and punch) is rigid, and the assignment is structural steel.

In the contact regions, which are three frictional contacts, the blank was represented as a contact body, while the other tools (die, blank holder, and punch) were represented as the target bodies. The coefficient of friction between the flat circular blank material and tool punch material interface is $\mu = 0.1$. The friction between the flat circular blank material and other tool material interface is $\mu = 0.05$. Three types of the spline punch wall curvature radius equal to $(R_{cp} = 0.5, 1, 1.5\text{ mm})$ were considered. The smallest radius was used to study the influence of punch geometric deep-drawing operation. The successive steps of the spline cup deep-drawing operation for effective stress are outlined in Figure 3.
3. **Experimental procedure**

To produce a spline cup, experimental tools (die, punch, and blank holder) were designed and constructed. All tools are manufactured from structural steel machined by a CNC machine and a wire
cut machine. To obtain a good surface finish and hardness, tools were polished and then hardened. All test experiments were performed using a universal testing machine-related deep-drawing operation with a capacity of 200 kN and 0-500mm/min crosshead speed. The deep drawing tools used in this research work-study are shown in Figure 4A.

The flat circular blank that was drawn with dimensions of \( D_b = 80 \text{ mm, and } t = 0.7\text{mm} \) is made of low carbon steel (1008-AISI). The deep drawing was performed using spline punch with dimensions equal to \( h=3 \text{ mm, } W = 9.64\text{mm, and } d = 34\text{mm} \) height, width, and diameter of spline punch, respectively. The inner dimensions die equal to \( h = 3 \text{ mm, } W = 11.34\text{mm, and } d = 36.7\text{mm,} \) which are the height, width, and diameter of the spline die respectively, and dies clearance (C) equal to 0.2 thickness was chosen, as shown in Figure 4B. All the experimental tests were performed in the Strength of Material Laboratory, Production Engineering Department, University of Technology/Baghdad.

Tests of deep drawing that include drawing processes to produce spline cups without flange with inner dimensions equal to (major axis \( D = 41.5\text{mm, minor axis } d = 34\text{mm,} \) \( (h = 3 \text{ mm, } W = 9.64\text{mm, and } d = 34\text{mm}) \) height, width, and diameter of the spline, respectively, and length equal to 31mm, as summarized in Figure 5.

![Figure 4.](image)

**Figure 4.** (A) The tools of the deep drawing process and (B) The spline die and punch used in the deep-drawing process.

![Figure 5.](image)

**Figure 5.** The spline cup produced using deep-drawing operation.
Three types of the wall curvature radius of spline punch equal to $R_{cp} = 0.5, 1,$ and $1.5$ mm, and punch profile radius equal to $R_p = 4.15$ mm were used to verify the effect of the wall curvature radius of punch on the distribution of stress, effective strain, and thickness over sidewall, the curvature of the major axis, and the curvature of the minor axis of the completely drawn spline cup and spline cup height. The wall curvature radius of the die and die profile radius equal to $R_{cd} = 1$ mm, and $R_d = 5$ mm. Using a laser machine, a square grid was printed on the flat circular blank with dimensions of $2.5 \times 2.5$ mm to study the strain distribution across the sidewall, the curvature of the major axis, and the curvature of the minor axis of the drawn spline cup, as shown in Figure 6A. When the sample is deformed, also the grid squares are deformed with the material and is visualized, the deformations imposed on a sheet as outlined in Figure 6B. A wire cut machine was used to cut the drawn spline cup into two parts to measure the spline cup wall thickness. Tool microscope and thickness micrometer were used to measure changes in the grid squares and the cup wall thickness after deformation. The length of the distorted grids radius and spline cup thickness were measured. The thickness, radial, and hoop strain distribution were measured.

The effective strain ($\varepsilon_{eff}$) was calculated from the thickness strain ($\varepsilon_t$), radial strain ($\varepsilon_r$), and hoop strain ($\varepsilon_{\theta}$) strain using the following equations.

\begin{align*}
  \varepsilon_t &= \ln \frac{t}{t_0} \quad (1) \\
  \varepsilon_r &= \ln \frac{R}{R_0} \quad (2) \\
  \varepsilon_{\theta} &= -(\varepsilon_r + \varepsilon_t) \quad (3) \\
  \varepsilon_{eff} &= \left(\frac{2}{3}(\varepsilon_t^2 + \varepsilon_{\theta}^2 + \varepsilon_t^2 + \varepsilon_{\theta}^2)\right)^{\frac{1}{2}} \quad (4)
\end{align*}

![Figure 6. (A) observe unshaped sheet with grids, (B) deformed grids on spline cup.](image)

4. Results and discussion

Figure 7 shows the results of the experimental work and the FEM method. The drawing load varies with the punch displacement under the effect of spline punch wall curvature radius in deep-drawing operation. It was shown that the numerical results of a spline cup deep-drawing are in good agreement with the results of the experimental results and lie within an average of 4% - 8%. The drawing force for the small punch wall curvature radius is higher than the large punch wall curvature radius. The maximum drawing force values of the experimental work and the FEM method are $42.25$kN and $40.150$kN, respectively, with the smallest punch wall curvature radius (0.5) at the minor axis curvature region at the completely drawn spline cup rim. This attributes to the bending intensity effects on the
small spline punch wall curvature radius. From this figure, it is clear that for both the experimental work and the FEM method, the drawing force for all values of the spline punch wall curvature radius reaches the maximum value and then started to decline because of decreasing the friction area between the blank and the die.

![The spline cup drawn from the blank](image)

**Figure 7.** The relationship between punch loads and punch displacement under the effect of spline punch wall curvature radius in deep-drawing operation.

Figure 8 shows the effect of the spline punch wall curvature radius on the thickness distribution along the sidewall, the curvature of the major axis, and the curvature of the minor axis of the completely drawn spline cup. From this figure, it is clear that at the spline cup corner, the thinning takes place and increases with decreasing the spline punch wall curvature radius. The maximum thinning takes place with the smallest value of the spline punch wall curvature radius \(R_{cp} = 0.5\ mm\) at the curvature of the minor axis (concave area), as shown in Figure 8C. While, at the spline cup rim, the maximum thickening takes place with the large value of the spline punch wall curvature radius \(R_{cp} = 1.5\ mm\) at the curvature of the major axis (convex area), as shown in Figure 8B.

Figure 9 refers to the effect of spline punch wall curvature radius on the distribution of effective strain over the sidewall, the curvature of the major axis, and the curvature of the minor axis of the completely drawn spline cup. This figure illustrates that in all regions for both the experimental work and the FEM method, the effective strain distributions of drawn spline cups are similar in shape and have the same trend. The maximum effective strain value with the smallest value of the spline punch wall curvature radius \(R_{cp} = 0.5\ mm\) at the curvature of the minor axis of the spline cup rim, as shown in Figure 9C, this is attributed to the excessive tension that takes place at the curvature of the minor axis. The minimum effective strain values for the experimental work and the FEM method are 0.482 and 0.536, with the highest value of the spline punch wall curvature radius \(R_{cp} = 1.5\ mm\) at the sidewall of the spline cup rim, as shown in Figure 9A.
**Figure 8.** Thickness distribution under the effect of spline punch wall curvature radius in deep drawing operation; (A) Across the sidewall, (B) Across the curvature of the major axis, (C) Across the curvature of the minor axis.
Figure 9. Effective strain under the effect of spline punch wall curvature radius in deep drawing operation; (A) Across the sidewall, (B) Across the curvature of the major axis, (C) Across the curvature of the minor axis.


5. Conclusion

- The complex shapes, such as spline shapes, can be produced by the deep-drawing operation.
- The drawing force for the small wall curvature radius of the spline punch is higher than that for a large wall curvature radius of the spline punch.
- The maximum thinning takes place with the smallest value of the wall curvature radius of the spline punch \( R_{cp} = 0.5 \text{ mm} \) at the curvature of the minor axis.
- The maximum thickening takes place with the large value of the wall curvature radius of the spline punch \( R_{cp} = 1.5 \text{ mm} \) at the sidewall.
- The maximum values of effective strain and stress with the smallest value of wall curvature radius of the spline punch \( R_{cp} = 0.5 \text{ mm} \) at the curvature of the minor axis at the spline cup rim.

6. References

[1] Namer N S M, Nama S A and Thabit JW 2015 Numerical and Experimental Study on Deep Drawing Process for AA2024-T4 Sheet (Journal of Applied and Experimental Mechanics) vol 1 pp 1–9

[2] Pathak K K and Anand V K 2017 Analysis of Deep Drawing Process-A Review (International journal of advanced production and industrial engineering) vol 2 pp 10–27

[3] Park D H, Kang S S and Park S P 2001 A study on Improvement of Formability for Elliptical Deep Drawing Process (Journal of Materials Processing Technology) vol 133 pp 662–665

[4] Jawed W K and Dawood S S 2016 Drawing of Hexagonal Shapes from Cylindrical Cups (Eng. & Tech. Journal) vol 34 pp 1235–1246

[5] Mahida K A and Shah J R 2015 Compare the FEA Analysis of Elliptic Cups using Simple Die and Conical Die(International Journal of Engineering Research & Technology) vol 4 pp 462–467

[6] AL- Gharrawi D S S and Tuaimah A2017 Experimental and Numerical Study the Influence of Sheet Metal Thickness on a Deep Forming Operation of Multi Stages for Hexagonal Shape (Al- Nahrain Journal for Engineering Sciences) vol 20 pp 585–599

[7] Jawad W K and Ikal A T 2019 Effect of Radial Clearance on Stress and Strain Distribution in the Astral Deep Drawing (Engineering and Technology Journal) vol 37 Part A, DOI: http://dx.doi.org/10.30684/etj.37.8A.4

[8] Younis K M, Jabber A S and Abdulrazaq M M 2018 Experimental Evaluation and Finite Element Simulation to Produce Square Cup by Deep Drawing Process (Al-Khwarizmi Engineering Journal) vol 43 pp 39–51

[9] Jawad W K and Ikal A T 2020 Redrawing Operation a Star Shape from Cylindrical Shape using Experimental and FE Analysis (Engineering and Technology Journal) vol 38 Part A no 1 pp 26–33

[10] Hassan M A, Hassab-Allah I M, Hezam L M A, Mardi N A and Hamdi 2015 M Deep Drawing of Asymmetric Cups through Conical Die without Blank Holder (Proceedings of the World Congress on Engineering) vol II