The Procedure of Experimental Work and Finite Element Simulation to Produce Spline Shape Multi-Stage Deep-Drawing Operation

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Abstract. This research deals with a multi-stage deep-drawing operation. The research aim is to produce spline shapes using two methods (direct and indirect) for three-stages based on experimental work and FE model procedure. The direct method was performed to produce spline shapes from the blank for the first stage, while the second and third stages from shapes of the first and second stages, respectively. The indirect method was performed to produce spline shapes from the cylindrical shapes of three-stages. The multi-stage deep-drawing was completed to perform the experimental procedure required to produce a spline shape with inner dimensions of major axis \( D = 41.5, 33.3, 28.8 \) mm, and minor axis \( d = 34, 27.2, 23.6 \) mm for the first, second, and third stages, respectively. Flat circular blanks (diameter \( D_b = 80 \) mm and thickness \( t = 0.7 \) mm) of low carbon steel (1008 – AISI) used in this research. FE analysis based on the ANSYS workbench program was used to model the multi-stage deep-drawing operation. The comparisons between results showed that the direct method was successful with the first stage, while it was failed with the second and third stages. For the three-stages, the maximum drawing force required to produce spline shape by the direct method is greater than the maximum drawing force required to produce spline shape by the indirect method. The maximum drawing force values equal to 41,650 kN, 33,175 kN, 33,11 kN for the first, second, and third stages, respectively. Also, for the three-stages, it was observed that it is possible to produce a complete spline shape without defects in the indirect method when comparing with the direct method.

Keywords. spline shapes, multi-stage deep-drawing operation, direct and indirect method, thickness, and strain distribution.

1. Introduction
The deep-drawing process is commonly using the sheet metal forming process. By which, hollow parts with various shapes are produced in one-stage drawing or multi-stage drawing, often having ample applications in automotive body panels, aerospace, electronics, and packing industries, etc. In the forming of parts that have geometrical complexity or flammability problems and cannot be formed by one-stage forming, multi-stage drawing processes are usually applied. Many research studies dealt with the multi-stage deep-drawing operation. AL- Gharrawi and Tuaimah [1] conducted a study to investigate the influence of the sheet thickness on a multi-stage deep-drawing operation for hexagonal shape using experimental work and numerical simulation. The results showed that the maximum drawing force decreases with the progression of drawing stages, higher thinning take place in the
shape profile region with the sheet thickness equal to \( t = 0.5 \text{ mm} \) (initial sheet thickness), and higher thickening takes place on the rim shape with the sheet thickness \( t = 1.2 \text{ mm} \) (initial sheet thickness). The multi-stage deep-drawing processes of square cups of pure titanium were investigated by Harada and Ueyama [2]. The results of both experimental and FE simulation showed that the pure titanium sheet was successfully drawn without cracks at the second stage, while at the third stage, the cracks were observed on the filet. Kim et al. [3] investigated scratch modeling of paint-coated sheet metal for a multi-stage deep-drawing process considering the contact pressure, the accumulated slip distance between the blank and dies, and the accumulated friction work. From the investigation results, it was found that the accumulated slip distance could be used to distinguish the scratched and non-scratched regions. In contrast, both of the maximum contact pressure and the accumulated friction work could not be used for this purpose. Younis et al. [4] studied the multi-stage deep-drawing process of cylindrical shape using the FE method. The produced cup wall thickness and the strain distribution along the cup wall of carbon steel (AISI 1008) had been evaluated. It was found that under the punch filet radius, more lamination appears in the area attributed to severe stretch at this area in the first stage, while increased lamination at the cup wall was taking place in the second and third stages. Jabbari1a and Basaki [5] carried out a three-steps deep-drawing process to optimize the sizes such as the punch diameter at each step, friction, clearance, and punch and die corner radius. To reduce the drawing step's number, i.e., from three-steps to two-steps deep-drawing operation, to remove the third step, the Taguchi design of experiment method was coupled with the FE analysis method. The constraints are uniform of cup thickness and minimum residual stress. Tetzel et al. [6] carried out a multi-stage micro deep-drawing operation of circular shape using experimental work and FE analysis. They studied the effect of the friction coefficient in the first stage and second stage. The results showed that for the maximum drawing force, the best suitable friction coefficient for the first stage is 0.225, while in the second stage is 0.211.

2. Finite element model
The spline shapes with inner dimensions of \( h = 3 \text{ mm}, W = 9.64 \text{ mm}, d = 34 \text{ mm}, D = 41.5 \text{ mm}, \text{ and } L = 31 \text{ mm} \) for the first stage, \( h = 2.4 \text{ mm}, W = 7.7 \text{ mm}, d = 27.2 \text{ mm}, D = 33.3 \text{ mm}, \text{ and } L = 43 \text{ mm} \) for the second stage, and \( h = 2 \text{ mm}, W = 6.7 \text{ mm}, d = 23.63 \text{ mm}, D = 28.8 \text{ mm}, \text{ and } L = 52 \text{ mm} \) for the third stage, where \( D = \text{ major axis}, h = \text{spline height}, W = \text{spline width}, d = \text{ minor axis}, \text{ and } L = \text{spline length} \), had been completed in the numerical simulations process as illustrated in Figure 1.

![Figure 1. Shows the geometry of the produced spline shape.](image)

The flat circular blank is formed with a diameter of \( D_B = 80 \text{ mm} \) and a thickness of \( t = 0.7 \text{ mm} \), prepared from a metal sheet made of low carbon steel (1008 – AISI) and has mechanical properties of the unformed flat circular blank and the cylindrical shapes of a three-stages deep-drawing process as shown in Table 1.
Table 1. The mechanical properties of the unformed flat circular blank and the cylindrical shapes of a three-stages deep-drawing operation.

| Property                      | Unformed blank value | Cylindrical shape of 1st stage value | Cylindrical shape of 2nd stage value | Cylindrical shape of 3rd stage value |
|-------------------------------|----------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Yield Stress (MPa)            | 220                  | 310                                  | 342                                  | 357                                  |
| Ultimate Stress (MPa)         | 378                  | 512                                  | 540                                  | 552                                  |
| Young Modulus (GPa)           | 200                  | 200                                  | 200                                  | 200                                  |
| Tangent Modulus (GPa)         | 0.5                  | 0.5                                  | 0.5                                  | 0.5                                  |
| Mass Density (gm/cm³)         | 7.8                  | 7.8                                  | 7.8                                  | 7.8                                  |
| Poisons Ratio                 | 0.31                 | 0.31                                 | 0.31                                 | 0.31                                 |

To model the multi-stage deep-drawing process, the FE analysis based on ANSYS code 19.0 workbench is utilized. The static structural analysis of the system is used to perform geometry and model tools of deep drawing. All parts (blank, punch, blank holder, and die) were designed and modeled using the Design Modeler. For the toolset – the stiffness behavior of blank is flexible, and the assignment is low carbon steel. Other tools stiffness behavior (die, blank holder, and punch) are rigid, and assignment is structural steel. For the connections (contacts), for the first stage, three frictional contact regions, blank contact with punch, blank holder and die. In comparison, in the second and third stages, two frictional contact regions blank contact with the punch and die. For all contacts, the blank represents the contact body, while the tools (die, blank holder, and punch) represent the target bodies. The friction coefficient between blank material and tool punch material interface is $\mu = 0.1$, while the friction coefficient between blank material and other tools material interface is $\mu = 0.05$. The element contact, mesh, and boundary condition between the flat circular blank and the tool (punch, die, blank holder) for the first stage, and between the tool (punch and die) and the shapes for the second and third stage used in this analysis are shown in Figure 2.

![Figure 2. The element (contact, boundary condition, and mesh) for the spline tools (punch, blank](image-url)
holder, and die) three-stages deep-drawing process. For both the cylindrical and spline shapes, the radial clearance between punch and die was selected to be 20% of the original sheet thickness of the spline shape for the three-stages. For the three-stages, two types of models (cylindrical and spline shapes) were simulated. The successive stages of producing the cylindrical and spline shapes for the three-stages are shown in Figure 3.

Figure 3. The successive stages of producing cylindrical and spline shapes for the three-stages deep-drawing using ANSYS code (19.0) workbench.

3. Experimental procedure

3.1. Material characteristics
The mechanical properties of the blank sheet used in the first stage and the shapes for the three-stages play a significant effect on the drawing and redrawing (converting) processes. In this research, the flat circular blank of low carbon steel with $D_0 = 80$ mm, and $t = 0.7$ mm was used. The chemical percentages of the low carbon steel sheet were found using the spectrometer device, and they are listed in Table 2. To obtain more numerical simulation results accuracy, according to designation number E8M of ASTM standard, tensile test samples were taken from the flat sheet and the three-stages cylindrical shape that was cut using a water jet machine, as shown in Figure 4.
Table 2. The chemical percentages of low carbon steel sheet.

| C% | Si% | Mn% | S%  | P%  | Cr% | Ni% | Mo% | V%  | Cu% | Al% |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.075 | 0.022 | 0.321 | 0.021 | 0.015 | 0.031 | 0.031 | 0.002 | 0.001 | 0.091 | 0.051 |

Figure 4. The tensile samples were taken of the flat sheet and the cylindrical shape of the three-stages deep-drawing process.

3.2. Experimental test

A three-stages deep-drawing operation was performed to produce the spline shapes with inner dimensions of h = 3 mm, W = 9.64 mm, d = 34 mm, D = 41.5 mm, and L = 31 mm for the first stage, h = 2.4 mm, W = 7.7 mm, d = 27.2 mm, D = 33.3 mm, and L = 43 mm for the second stage, and h = 2 mm, W = 6.7 mm, d = 23.63 mm, D = 28.8 mm, and L = 52 mm for the third stage. The spline shapes were produced in two methods (direct and indirect) of the three-stages deep-drawing operation.

In the direct method, the spline shape (S₁) was produced directly by drawing from the flat circular blank (B to S₁), while in the second and third stages, the spline shapes (S₂, S₃) were produced by convert the spline and cylindrical shapes from the first and second stages respectively, (S₁ to S₂, S₂ to S₃), (C₁ to S₂, C₂ to S₃), and in the indirect method, convert the cylindrical shapes into spline shapes for the three-stages (C₁ to S₁, C₂ to S₂, C₃ to S₃).

To produce the spline shape, the experimental tools (dies and punches) were designed and constructed; the tools are manufactured from a steel tool that was machined by a CNC machine and wire cut machine. All the experiments were completed using a testing machine with a capacity of 200 KN and 100mm/min crosshead speed. The three-stages deep-drawing operation tools set-up in the experimental procedure is shown in Figure 5 (All the experiments were conducted in The Strength of Material Laboratory, Production Engineering Department, University of Technology/Baghdad).
The three-stages deep drawing was implemented using the cylindrical and spline dies and punches with dimensions listed in Table 3. For the three-stages, the radial clearance of 20% t is selected. The three-stages deep-drawing operation tools (punches and dies) used in the experimental procedure are shown in Figure 6.

Table 3. The dimensions of used spline and cylindrical punches and dies in the three-stages deep-drawing process.

| Stage  | Punch (Spline Shape) (mm) | Die (Spline Shape) (mm) | Punch (Cylindrical Shape) (mm) | Die (Cylindrical Shape) (mm) |
|--------|---------------------------|-------------------------|-------------------------------|-------------------------------|
|        | h  | W  | d  | h  | W  | d  | h  | W  | d  |
| 1st Stage | 3  | 9.64 | 34 | 3  | 11.34 | 36.7 | 41.5 | 43.2 |
| 2nd Stage | 2.4 | 7.7  | 27.2 | 2.4 | 9.4  | 28.9 | 33.3 | 35  |
| 3rd Stage | 2  | 6.7  | 23.63 | 2  | 8.4  | 25.33 | 28.8 | 30.5 |
All the experiments were performed by applying the drawing and redrawing process based on the direct and indirect methods, for comparing between them in terms of drawing force, thickness distribution, and strain across the sidewall, the curvature of the major axis, and the curvature of the minor axis of the spline shape for the three-stages deep drawing process. A square grid was printed on the flat circular blank with a dimension of 2.5 × 2.5 mm engraving using the fiber laser machine on the surface of the circular blank sheet with very little depth to study the strain and thickness distribution across the sidewall. The curvature of the major axis and the curvature of the minor axis of the drawn spline shape. After the drawing and redrawing operations of the three-stages, the square grid stayed unchanged at the bottom of the spline shape while its dimensions were changed at the wall of the spline shape, as shown in Figure 7.
4. Results and discussion
Two methods (direct and indirect) were performed to produce a spline shape with minimal defects, as shown in Figure 8. From this figure can clearly be observed that the direct method was successful with the first, second, and third stages when the spline shapes are produced from (B to S1), (C1 to S2), and (C2 to S3), respectively, while this method was failed with the second and third stages when the spline shape produced from (S1 to S2), and (S2 to S3), respectively, due to the severe deformation that causes thinning and tearing in the wall shape for the second and third stages. Also, it was shown that the indirect method was successful with three-stages (C1 to S1), (C2 to S2) and, (C3 to S3). The shapes that are produced by the indirect method for the three-stages are without tearing, thinning, and wrinkling compared with the direct method when the spline shape produced from (S1 to S2), and (S2 to S3), due to the difference between the cantering of the convex (curvature of major axis) and concave (curvature of the minor axis) areas of both the die and punch, spline shape that causes the distortion in the direct method of the second and third stages.

Figure 8. The direct and indirect methods of producing the spline shape based on the three-stage deep-drawing process.

Comparisons among the drawing forces with the punch displacement of the spline shapes produced by direct and indirect methods of the three-stages deep-drawing operation are illustrated in Figure 9. This Figure clarifies that for the three-stages, the maximum drawing force that is required to produce the spline shape by the direct method is higher than the maximum drawing force that is required to produce the spline shape by the indirect method. This is attributed to the spline shape produced by the direct method is facing higher bending and unbending than the spline shape produced by the indirect method. The maximum drawing force value equal to 41.650 kN, 33.175 kN, 33.112 kN for the first, second, and third stages. Also, from this figure can be observed that as the draw stages progress, the drawing force is decreasing; this is attributed to the reduction percentage of the shape decreases as the draw stages progress.
Figure 9. Comparison among the drawing load with punch displacement required by the spline shape by direct and indirect methods for the three-stages deep-drawing process.

The comparisons among the thickness distribution over the sidewall, the curvature of the major axis, and the curvature of the minor axis of the spline shape produced by direct and indirect methods for the three-stages deep-drawing operation are shown in Figures (10-11). These figures show that at the bottom of the spline shape until the shape corner, there is no variation in the thickness of the three-stages deep-drawing process. Also, for both methods, it was found that the thinning takes place and arrives at the maximum value with the spline shape that is produced by direct method at the curvature of the minor axis (concave area). This is attributed to the metal flow difficulty in the area of curvature of the major axis (convex area) and the curvature of the minor axis (concave area) of the spline shape that is produced by direct method resulting from the high-stress concentration in these areas. The best thickness distribution is obtained in the wall of the spline shape produced by the indirect method when compared with the direct method.
Figure 10. Comparing the behavior of the thickness distribution over the sidewall, the major axis curvature, and the minor axis curvature of the spline shape produced by the direct method for the three-stages deep-drawing process.
Figure 11. Comparing the behavior of the thickness distribution over the sidewall, the major axis curvature, and the minor axis curvature of the spline shape produced by the indirect method for the three-stages deep-drawing process.

The comparisons of the effective strain distribution across the sidewall, the curvature of the major axis, and the curvature of the minor axis of the spline shape produced by direct and indirect methods of the three-stages deep-drawing operation are outlined in Figures (12-13). These figures clearly showed that for the three-stages deep-drawing, note at the shapely bottom until the shape corner, the effective strain equal to zero. Also, from these figures, it can be observed that the effective strain starts to elevate from the shape corner area to the spline shape rim. The higher effective strain
values are 0.612, 1.283, and 1.691 for the three-stages, respectively, occurs with the spline shape that is produced by the indirect method, particularly along the curvature of the minor axis (concave) when compared with the direct method due to increasing the deformation with progressive stages (draw stages of the cylindrical cup that used to produce the spline cup in the indirect method progressive one step compared to the direct method).

Figure 12. Comparing the behavior of the effective strain distribution over the sidewall, the major axis curvature, and the minor axis curvature of the spline shape produced by the direct method for the three-stages deep-drawing process.
Figure 13. Comparing the behavior of the effective strain distribution over the sidewall, the major axis curvature, and the minor axis curvature of the spline shape produced by the indirect method for the three-stages deep-drawing process.

5. Conclusion

- The spline shapes can be produced using the direct method when the spline shapes are produced from \( S_1 \) to \( S_2 \), \( S_2 \) to \( S_3 \), and \( S_3 \) to \( S_4 \) for the three-stages deep-drawing process.
- The spline shapes can be produced using the indirect method for the three-stages deep-drawing process.
The maximum drawing force values equal to 41.650 kN, 33.175 kN, 33.11 kN for the first, second, and third stages, respectively.

The maximum drawing force required to produce spline shape by the direct method is greater than the maximum drawing force required to produce spline shape by the indirect method for the three-stages deep-drawing process.

The higher effective strain values are 0.612, 1.283, 1.69 for three-stages, respectively, with the spline shape produced by the indirect method, especially along the curvature of the minor axis concave area when compared with the direct method for the three-stages deep-drawing.

The spline shapes produced by the indirect method are without tearing and wrinkling.

6. References

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