Experimental and Analytical Investigation of Deep Drawing Process for producing Pentacle Cups

Zainab H. Mohsein
Production Engineering and Metallurgy Department, University of Technology, Iraq
zainab.h.mehsen@uotechnology.edu.iq (corresponding author)

Waleed K. Jawad
Production Engineering and Metallurgy Department, University of Technology, Iraq
waleed.k.jawad @uotechnology.edu.iq

Aseel H. Abed
Production Engineering and Metallurgy Department, University of Technology, Iraq
aseel.h.abed @uotechnology.edu.iq

Received: 15 February 2024 | Revised: 26 February 2024 and 2 March 2024 | Accepted: 6 March 2024

 DOI: https://doi.org/10.48084/etasr.7074

ABSTRACT

Sheet metal forming is a critical process in modern manufacturing, used to create both finished and semi-finished products. In this industry, there is an increasing demand for fast and cost-effective manufacturing and modification of dies. Therefore, improving theoretical and experimental engineering approaches to reduce manufacturing costs and lead-time between design and production is essential. The development of numerical methods has made Finite Element Analysis (FEA) a valuable tool for predicting product deformation. This study used three forming methods to create a pentacle cup from a low-carbon steel sheet (1008-AISI) with a thickness of 0.7 mm and a diameter of 80 mm. ANSYS Workbench 3-D modeling software was utilized to simulate the drawing procedures. The resulting product's wall thickness and strain were measured and graphed to demonstrate the impact of the different forming methods. The first method involved direct formation by drawing a circular blank metal into a pentacle shape. The second method involved redrawing a cylindrical cup into a pentagonal cup, while the third method entailed converting a pentagonal cup into a pentacle cup. The results showed that the second forming method produced the highest maximum punch load reaching approximately 42.24 kN in experimental testing and 36.66 kN in Finite Element Modeling (FEM), exceeding that of the third forming method. The maximum thinning at cup curvature was observed in the pentacle cup created by the second method, particularly in the major and minor areas, and was more pronounced than in the pentacle cups produced by the third forming method. Ultimately, the third forming method was identified as the optimal technique for producing a pentacle cup with less thinning at the cup curvature and a more uniform distribution of thickness and strain. Overall, this study highlights the importance of advancements in theoretical and experimental engineering approaches to reduce manufacturing costs and improve the efficiency of the sheet metal forming process. The findings from this study can lead to the development of optimal forming techniques for creating high-quality products.

Keywords-pentacle cup; pentagonal cup; direct method; convert method; FEM

I. INTRODUCTION

In manufacturing industry, ensuring high-quality standards is crucial because using sheet metal components involves complex working environments and conditions [1]. The level of contentment a product provides its users is one of the most important factors considered when evaluating its overall quality. This suggests that a product's quality cannot be solely judged based on its design or functionality but should also be evaluated in terms of the level of satisfaction it provides to its users over time [2]. The appropriate definition of parameters that affect quality is essential. Implementing controlled quality measurements to prevent defects can significantly reduce the need for trial and error or tryout methods. The growing demand for high-quality products and the utilization of modern techniques for optimization have resulted in a need for extensive research in sheet metal forming, mainly due to the continuously increasing complexity of the formed parts in modern times. Industries frequently employ the deep drawing technique to produce cup-shaped components in large quantities [1, 3]. The products manufactured through the deep drawing process find broad applications in various industries, including aerospace, automobile, marine, beverage, etc. [4, 5]. The process of deep drawing is impacted by multiple factors, such as the die radius, the gap between the die and the punch, the fillet radius of the die, the punch profile radius, the lubricant type utilized, the speed of the press, and the characteristics of the material being used. Authors in [6] identified the optimal levels of process parameters to produce the desired product quality. Proper selection of these parameter levels can lead to the manufacturing of products without any defects. The analysis of the relevant literature indicates that research on different aspects of modeling, simulation, and process optimization for deep drawing has been continuously advancing over the past few decades. Authors in [7] conducted a study to verify the effect of tooling geometry, such as die and punch arc radius, on wrinkling and fracture limitations using the FEA software LSDYNA 3D. They formed a cylinder cup of 25 mm diameter and 13 mm height made of pure aluminum (AA1100). The results showed that wrinkling limits were independent of the arc radius of the die. However, the fracture limits decreased with increased punch radii due to the increased punch load on the drawn wall. Authors in [8] utilized 3D simulation and ABAQUS/EXPLICIT software to examine how various die designs affect the process, including geometrical and physical parameters, on thinning and residual stresses during the deep drawing process of a circular cup made from mild steel. Their analysis revealed that the recommended die radius should be about ten times the blank thickness, while the punch radius should be no less than four times the sheet thickness. Additionally, the research indicated that the ideal friction coefficient between the die and the blank material falls within the range of 0.125 to 0.2. In addition, the distance between the punch and blank should be between 0 and 0.3 to reduce residual stress and thinning. Authors [9] proposed an analytical approach adopting the SLAP method to predict the maximum variation in the blank holder force (VBHF) during the punch stroke to prevent cracks in the deep drawing process. The study employed a steel sheet with an SPCD grade and a thickness of 0.2 mm for analysis. The maximum VBHF analytical results obtained from the SLAP method were compared to FEM simulations, with no significant difference. The analytical approach effectively predicted the maximum variation in the blank holder force, which could help prevent cracks in the cup produced during deep drawing. Authors in [10] investigated the influence of punch and die radii, lubrication, and blank holder pressure on the formability of AA6061 alloy with a thickness of 2 mm using a deep drawing process. The commercial FEM in CAD modeling was implemented for the numerical simulation of drawing a square cup. The simulation exhibited that the punch force increased with the blank holder pressure and friction coefficient. Authors in [11] reviewed the effects of process parameters, such as Blank Holder Force (BHF) and friction, on metal forming. BHF is a crucial process parameter that needs to be chosen carefully due to its impact on the strain path of the cup flange. The coefficient of friction also affects the quality of the surface produced and the distribution of thickness. Authors in [12] studied the deep drawing process of SPCC carbon steel and its wrinkle defect. The study involved varying the BHF number on the blank holder materials to investigate its effect on the wrinkle defect. The cylindrical cup had an interior diameter of 58 mm, a flange diameter of 76 mm, and thickness ranging from 0.8 mm to 0.1 mm. The punch and die radii were 0.3 mm and 3 mm, respectively. Using SolidWorks of 2017, the simulation revealed the presence of wrinkle phenomena in the deep drawing technique. The findings suggested that the wrinkle defect was reduced as the BHF number increased. Increasing the BHF number can effectively diminish the wrinkle defect in deep drawing processes.

Authors in [13] researched the effect of temperature, strain rate, and anisotropy on the flow behavior of AISI 304 stainless steel using a conical die. They utilized Ansys APDL software to perform finite element simulations and analyze these factors. The simulation results disclosed that the strain varied more in the r0 and r45 directions compared to the r90 direction. Furthermore, increasing the temperature caused a reduction in the drawing stress of approximately 33%. The planar isotropy values indicated that earing occurred in the r45 direction. Authors in [14] investigated the formability of corrugated circular cups made from extra-low carbon steel (SPCC) and stainless steel (SUS304) with diameter ranging from 70 to 95 mm and thickness from 0.3 to 0.5 mm. Deep drawing used a roller die and solid powders as lubricants. The authors examined the influence of blank diameter on formability. They noted that cups drawn from blanks with diameter of 70 to 90 mm were free from defects, while cracks occurred at the base of cups drawn from a 95 mm-diameter blank. They also studied the effect of blank thickness on formability and observed that it was good. Authors in [15] investigated the impact of lubrication on the Coefficient of Friction (CoF) values for DP590 steel sheet in both Lubricated (L) and Non-Lubricated (NL) conditions through simulation. The researchers varied different processing conditions, such as temperature, blank holder pressure, blank diameter, and lubrication, to determine their effects on the formability and load required for cup drawing. The study's findings demonstrated that the interaction between temperature and lubrication significantly impacted the material's formability and helped decrease the load required for cup drawing. Specifically, under lubricated conditions at 400 °C, the experimental measurement of the Limiting Drawing Ratio (LDR) was found to be 1.933, which was 4.35% higher than under other processing conditions. Overall, the study suggests that lubrication and temperature are essential factors in improving the formability of DP590 steel sheet and reducing the load required for cup drawing. The study aims to compare three forming methods, i.e. direct formation, redrawing a cylindrical cup, and converting a pentagonal cup, for producing pentacle cups implementing ANSYS Workbench 3-D modeling software. It emphasizes the significance of enhancing engineering approaches to improve manufacturing efficiency and lower costs in sheet metal forming, offering insights for developing top-quality products.

II. NUMERICAL SIMULATION

A finite element simulation was performed to model the deep drawing process, predict the distribution of thickness, and predict strain behavior in pentacle-shaped products using ANSYS version 21. Table I presents the physical characteristics of steel with a low carbon content employed in the simulation. The stress and strain values were obtained practically from true stress-true strain curves to conduct simulations accurately.

TABLE I. MECHANICAL CHARACTERISTICS OF LOW CARBON STEEL

Property	Value
Young's modulus	200 GPa
Density	7.8 g/cm^3
Poisson ratio	0.3
Yield stress	205 MPa

The model utilized in this study consists of three components: punch, die, and cup. The punch, die, and blank holder are rigid bodies represented by the target element (TARGE 170). In contrast, the deformable body (cup) was acted upon by 3-D 8-node contact elements of CONTA174, as shown in Figure 1. The model was generated using the ANSYS pre-processor and meshed deploying an element size of 3 mm for both punch and die. The cup material was meshed employing a tetrahedral mesh and the body sizing method, with an element size of 2 mm, and coefficient of friction equal to 0.05 [16], as illustrated in Figure 1.

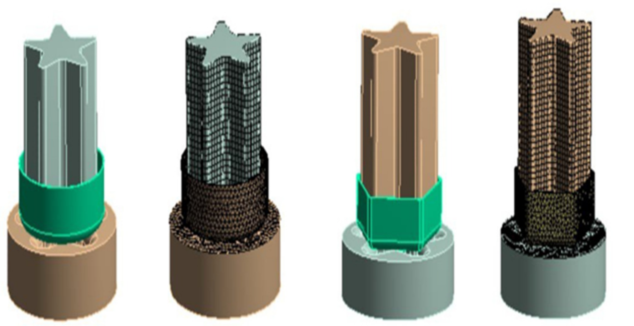


Fig. 1. Model generation and meshing using ANSYS 21.

In order to accurately simulate the intricate contact that occurs between the cylindrical cup and the drawing tool utilized in the second forming process and also between the pentagonal cup and the drawing tool employed in the third forming process, an automatic contact technique was employed in ANSYS 21. The ultimate stage of producing pentacle cups using two different forming methods is presented in Figure 2.

III. EXPERIMENTAL WORK

A. Deep Drawing Tool Design

The first step in the deep drawing process involved optimizing the blank's geometry and shape to achieve the desired cup shape. The actual surface area required was determined. The first method used a circular blank with a diameter of 80 mm to form a pentacle shape, as depicted in Figure 3(a). The second method engaged a cylindrical cup with a diameter of 41.5 mm and a height of 30 mm to create the pentacle cup, as observed in Figure 3(b). The third method involved using a pentagonal cup with a diameter of 41.4 mm and a height of 30 mm, as demonstrated in Figure 3(c). The capability of drawing was estimated by considering the LDR as the primary factor [17]. Furthermore, the design process of the tools included consideration of the geometrical parameters of both the punch's and die's corner radii [18].

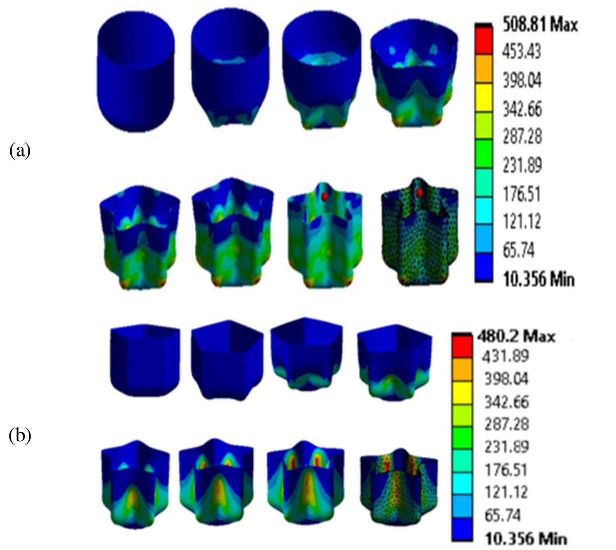
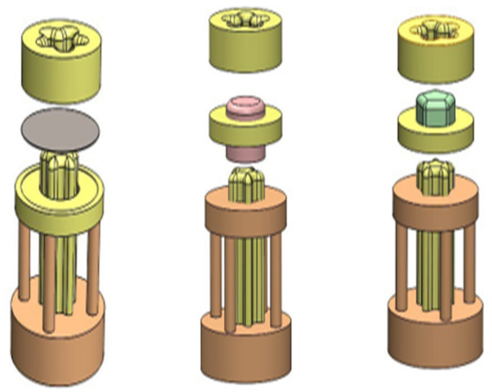


Fig. 2. (a) Pentacle cups for the (a) second and (b) third forming method using ANSYS.



(a) (b) (c)

Fig. 3. Shows the procedure of different forming methods.

The tool dimensions for the three methods are presented in Table II and Figure 4. The dies are constructed from tool steel and are machined using wire cut and CNC turning processes. Figure 5 displays the punches and dies utilized in the experimental investigation. The Maximum Drawing Force (MDF) required to draw the component was calculated by [19]:

$$MDF = \pi.(d_1 + t).t.R_m .1.2.\left(\beta - {}^{1}/_{\beta max} - 1\right) \quad (1)$$

BHF is typically around the one-third of the drawing force, as suggested in [17]. Equation (2) [19] can also be used to define the BHF:

$$BHF = (\pi /4)\,[D^2 - (d^1 + 2\,r)2]\,p \quad (2)$$

(a)

(b)

(c)

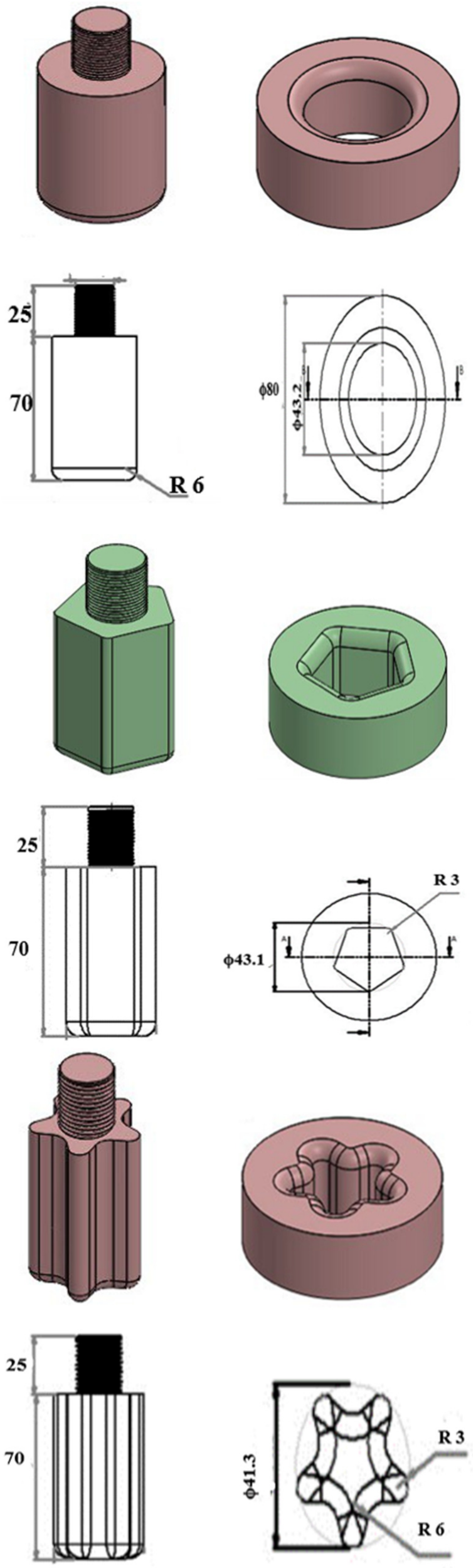


Fig. 4. (a) Tools employed to form a cylindrical cup through the drawing process, (b) drawing tools employed in forming the pentagonal cup, (c) the drawing tools used to forming pentacle shape.

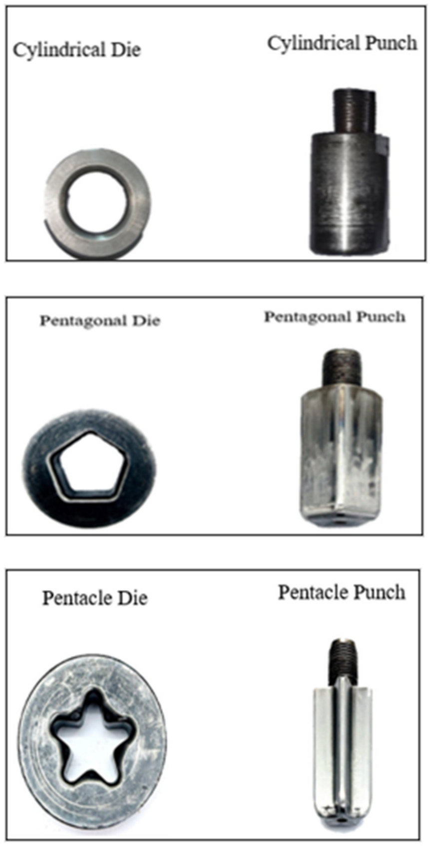


Fig. 5. Tools utilized in the experimental work.

TABLE II. TOOL DIMENSIONS FOR THE THREE METHODS

Cup	Punch	Die
Cylindrical cup	41.5 mm	43.2 mm
Pentagonal cup	41.4 mm	43.01 mm
Pentacle cup	41.3mm	43 mm

B. Materials

The present study involves using low-carbon steel for deep drawing the pentacle cup, which is known for its high formability compared to other types of steel. The material properties of low-carbon steel are presented in Table III, obtained by performing a tensile test on a Universal Testing Machine (UTM). The tensile test samples were prepared following ASTM standards, as depicted in Figure 6(a). The material's mechanical properties were evaluated in terms of the true stress-strain curve, as shown in Figure 6(b), which follows Hooke's law for elastic behavior. The normal anisotropy (r) and planar anisotropy (r) were determined by calculating the r-values along the three rolling directions (0°, 45°, and 90°) using (3) and (4), respectively. These calculations were performed to gain a better understanding of the material's anisotropy. The strain hardening exponent (n) was also determined employing the Hollomon equation [20, 21], which involved analyzing the load elongation data obtained from the tensile test.

$$\bar{r} = \frac{1}{4}(r_0 + 2r_{45} + r_{90}) \quad (3)$$

$$\Delta r = \frac{1}{2}(r_0 - 2r_{45} + r_{90}) \quad (4)$$

TABLE III. LOW-CARBON STEEL PROPERTIES

Rolling direction	Yield stress (MPa)	Lankford's coefficient r	Normal anisotropy coefficient r	Planar anisotropy Δr	Strain hardening exponent n
0	216	1.48	1.20	0.57	0.21
45	204	0.92			0.20
90	233	1.51			0.22

(a)

(b)

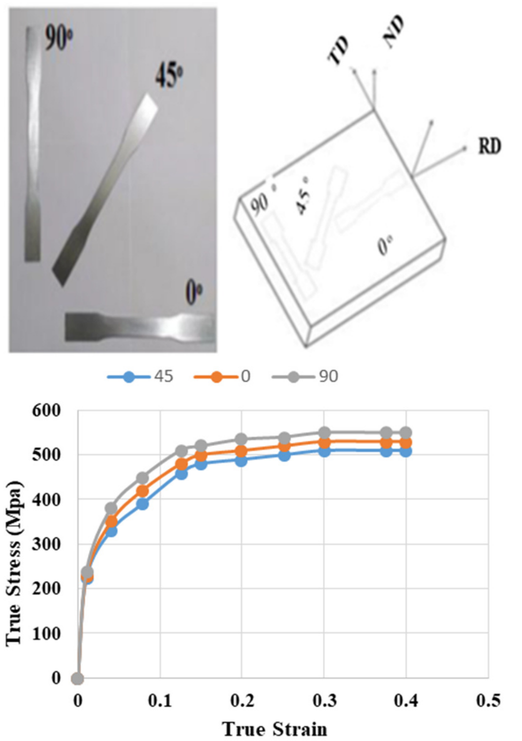
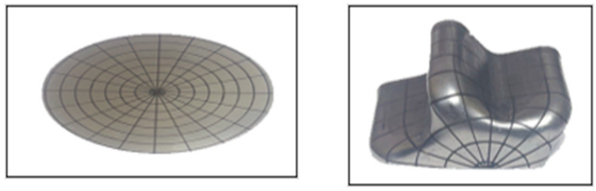


Fig. 6. (a) Tensile test specimens according to the rolling direction, (b) relationship between true stress-true strain curves at various angles to the rolling direction of the material.

C. Deep Drawing Operation

The drawing experiments for this study were conducted implementing a WDW200E testing machine with a maximum loading capacity of 200 kN and equipped with a computerized control unit that generated a load-displacement curve to monitor the material behavior during the deformation process. The drawing operation was carried out at a constant velocity of 250 mm/min. Three different methods were employed to create a pentacle cup with a height of 30 mm and dimensions of 41.3 mm. The first method, called the direct method, involves directly drawing the pentacle cup from a blank with an 80 mm diameter. This method involves the use of drawing tools, such as a punch and a die of pentacle forms to perform the drawing procedure. The second method, called the "convert" method, entails creating a cylindrical cup using a circular blank with 80 mm diameter. This cylindrical cup is then transformed into a pentacle cup through the redrawing process. The third method is a conversion process that produces a pentacle cup from a pentagonal polygon cup. To analyze the strain distribution within the cup during the drawing operation, a grid pattern of radii circles (5, 10, 15, 20, 25, 30, 35,... mm) was printed on undeformed blanks putting into service a mechanical grid marker. The grid pattern consisted of 8 intersecting lines that were 45 degrees apart. The drawn cup was divided into two parts to measure the cup wall thickness, as portrayed in Figure 7. During the deformation process, cup wall thickness and grid circle changes were measured with a digital thickness micrometer and a tool microscope. The cup thickness and length of the distorted grid radius were measured along 8 intersecting lines to obtain accurate and comprehensive data.



(a) (b)

Fig. 7. (a) Pentacle cup with deformed grids, (b) cup divided.

IV. ANALYSIS METHODS

The methodology adopted to investigate the deep-drawing process of the pentacle cup is based on [22–23]. The analytical model utilized in this investigation is based on several assumptions, including the neglect of elastic strains due to their relatively small magnitude in comparison with the plastic strains, the use of an isotropic material, and the assumption of Von Mises material with non-linear strain hardening. Additionally, the model assumes that the radial, circumferential, and thickness are principal directions, denoted as ρ, θ, and z, respectively. Bending and unbending effects are ignored since their impact is minimal when the die profile radius is compared to the sheet thickness. Furthermore, shear stress across the thickness is neglected, and a straight cup wall is assumed. The governing equations for the analytical model involve the definition of Von Mises stress, which is expressed as [24-26]:

$$\sigma_s = \left\{[(\sigma_\rho - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_\rho)^2]\right\}^{1/2} \quad (5)$$

Accurately predicting the behavior of the metal during a deep drawing process requires a comprehensive understanding of the plastic strains in the three principal directions: the circumferential direction (ε_ρ), thickness direction (ε_z), and radial direction (ε_θ). The corresponding strains can be expressed by:

$$\varepsilon_\theta = \ln\frac{\rho}{R}$$
$$\varepsilon_z = \ln\frac{S}{S_O} \quad (6)$$
$$\varepsilon_\rho = -(\varepsilon_\theta + \varepsilon_z)$$

The effective incremental strain is a significant parameter that defines the extent of deformation that takes place at every stage of the deep drawing process. Its value depends on several factors, such as the initial thickness of the blank (S_0) and the initial blank diameter (R). Mathematically, the effective incremental strain can be defined as:

$$d\varepsilon_i = \left\{\left[\left(d\varepsilon_\rho - d\varepsilon_\theta\right)^2 - (d\varepsilon_\theta - d\varepsilon_z)^2 - \left(d\varepsilon_z - d\varepsilon_\rho\right)^2\right]\right\}^{\frac{1}{2}} \quad (7)$$

The thinning estimate was theoretically anticipated in this research [27, 28]:

$$T = \frac{t - t_0}{t}\ 100\% \quad (8)$$

V. RESULTS AND DISCUSSION

The study employed three methods, (Figure 8), to create a pentacle shape with minimal defects. However, the figure reveals that the first method was unsuccessful in producing the desired shape, resulting in significant deformation, thinning, and tearing of the wall. On the other hand, the second and third methods were successful in producing pentacle cups with minimal defects by using different tool geometries and forming conditions to achieve the desired shape while minimizing the likelihood of defects. It is worth noting that the success of these methods is influenced by several factors, including material properties, tool geometry, and forming conditions. Figure 8 provides a helpful visual representation of the general trends observed in these forming methods. The figure emphasizes the importance of selecting appropriate forming methods to achieve the desired shape with minimal defects. This is particularly relevant for complex shapes like the pentacle, where significant deformation can result in material failure and defects. Therefore, manufacturers must carefully consider the intended application of the component and select the appropriate forming method to achieve the desired shape with minimal defects and resultant product quality.

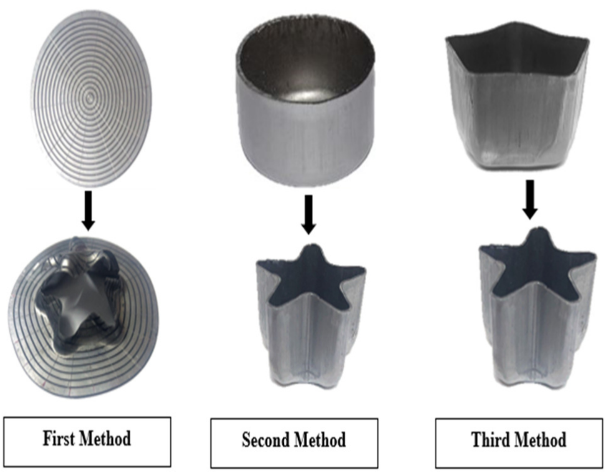


Fig. 8. The direct and convert methods of producing the pentacle shape.

Figure 9 compares the drawing forces and punch displacement of pentacle shapes produced by the second and third methods of deep-drawing operations. The purpose of these graphs is to illustrate the differences between the two methods in terms of the forces required and the punch displacement needed to create the pentacle shapes. This figure shows that the amount of force needed to create a pentacle shape by converting a cylindrical cup is greater than the force required to create the same shape by converting a pentagonal cup. The reason for this is that the process of bending and drawing the cylindrical cup into a pentacle shape increases the amount of deformation that the metal sheet undergoes, which, in turn, leads to more severe strain hardening and work hardening. This increased hardening of the metal makes it more resistant to deformation and thus requires more force to shape it. According to the data provided, the second forming method demands a maximum drawing force of 42.24 kN for the EXP model and 36.66 kN for the FEM model.

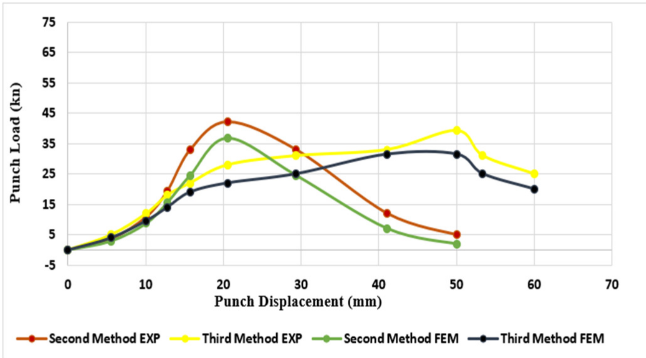
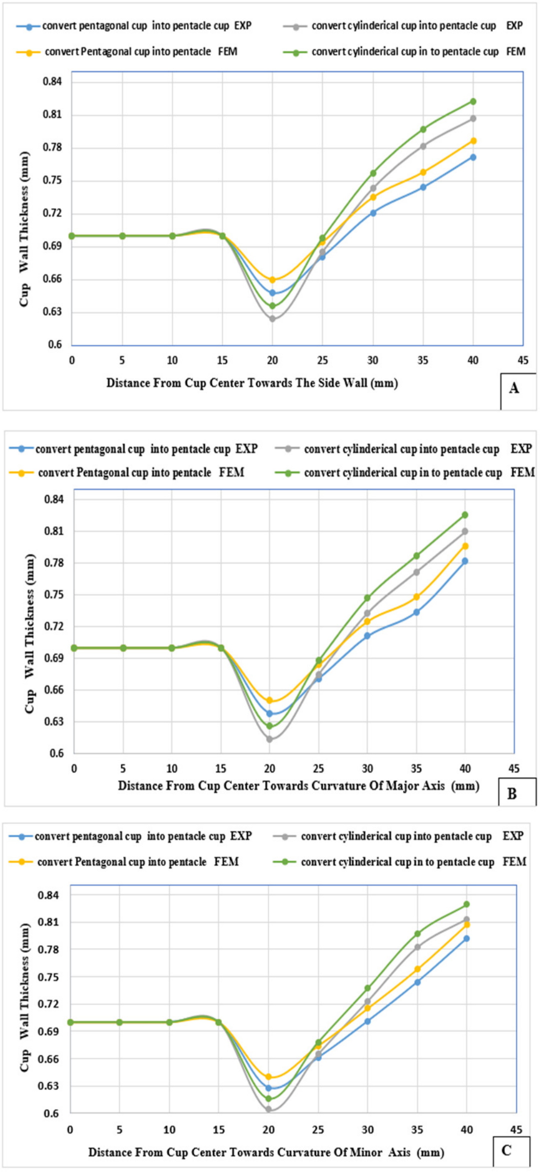


Fig. 9. The impact of the forming methods on drawing load.

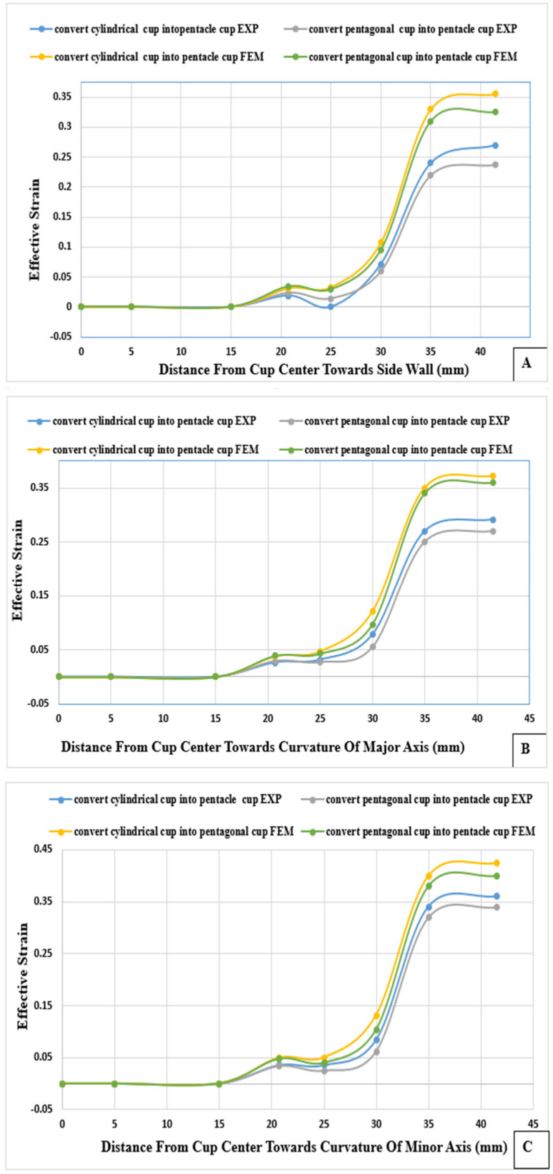
Figure 10 compares the thickness distribution along the sidewall and the curvature of the major and minor axes of the pentacle shape produced by different forming methods. The thickness variation was measured from the center of the cup's base to the highest point on the wall. Based on the diagram, it can be inferred that there is no alteration in the thickness at the bottom of the cup for both manufacturing techniques. This is primarily due to the influence of friction and drawing force, which play a crucial role in preventing any distortion underneath the flat surface of the punch. Thinning of the metal sheet occurs in the curved section of the cup on both major and minor axes. However, in the major axis, the metal sheet experiences less deformation due to the smaller circumference of the cup in that direction. As a result, the material is less thinned, and the wall thickness is thicker in this direction. Conversely, in the minor axis, the metal sheet undergoes more substantial deformation due to the larger circumference of the cup in that direction, resulting in a more significant thinning of the material and a thinner wall thickness. With the second forming method, the area where the maximum thickening was observed was at the end of the cup wall, towards the sidewall. This can be attributed to the presence of compressive hoop stress, which is more significant in this method, resulting in an increase in thickening.

Figure 11 portrays how different forming methods impact the distribution of equivalent strains across the cup wall, including the sidewall area, major axis curvature, and minor axis curvature. The figure indicates that the distribution of effective strain along the sidewall of the cup is generally uniform, with relatively low values compared to the major and minor axis curvatures, because the sidewall is typically a straight or nearly straight section of the cup and experiences less deformation than the curved sections. The major axis curvature of the cup wall generally experiences lower equivalent strain values than the minor axis curvature, as the material is compressed rather than stretched during this part of the forming process. Interestingly, maximum equivalent strains in the minor region of the cup were achieved with the second forming process. This suggests that the specific forming method can have a significant impact on the strain distribution across different areas of the cup wall. In summary, Figure 11 highlights the importance of carefully considering the forming method used in deep drawing processes and its impact on the distribution of equivalent strains across the cup wall. By optimizing the forming method, manufacturers can produce cups with the desired mechanical properties and final shape.



(a)
(b)
(c)

Fig. 10. Thickness distribution of the produced component versus forming methods.



(a)
(b)
(c)

Fig. 11. Strain distribution versus forming process.

VI. CONCLUSIONS

It is concluded that the first forming method cannot achieve a pentacle shape due to the induced excessive strain and stress on the material. The second forming method demonstrated the highest maximum load, surpassing the third method, due to more metal drawing and the higher percentage reduction. However, the third method exhibited greater strain hardness despite drawing less metal, leading to a lower maximum load. The finished product displayed the most favorable distribution of thickness, stresses, and strains when the third forming method was employed. Additionally, experimental outcomes and simulated results exhibited agreement, with an average discrepancy ranging from 5% to 25%. Finally, the major and minor areas at the cup wall's end experienced the highest effective strains due to maximum tensile stress imposed during the second forming method.

ACKNOWLEDGMENT

The authors express their gratitude for the support and encouragement provided by the Department of Production Engineering at the University of Technology throughout the project.

REFERENCES

[1] J. Jeswiet *et al.*, "Metal forming progress since 2000," *CIRP Journal of Manufacturing Science and Technology*, vol. 1, no. 1, pp. 2–17, Jan. 2008, https://doi.org/10.1016/j.cirpj.2008.06.005.

[2] D. Janardhan, "Determination and optimisation of cylindrical grinding process parameters using Taguchi method and regression Analysis," *International Journal of Engineering Science and Technology*, vol. 3, pp. 5659–5665, Jul. 2011.

[3] S. Reddy, S. Rajesham, R. R. Pinninti, and A. C S Reddy, "Evaluation of Limiting Drawing Ratio (LDR) in Deep Drawing by Rapid Determination Method," *International Journal of Current Engineering and Technology*, vol. 4, no. 2, pp. 757–762, Apr. 2014.

[4] K. Roll, "Simulation of sheet metal forming-necessary development in the future," in *LS-DYNA Anwenderforum*, German, 2008, pp. 59–68.

[5] J. Sutherland *et al.*, "A global perspective on the environmental challenges facing the automotive industry: State-of-the-art and directions for the future," *International Journal of Vehicle Design*, vol. 35, no. 1–2, pp. 86–110, Jan. 2004, https://doi.org/10.1504/ijvd.2004.004050.

[6] N. S. M. Namer, S. A. Nama, and J. W. Thabit, "Numerical and Experimental Study on Deep Drawing Process for AA2024-T4 Sheet," *Journal of Applied and Experimental Mechanics*, vol. 1, no. 1, pp. 1–9, 2015.

[7] P. V. R. R. Reddy, B. V. S. Rao, G. C. M. Reddy, and P. R. Prasad, "Parametric Studies on Wrinkling and Fracture Limits in Deep Drawing of Cylindrical Cup," *International Journal of Emerging Technology and Advanced Engineering*, vol. 2, no. 6, pp. 218–222, 2012.

[8] M. El Sherbiny, H. Zein, M. Abd-Rabou, and M. El shazly, "Thinning and residual stresses of sheet metal in the deep drawing process," *Materials & Design*, vol. 55, pp. 869–879, Mar. 2014, https://doi.org/10.1016/j.matdes.2013.10.055.

[9] S. Candra, I. M. L. Batan, W. Berata, and A. S. Pramono, "Analytical Study and FEM Simulation of the Maximum Varying Blank Holder Force to Prevent Cracking on Cylindrical Cup Deep Drawing," *Procedia CIRP*, vol. 26, pp. 548–553, Jan. 2015, https://doi.org/10.1016/j.procir.2014.08.018.

[10] U. Pranavi, P. J. Ramulu, C. Chandramouli, D. Govardhan, and P. R. Prasad, "Formability analysis of aluminum alloys through deep drawing process," *IOP Conference Series: Materials Science and Engineering*, vol. 149, no. 1, Jun. 2016, Art. no. 012025, https://doi.org/10.1088/1757-899X/149/1/012025.

[11] R. Dwivedi and G. Agnihotri, "Study of Deep Drawing Process Parameters," *Materials Today: Proceedings*, vol. 4, no. 2, Part A, pp. 820–826, Jan. 2017, https://doi.org/10.1016/j.matpr.2017.01.091.

[12] B. Mulyanto and D. S. Khaerudini, "Simulation and Experimental Investigation of Wrinkle Defect in Deep Drawing Process of Carbon Steel Spcc Shaped Cylinder Flange Cup," *Sinergi*, vol. 24, no. 3, pp. 197–206, 2020, https://doi.org/10.22441/sinergi.2020.3.004.

[13] A. K. Choubey and C. Sasikumar, "Effect of Anisotropy, Temperature, Strain Rate on Deep Drawing Using Conical Die," *Journal of Metallic Material Research*, vol. 3, no. 1, pp. 20–24, Apr. 2020, https://doi.org/10.30564/jmmr.v3i1.920.

[14] Y. Harada, Y. Nishikubo, and I. Tanaka, "Drawability of Functional Corrugate Cup Using Roller Die," *Materials Transactions*, vol. 61, no. 2, pp. 222–227, 2020, https://doi.org/10.2320/matertrans.MT-ML2019004.

[15] S. Pandre, N. Kotkunde, A. Morchhale, S. K. Singh, and A. Saxena, "Comparative study of formability characteristics in deep drawing of DP 590 steel using analytical models," *Advances in Materials and Processing Technologies*, vol. 8, no. sup3, pp. 1730–1740, Oct. 2022, https://doi.org/10.1080/2374068X.2021.1945273.

[16] W. Rajhi, "Numerical Simulation of Damage on Warm Deep Drawing of Al 6061-T6 Aluminium Alloy," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4830–4834, Oct. 2019, https://doi.org/10.48084/etasr.3148.

[17] S. L. Semiatin, *ASM Handbook, Volume 14B: Metalworking: Sheet Forming*. Almere, Netherlands: A S M International, 2006.

[18] "Home," *ASM International*. https://www.asminternational.org/.

[19] W. Jawad and A. Ikal, "Effect of Radial Clearance on Stress and Strain Distribution in the Astral Deep Drawing," *Engineering and Technology Journal*, vol. 37, no. 8A, pp. 332–340, Aug. 2019, https://doi.org/10.30684/etj.37.8A.4.

[20] Schuler, *Metal Forming Handbook*. Berlin, Germany: Springer, 1998.

[21] D. Ravi Kumar, "Formability analysis of extra-deep drawing steel," *Journal of Materials Processing Technology*, vol. 130–131, pp. 31–41, Dec. 2002, https://doi.org/10.1016/S0924-0136(02)00789-6.

[22] W. Rajhi, B. Ayadi, A. Alghamdi, and N. Messaoudene, "An Anisotropic Elastic-plastic Model for the Optimization of a Press Machine's Auxiliary Worktable Plate Thickness," *Engineering, Technology & Applied Science Research*, vol. 8, no. 2, pp. 2764–2769, Apr. 2018, https://doi.org/10.48084/etasr.1934.

[23] W. Khalid Jawed and S. Salman Dawood, "Drawing of Hexagonal Shapes from Cylindrical Cups," *Engineering and Technology Journal*, vol. 34, no. 6A, pp. 1235–1246, Jun. 2016, https://doi.org/10.30684/etj.34.6A.17.

[24] M. J. Jweeg, A. I. Mohammed, and M. S. Jabbar, "Investigation of Thickness Distribution Variation in Deep Drawing of Conical Steel Products," *Engineering and Technology Journal*, vol. 39, no. 4A, pp. 586–598, Apr. 2021, https://doi.org/10.30684/etj.v39i4A.1908.

[25] J. Hu, Z. Marciniak, and J. Duncan, *Mechanics of Sheet Metal Forming*. Oxford, UK: Butterworth-Heinemann, 2002.

[26] W. F. Hosford and R. M. Caddell, *Metal Forming: Mechanics and Metallurgy*, 3rd edition. Cambridge, MA, USA: Cambridge University Press, 2007.

[27] A. Rastbood, Y. Gholipour, and A. Majdi, "Finite Element Based Response Surface Methodology to Optimize Segmental Tunnel Lining," *Engineering, Technology & Applied Science Research*, vol. 7, no. 2, pp. 1504–1514, Apr. 2017, https://doi.org/10.48084/etasr.1045.

[28] E. A. Abbas and K. K. Mansor, "Numerical and Experimental Investigation of the Effect of Strength of Aluminum 6061 Alloy on Thickness Reduction in Single-Point Incremental Forming," *Advances in Science and Technology. Research Journal*, vol. 17, no. 4, pp. 271–281, Aug. 2023, https://doi.org/10.12913/22998624/170713.

[29] A. S. Bedan, A. H. Shabeeb, and E. A. Hussein, "Improve Single Point Incremental Forming Process Performance Using Primary Stretching Forming Process," *Advances in Science and Technology. Research Journal*, vol. 17, no. 5, pp. 260–268, Oct. 2023, https://doi.org/10.12913/22998624/172907.