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The influence of different forming techniques on the performance and outcomes of the deep drawing process for intricate geometries

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ABSTRACT

This study explores the creation of a complex, eight-vertex shape through a deep-drawing process using two distinct approaches. The first, known as the direct method, involves forming the desired shape directly from metal sheets. The second approach, referred to as the indirect method, requires an intermediate step where a cylindrical shape is initially drawn and then reshaped into the final complex form through a redrawing process. A comparison was conducted between the two methods to evaluate their performance in terms of drawing force, thickness distribution, as well as stress and strain behavior. Low-carbon steel (1008-AISI) sheets with a thickness of 0.7 mm and a diameter of 80 mm were utilized for the experiments. The simulation of these processes was carried out using ANSYS 18.0 software. The findings revealed that the maximum drawing force recorded during the direct drawing process was 41 KN (experimental) and 30 KN (finite element simulation). Additionally, the redrawing process led to an increase in effective stress and strain, reaching peak values of 835.23 MPa (stress) and 0.442 (strain, simulation) or 0.345 (strain, experimental) in the minor axis curvature region. The redrawing process also resulted in the most significant thinning of 7.143% (simulation) and 5.722% (experimental) at the same curvature zone. The direct drawing process, however, exhibited superior uniformity in thickness, stress, and strain distributions.

Keywords: formability, low carbon steel, cylindrical shape, sheet metal forming, deep drawing.

INTRODUCTION

The deep drawing process involves shaping a flat sheet of metal into various forms by pulling it radially into a die cavity using a punch. In this method, the metal sheet, or blank, is placed over the die, and a blank holder is applied to secure the workpiece. While the punch deforms the metal plastically to create the desired shape, excessive stress beyond the material's yield strength can lead to failure. However, if the applied stress stays within the yield limit, the process remains effective, adhering to the forming principles [1]. When drawing complex shapes, the risk of failure increases due to the challenging material flow. In such cases, the deep drawing process can be carried out in either a single-stage or a multi-stage method. In the first case, the sheet is formed directly into the final complex shape in one operation. However, achieving sufficient depth may be difficult. Alternatively, a multi-stage method can be employed to enhance formability. In this case, the first stage involves forming the sheet into a simple cylindrical cup, which is then further transformed into the desired complex shape in subsequent stages [2].

Numerous studies have explored factors influencing single and multi-stage forming techniques. Narayanasamy and Loganathan [2] investigated the formation of cylindrical components from circular metal sheets using conical dies and flat-bottomed punches. Their findings highlighted that conical dies achieve a higher draw ratio compared to traditional methods. Additionally, the use of conical dies eliminates the need for blank holders or clamping rings, which can reduce issues like wrinkling or buckling of the sheet metal. Notably, thicker sheets did not exhibit wrinkling when processed with conical dies.

Azam et al. [3] proposed an innovative approach to enhance the formability of square cups in deep drawing without requiring blank holders or draw beads. This method utilized a conical die with a square aperture and a flat-headed square punch. Results demonstrated the capability to produce square shapes with a higher draw ratio than conventional techniques for both aluminum and brass. Furthermore, the new approach required less drawing force, minimizing defects associated with excessive force, and enhancing the overall efficiency of the forming process. Abdullah et al. [4] introduced an innovative approach to crafting elliptical shapes, using flat-headed elliptical punches and conical dies with elliptical apertures, all without relying on blank holders or draw beads during the drawing process. Their findings highlighted that this method outperformed traditional drawing techniques. Notably, the conical cups produced with this configuration were defect-free, showcasing the method's efficiency.

In another study, Walid et al. [5] explored a novel way to produce square shapes by altering the geometry of the die. They used a conical die with a square aperture in combination with a square punch. This modification aimed to achieve a higher limit drawing ratio compared to conventional methods employing square dies and punches. By adopting this technique, the researchers successfully minimized the defects commonly associated with traditional methods.

Adnan and Ali [6] focused their research on the influence of punch wall corner radius, sheet thickness, and drawing speed on the deep drawing of hexagonal cups. Their experimental and simulation results showed that the most significant thinning occurred at the cup corners when the punch radius was 1 mm. Conversely, maximum thickening was observed at the cup edges when the punch radius was 7 mm. Additionally, the largest strain values-radial, hoop, thickness, and effective-were recorded at the cup's edge with a 7 mm punch radius.

Abdullah [7] proposed a reverse drawing method for multi-stage deep drawing to create cylindrical shapes. This technique demonstrated superior performance over traditional drawing processes, yielding products with reduced strain hardening, minimal thinning, and lower stress concentrations in curved areas. Furthermore, the reverse drawing method allowed for fewer stages, ultimately lowering production costs.

Kadhim and Waleed [8] investigated the deep-drawing process for producing spline-shaped components through both experimental work and finite element modeling. Their study analyzed the impact of punch wall curvature radius on drawing force and thickness distribution. Results revealed strong alignment between experimental and numerical findings, with deviations averaging 4%–8%. The drawing force and thinning were higher for punches with smaller wall curvature radii, with the maximum force and thinning observed at a radius of 0.5 mm. Araveeti [9] addressed the optimization of blank design for square cup formation, employing finite element simulations and experiments with 1 mm thick deep-drawing quality cold-rolled steel sheets. The primary goal was to maximize drawing depth while avoiding fractures and failures. The study concluded that an almost circular blank profile was optimal for square cup production, offering the best balance between depth and structural integrity.

In this current research, the design and development of dies for creating a complex eight-vertex shape were investigated. Two methods were tested: the direct approach, where the complex shape was drawn directly from a blank, and an alternative method, which involved first producing a cylindrical shape and then transforming it into the desired complex form. These methods were compared according to drawing force, thickness distribution, and stress and strain distribution. The indirect method outperformed the direct method in several key areas, such as drawing force, thickness distribution, and stress and strain distribution. The findings offer valuable insights for advanced die design and forming processes. Additionally, these findings will be utilized in future studies to analyze various process conditions and optimize deep drawing operations.

Numerical simulation

To create intricate shapes with dimensions of 41.5×34.69 mm and a height of 30 mm, numerical simulations were carried out using two techniques: the drawing process and the redrawing process. The simulations were performed using ANSYS 18.0 software. For the drawing process, both the flat metal sheet and the tools involved (punch, die, and blank holder) were modeled in 3D. Similarly, the redrawing process involved a cylindrical metal blank and tools (punch and die), also modeled in 3D [10–16]. The metal blanks for both processes were treated as solid models, as were the tools involved in each stage, as illustrated in Figure 1. The 3-D 8-node structural solid element of (SOLID185) has been utilized for blank. while the tool set has been considered as rigid bodies. to accurately capture the complex interaction between blank and tooling, an automatic contact procedure has been utilized. For rigid -flexible contact, TARGE170 elements have been utilized to define 3D target surfaces. These were associated with the deformable body (blank) represented by 3D 8-node contact elements of CONTA174.

The meshing for all components was done automatically. For the tools in both methods, a body sizing of 2 mm was applied, while a tetrahedral mesh with the same element size was used for the sheet material in the drawing process and the cylindrical blank in the redrawing process, as depicted in Figure 2. The contact surfaces between the blanks and the tools were identified, and the contact was set up automatically for both processes, as shown in Figure 3.

To ensure a realistic simulation and simplify the solution procedure, the following boundary conditions were applied: The blank material's temperature was assumed constant, with no heat transfer occurring between the blank and the tools, as thermal effects were considered negligible within the deformation timescale (quasi static analysis). The tools (punch, die, and blank holder) were modeled as rigid bodies, as their deformations were minimal compared to the workpiece and did not significantly influence the forming process. The punch moved vertically (y-axis) at a steady speed of 50–100 mm/min, ensuring a controlled and realistic forming rate. The die remained stationary, providing a stable reference. The blank was allowed to move freely in all directions, ensuring an accurate

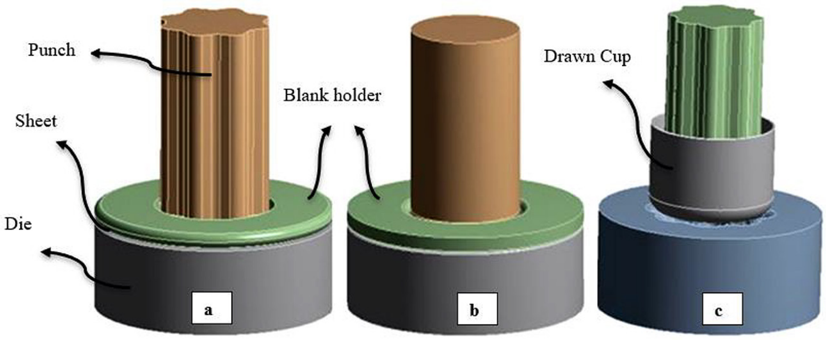

Figure 1. Illustrates the engineering designs of the drawing dies as modeled and analyzed using the ANSYS Workbench software, (a) forming desired shape directly from the blank, (b) first forming a cylindrical shape and then, (c) transforming it into desired shape

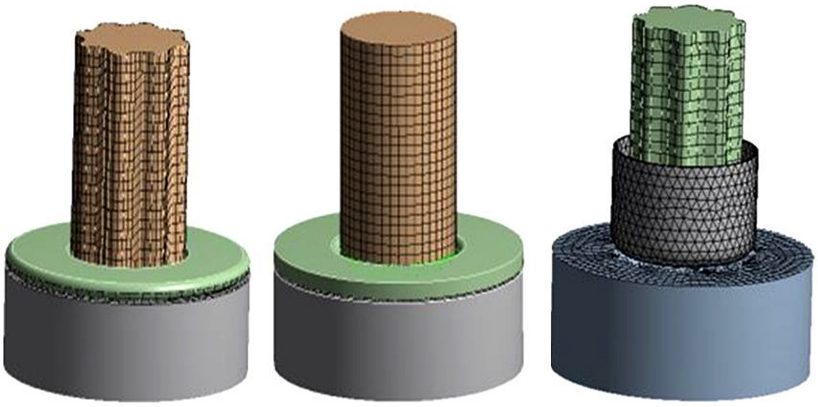

Figure 2. Illustrates the meshing setup for the models of drawing and redrawing dies, which was carried out using the ANSYS Workbench software

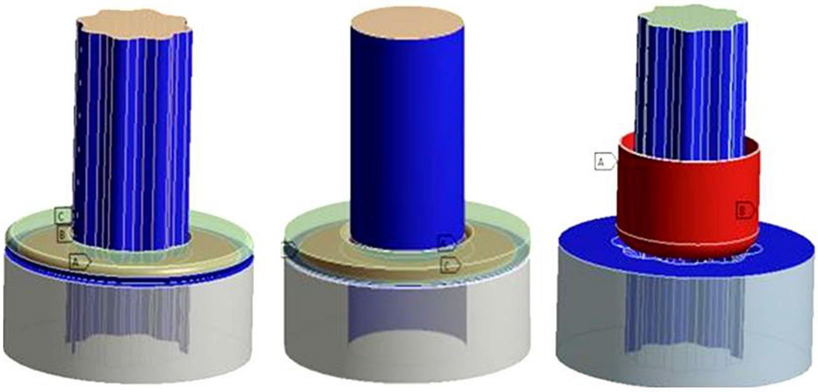

Figure 3. Illustrates the modeling process for drawing and redrawing dies using ANSYS Workbench. It demonstrates how the contact interactions are set up and analyzed, providing insights into the simulation workflow for these dies

representation of material flow without artificial constraints that could affect the deformation behavior. These simplifications were made to reduce computational complexity while maintaining accuracy, as validated by prior studies in deep drawing simulations. These conditions were established to accurately replicate the real-world processes, ensuring the analysis closely mirrors practical scenarios.

Additionally, a constant friction coefficient ($\mu = 0.1$) was applied under dry conditions, both at the interface between the tools and the blank during the first stage and between the tools and the formed cup during the drawing and redrawing stages. The boundary conditions for these simulations were implemented using ANSYS Workbench, as seen in Figure 4. The sequential stages of forming the complex shape are demonstrated in Figure 5.

EXPERIMENTAL PROCEDURE

Material selection

For the experimental procedure, cold-rolled low carbon steel (1008-AISI) sheets with a thickness of 0.7 mm and a diameter of 80 mm were selected. The chemical composition of these sheets is provided in Table 1. To ensure precise simulation results during the drawing and re-drawing processes, tensile specimens were prepared from both the flat metal sheets and the cylindrical shapes. These specimens were carefully cut using a wire-cut EDM machine, as illustrated in Figure 6. Table 2 summarizes the mechanical properties of both the blank sheets and the cylindrical shapes. From the findings from the table, there are some differences in mechanical properties in these cases. The differences arise because, in the second case (cylindrical

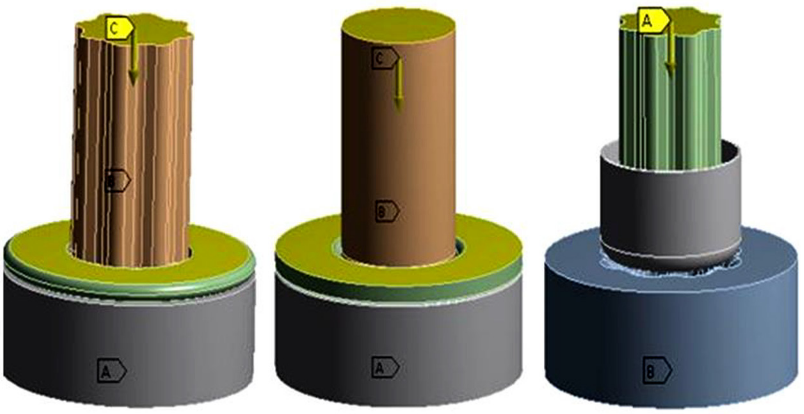

Figure 4. illustrates the boundary conditions applied to the simulation models for drawing and redrawing dies in ANSYS Workbench. These conditions were established to accurately replicate the real-world processes, ensuring the analysis closely mirrors practical scenarios

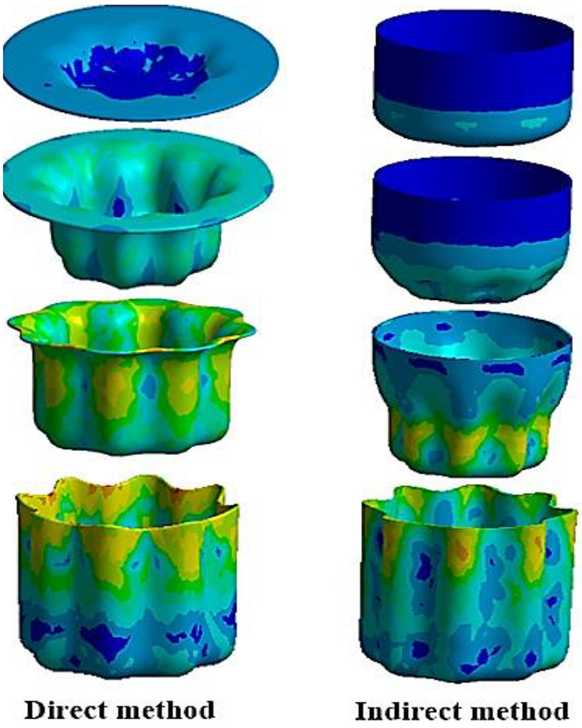

Figure 5. Illustrates the different stages involved in creating the complex cup using both direct and indirect methods

workpiece type), the metal has already undergone forming processes for creating the cylindrical part (transform from sheet into cup). These prior operations change the material properties due to strain distribution and work hardening. While, in the first case (sheet type) involves direct forming from a flat sheet, which has not been previously shaped. As a result, differences in mechanical behavior are observed between the two cases. The process parameters used in this study remained constant for both cases. A drawing speed of 100 mm/min was used, and the experiments were conducted under dry conditions (without lubrication between blank and tool). Keeping these parameters unchanged ensured a fair comparison between the two cases, allowing the influences of the forming techniques to be accurately analyzed.

Experimental test

The process for creating complex shapes begins by positioning the drawing tool on the Universal Testing Machine (WDW200E) model. Both drawing and re-drawing procedures were carried out using a cylindrical die with intricate details, as depicted in Figure 7.

To produce the complex shapes measuring 41.5×34.69 mm in area and 30 mm in height, two methods were employed. The first, known as the direct drawing process, involves creating the shapes directly by drawing metal sheets using the specialized die. The second approach, the indirect method or redrawing process, starts with a cylindrical shape that is first drawn from metal sheets and then further shaped using both cylindrical and complex dies, as illustrated in Figure 8. It should

Table 1. Shows the composition of elements in low carbon steel

	C%	Si%	Mn%	P%	Cr%	Ni%	Mo%	Cu%
Testing	0.062	0.026	0.169	0.016	0.055	0.035	0.002	0.006
AISI	>=0.08	0.01	0.25-0.4	>=0.04	>=0.05			

Figure 6. The tensile test specimens were taken from sheets of metal and cylindrical shapes according to ASTM standard E8M specification

Table 2. Mechanical properties of tensile test specimens were taken from sheet metal and cylindrical cups

Method	Yield stress (MPa)	Ultimate tensile stress (MPa)	Tangent modulus (GPa)
Direct	226	380	0.5
Indirect	308	515	0.72

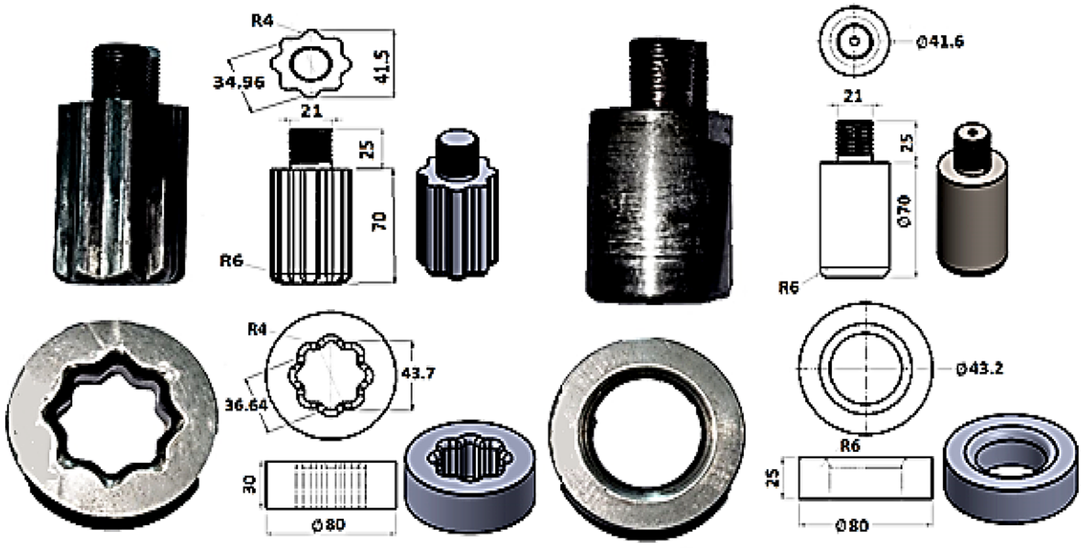

Figure 7. The shapes and geometries of the dies and punches used for direct and indirect methods

be noted that the indirect method needs a greater number of tools to complete the process. This is because it first necessitates cylindrical-shaped punch and die to form the sheet into cylindrical cup. Then, additional tools (another punch and die) are needed to further transform the cylindrical into the desired intricate shape. therefore, the cost associated tom manufacturing these tools in the indirect forming are high compared to direct one.

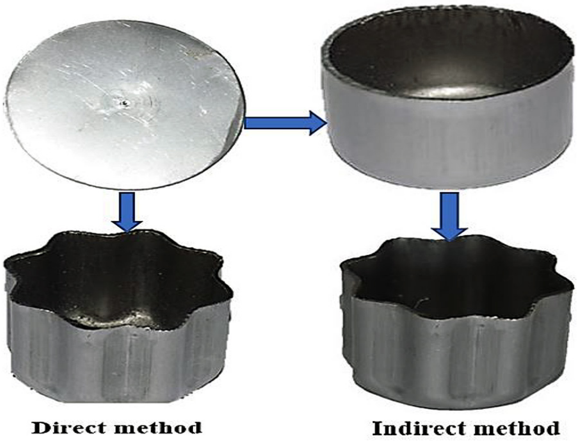

Figure 8. The complex cup is produced in direct and indirect ways

Strain measurement

To evaluate the stress and strain limits within the acceptable range for products created through the forming process, grids measuring 2.5×2.5 mm were etched onto the surface of the sheet metal using a fiber laser, as depicted in Figure 9A. Following the drawing and re-drawing steps, the dimensions of the grids changed, as shown in Figure 9B. The dimension changes of the grids were measured using a projector profile device. To assess the thickness change, the shape was cut into two halves, and the thickness was compared to the original grid dimensions before the forming process. The thickness strain, radial strain, hoop strain, and effective strain were then calculated using equations (1, 2, 3, and 4), respectively [17–18].

$$\epsilon_t = ln\frac{t}{t_\circ} \tag{1}$$

$$\epsilon_r = ln\frac{R}{R_\circ} \tag{2}$$

$$\epsilon_\theta = -(\epsilon_r + \epsilon_t) \tag{3}$$

$$\epsilon_{eff} = \sqrt{\frac{2}{3}(\epsilon_r{}^2 + \epsilon_\theta{}^2 + \epsilon_t{}^2)} \tag{4}$$

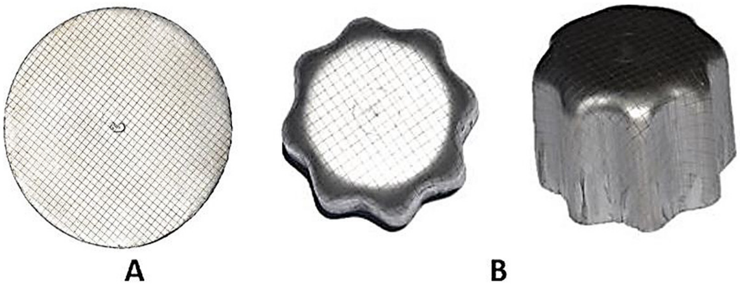

Figure 9. The grid's square before and after distortion

RESULTS AND DISCUSSION

Figure 10 illustrates the relationship between drawing force and displacement during the drawing and redrawing process, from start to finish. As shown, the drawing and redrawing forces initially rise until they reach a peak, after which they decrease. This trend occurs because friction between the sheet metal surface and the punch is reduced during both processes. In the drawing process, friction decreases as the sheet is drawn, while in the redrawing process, it is affected by the cylindrical base shape and the punch. The maximum drawing force occurs during the drawing process, surpassing the redrawing force in both experimental and simulation tests. This is due to the fact that redrawing involves more bending and strain hardening, and its reduction percentage is lower compared to the drawing process. Figure 11 displays the impact of the forming process on the thickness distribution along the sidewall, and the curvature of the major and minor axes of a fully drawn shape, measured through both numerical simulations and experimental methods. The thickness change is tracked from the center of the shape to its rim, as well as along the minor and major axis curvatures and sidewalls. The figure shows no variation in the thickness at the shape base after the drawing and redrawing process, as friction between the punching noise and the base helps prevent distortion. However, the thickness decreases near the corners, indicating difficulty in metal flow due to maximum stress concentration in that region. Thickness then varies along different areas due to changing tension levels, with more thickening observed at the throat, particularly in the minor axis curvature, during the redrawing process due to compressive hoop stress.

Figure 12 focuses on the effective strain distribution along the sidewall and curvatures of

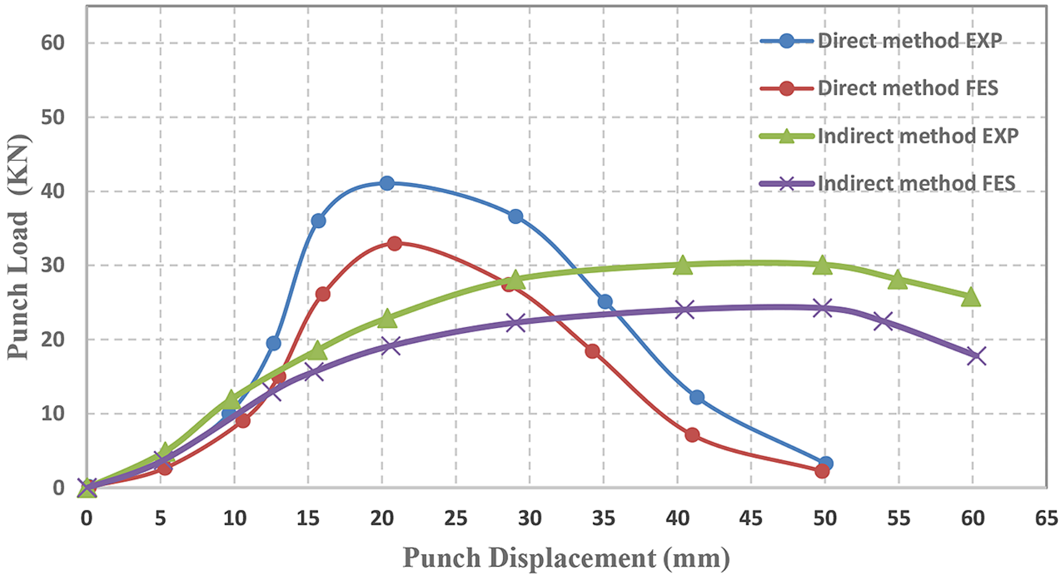

Figure 10. Effect of the drawing and redrawing process on the relationship between drawing force and displacement

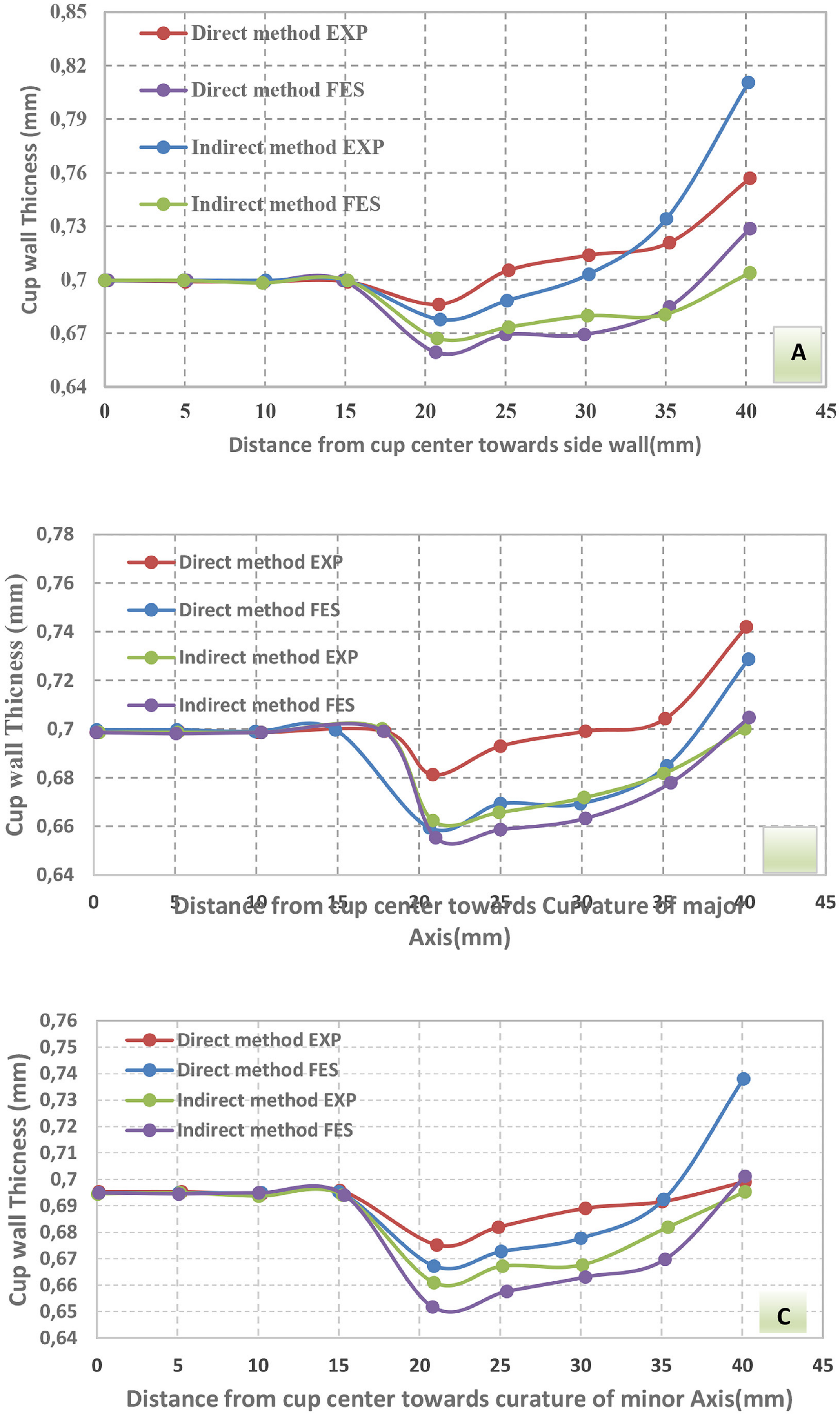

Figure 11. (A, B and C): Shows the effect of the drawing and redrawing process on thickness distribution

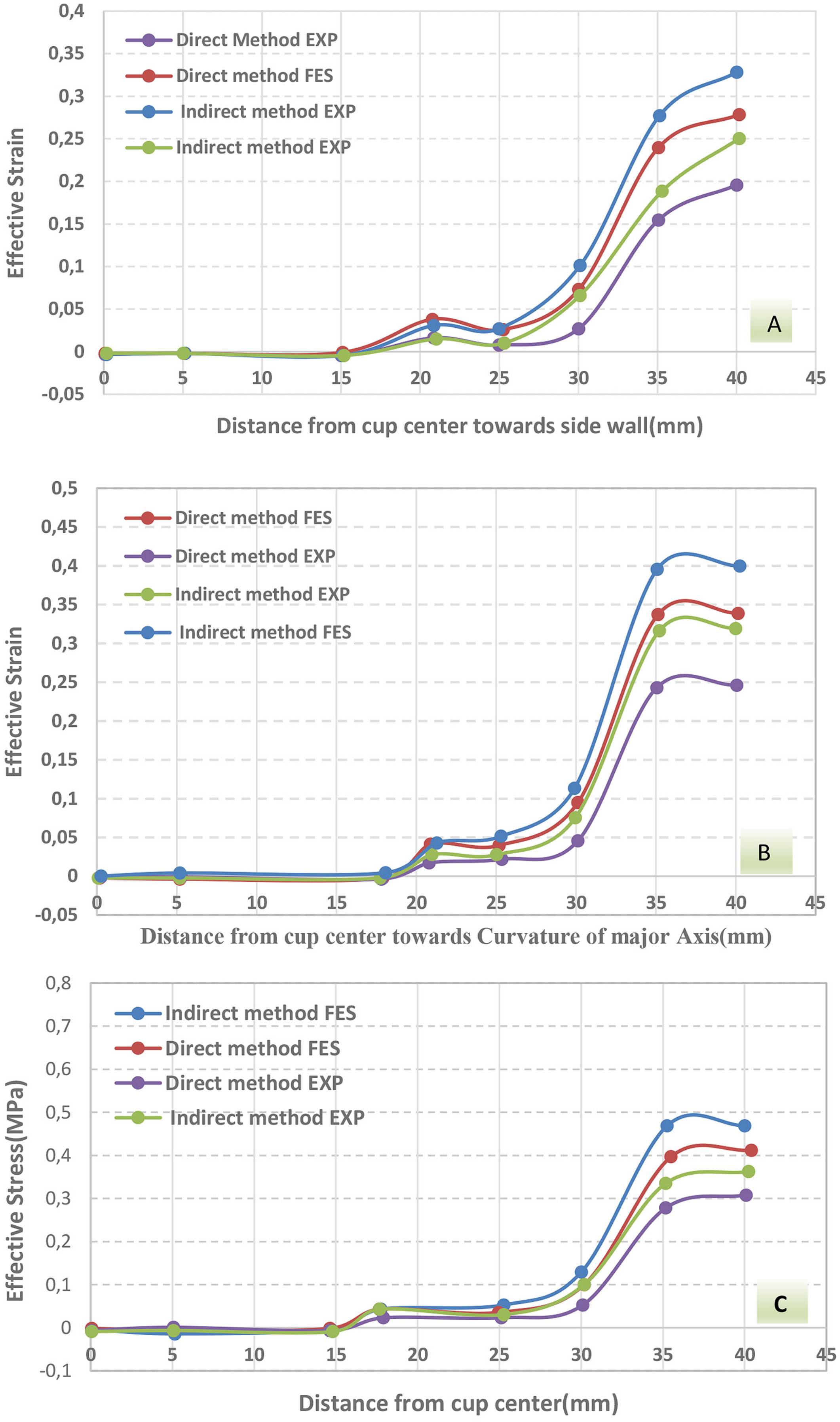

Figure 12. (A, B and C): Shows the effect of the drawing and redrawing process on effective strain distribution

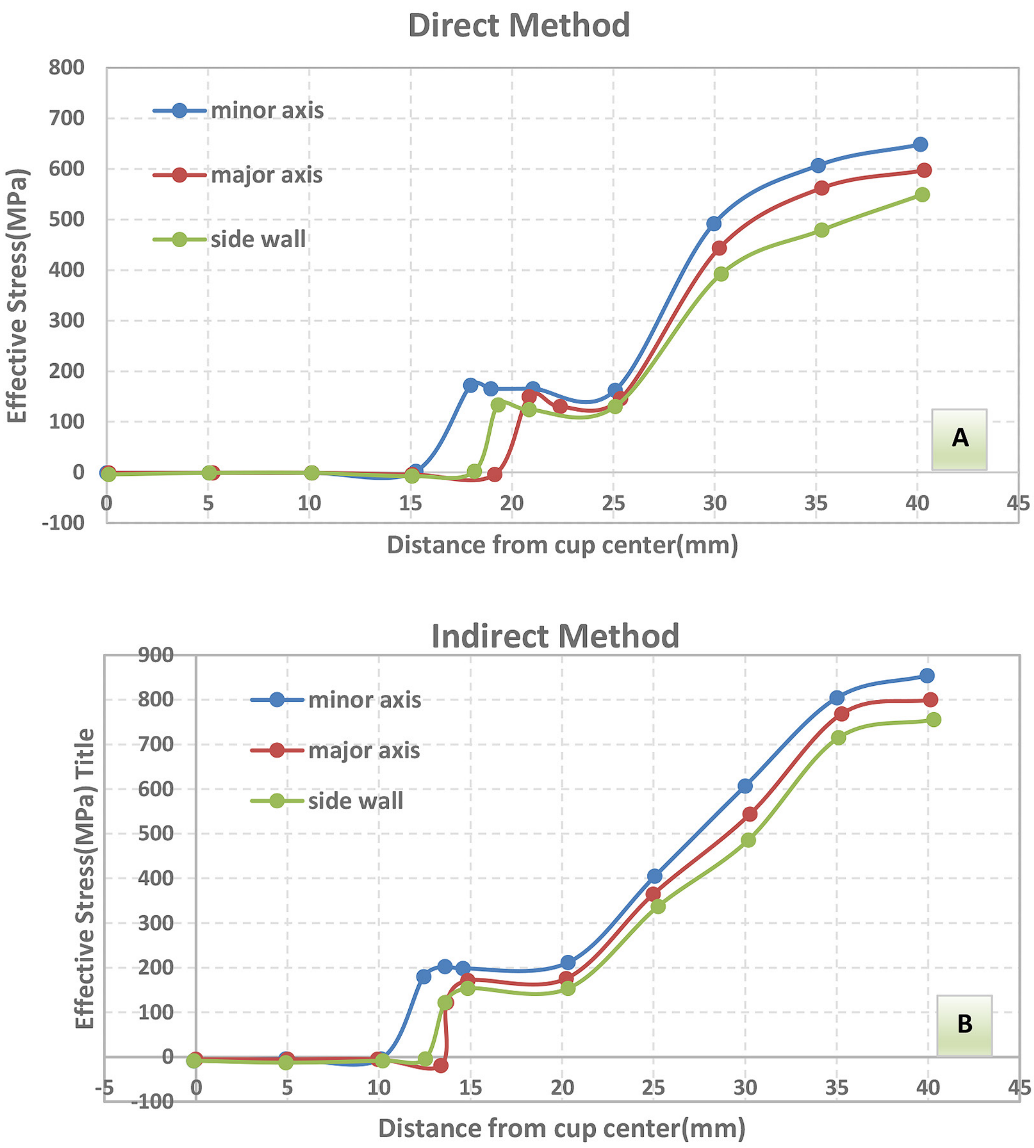

Figure 13. (A , B): Shows the effect of the drawing and redrawing process on effective stress distribution

the major and minor axes in a completely drawn shape, based on both numerical simulations and experimental results. Effective strain is measured from the center to the rim, with the strain being zero at the base. This occurs due to friction preventing distortion between the sheet metal and the punch for the drawing process, and between the base of the cylinder cup and the punch in the redrawing process. The effective strain increases toward the shape's end, reaching its peak at the minor axis curvature in the redrawing process, where tensile stress is highest.

Figure 13 addresses the effective stress distribution along the sidewall and curvatures of the major and minor axes in a fully drawn shape, based on both numerical simulations and experimental work. The results indicate that equivalent stress is zero beneath the flat face of the punch in both methods. Effective stress then increases, reaching its highest point at the top of the shape, with values varying across the wall. Notably, the stress distribution along the sidewall in the redrawing process and the drawing process both follow similar patterns, but with different magnitudes, peaking at the top, especially near the minor axis curvature in the indirect method.

The summarized results revealed that the maximum drawing force recorded during the direct drawing process was 41 KN in the experimental results and 30 KN in the finite element simulation. Additionally, the redrawing process led to an increase in effective stress and strain, with peak values of 835.23 MPa (stress) and 0.442 (strain, simulation) or 0.345 (strain, experimental) in the minor axis curvature region. Moreover, the redrawing process also resulted in the most significant thinning of 7.143% (simulation) and 5.722% (experimental) at the same curvature zone. The direct drawing process, however, exhibited superior uniformity in thickness, stress, and strain distributions. These results agree well with [19, 20].

CONCLUSIONS

Two methods were used to create a complex shape: the direct method and the indirect method. A comparison of these methods led to the following conclusions:

- The direct method was found to be more cost-effective than the indirect method, particularly in terms of mold and laboratory expenses.
- The indirect method outperformed the direct method in several key areas, such as drawing force, thickness distribution, and stress and strain distribution.
- The direct method is not ideal for producing complex shapes in multi-stage drawing processes, as it is challenging to maintain proper alignment between the die and the product.
- However, the direct method works well for cylindrical shapes in multi-stage drawing processes, as centering control between the die and the product is easier.
- The highest drawing force occurred with the direct method, which was greater than that of the indirect method. This is because the indirect method involves more bending, while the direct method focuses on drawing.
- The maximum thinning of thickness was observed with the direct method due to the drawing of cylindrical shapes from metal sheets, followed by redrawing to form the complex shape.

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