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Progressive Die Sequence Design for Deep Drawing Round Cups Using Finite Element Analysis

Taylan Altan

Nitin Jain

Xiaoxiang Shi

ERC for Net Shape Manufacturing, The Ohio State University, Columbus, OH 43210

Gracious Ngaile
Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695
e-mail: gngaile@eos.ncsu.edu

Bryan Pax

Brent Harman

Greg Homan

Pax Machine Works, Celina, OH 45822

A methodology for progressive die sequence design for forming round cups using finite element method (FEM) based simulations is discussed. The process sequence design developed was applied to forming of an automotive part and was compared with the design obtained from past experience. The methodology proposed in this paper has shown that the integration of design experience and FEM simulations can enhance the robustness of the procedure for die design sequence and reduces the die development cost considerably. [DOI: 10.1115/1.2039942]

1 Introduction

In the stamping industry, the design of progressive dies relies heavily on past experience and several prototype die tryouts. Figure 1 (Part A) shows the process sequence of a round part manufactured using progressive dies. A progressive die performs a series of fundamental forming operations at two or more stations during each press stroke as the strip stock moves through the die. The most critical and challenging issues in this task are how to determine (a) the minimum number of required forming steps and (b) the corresponding tooling shapes while maintaining the specified thickness distribution in the formed part. This procedure requires extensive resources and increases the process development time and cost. A computer aided approach is highly desirable to design a robust progressive die sequence quickly and at reduced expense.

Knowledge-based systems have been explored to determine required forming stages in deep drawing and two-dimensional forging problems [1–5]. Knowledge for these systems is derived from plasticity theory, experimental results, and the empirical know-how of field engineers. This approach has shown some success. However, it cannot consider the process conditions that are not already stored in the knowledge base. In earlier studies, related to the subject of this paper, Cao [6] used numerical simulations and sensitivity analysis to optimize the number of forming stages in a multi-step deep drawing problem. Kim [7] carried out tool design analysis for multi-step drawing using the finite element method (FEM). In these studies, only design improvements in existing multi-step tooling were carried out.

In the present study, an attempt is made to develop a FE simulation-based design strategy for progressive die sequence in deep drawing of round cups. The analysis was carried out by a commercial implicit FEM code, DEFORM 2D. The design sequence obtained from FEM was compared with that obtained using past experience and trial-and-error approach. The results indicated that the FEM based strategy is approximately equivalent to that practiced by engineers with many years of experience.

2 Die Design Strategy for FEM Based Approach

The objective of this study was to design the progressive die sequence for an automotive part shown in Fig. 2 (Part B) using FEM simulation. The die design procedure must determine: (a) number of forming stages, (b) tool geometry for each stage (punch/die diameter, punch corner and die corner radii), (c) drawing depth for each stage and (d) blank holder force for each stage. In order to develop an appropriate die design strategy, for forming part B (Fig. 2), the forming stages of an example part, part A shown in Fig. 1, were investigated using FE simulations. Geometric parameters for various stages of the example part were provided by the stamping company sponsoring this research. The following design guidelines were obtained from this investigation:

- Higher draw ratios are used in the initial forming stages. Figure 3 shows the trends for the variation of punch diameters and maximum wall thinning. The punch diameter is reduced rapidly during the initial stages of deformation and relatively little in the later stages. Based on this trend, it was decided to constrain the maximum wall thinning below 4% in the first forming stage of part B. In the example part, A, the ratio of the punch corner radius to die corner radius was kept to less than 1 in all the forming stages, i.e., the ratio varied from 0.75 to 0.95. This condition was taken into account in determining the punch corner and die corner radii for various forming stages of part B.
- The example part, A, with a height of 19 mm was manufactured using six forming stages. Since the height of part B is 80 mm, we assumed that this part would require more than six forming stages.

3 Process Sequence Design

The design guidelines discussed above and others obtained from die design handbooks [8] were applied in the design of progressive die sequence for part B. Figure 4 shows the flow chart of the steps conducted to determine the parameters of the first forming stage for part B using FEM.

3.1 Simulation Model. The simulation model used is shown in Fig. 5. The geometry was modeled over a unit radian about the Z axis due to axisymmetric deformation mode. The sheet was meshed with axisymmetric quadrilateral element with eight elements along the thickness to capture thickness distribution. The dies were modeled to be rigid and the stress strain relation for the deforming material was $\bar{\sigma}=657\bar{\varepsilon}^{0.24}$ MPa. A Coulomb friction coefficient, $\mu=0.1$, was selected as the thinning distribution from FEM simulation using this value that matched experimental results for the example part A. The initial blank diameter, d_b, was determined to be 165 mm through volume constancy using the part dimensions given in Fig. 2. The punch velocity of 150 mm/s was used in the simulations.

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Fig. 1 A round cup manufactured using progressive dies (Part A)

3.2 Blank-Holder Force for the First Stage. The blank holder force for the first stage was determined by performing simulations with different blank-holder forces. If the blank-holder force is insufficient, the FEM simulation shows that the blank holder will move upwards (Fig. 5) resulting in flange wrinkling. In the first forming stage the minimum blank holder force of 50 kN was selected to prevent wrinkling, i.e., the upward movement of the blank holder. A similar strategy was used to determine the blank holder forces in subsequent forming stages.

3.3 Punch Diameter, Die Diameter and Drawing Depth for the First Stage. The punch diameter and the drawing depth have maximum influence on wall thinning. The maximum wall thinning was constrained to be less than 4% in the first stage. Moreover, in the first stage, the cup is drawn completely without flange to put more material into the die cavity. Table 1 shows the simulation matrix used to determine the optimum (dimensions to constrain the wall thinning below 4% and minimize the number of forming stages) punch diameter for the first stage. The draw ratios of 1.65, 1.6 and 1.55 were obtained from die design handbook [8] for the initial determination of punch diameters. The punch diameters of 100, 97, and 95 mm were calculated from these ratios. The die clearance was taken as **1.1**t_0 while t_0 is the initial sheet thickness. The last column in Table 1 shows the maximum wall thinning obtained from FEM. The maximum wall thinning is less than 4% for punch diameters of 97 and 100 mm. In order to reduce the number of forming stages, the punch diameter of 97 mm was selected.

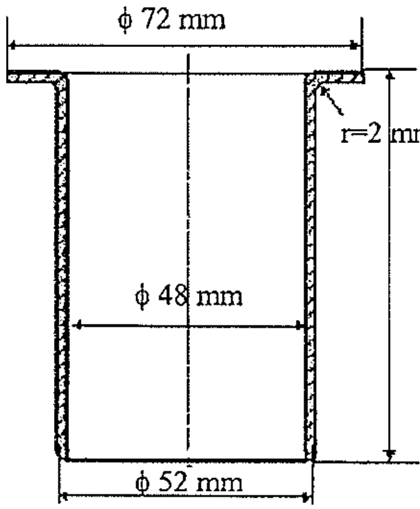

Fig. 2 Geometry of part B (blank thickness: 2.15 mm)

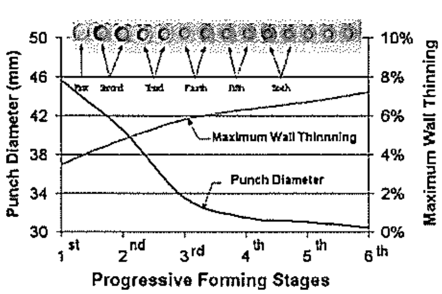

Fig. 3 Variation of the punch diameter and wall thinning in progressive forming stages (example part, A)

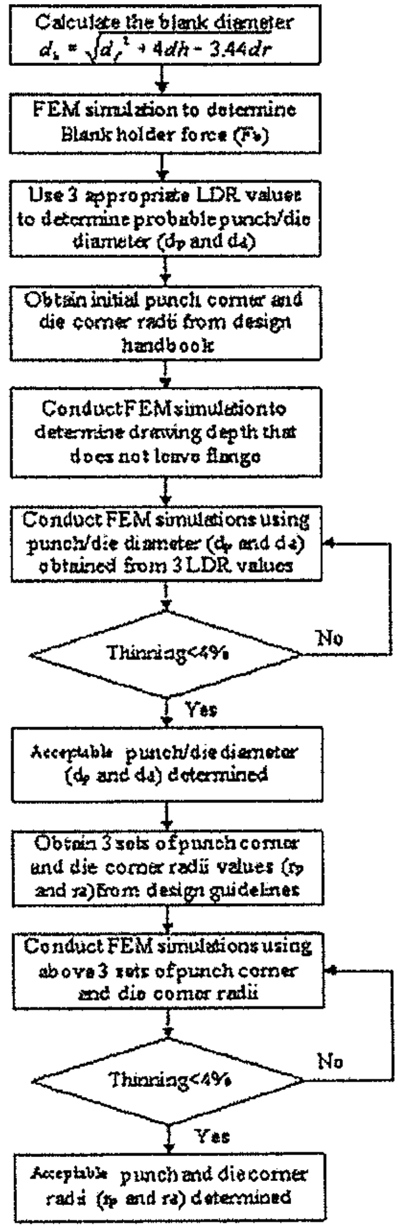

Fig. 4 Flow chart to determine the design parameters of the first forming stage for part B

The most important output from FEM simulations is the location of the maximum thinning in the part. Design engineers can use this information to select the punch diameters for subsequent stages. The punch radius for the first stage was selected to be 48.5 mm. After the first stage drawing, the maximum wall thinning of 3.72% is observed in the part at a distance of 43.7 mm from the center line (Fig. 6). Hence any punch radius equal to or more than 43.7 mm in the second stage will hit the maximum thinning area which would result in significant wall thinning. Therefore, the second stage punch radius should be smaller than 43.7 mm. The FEM simulations thus gave the upper limit for the next stage punch diameter. Simulations were then carried out to determine

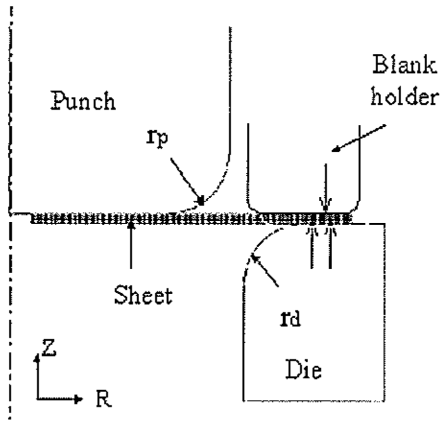

Fig. 5 Simulation model

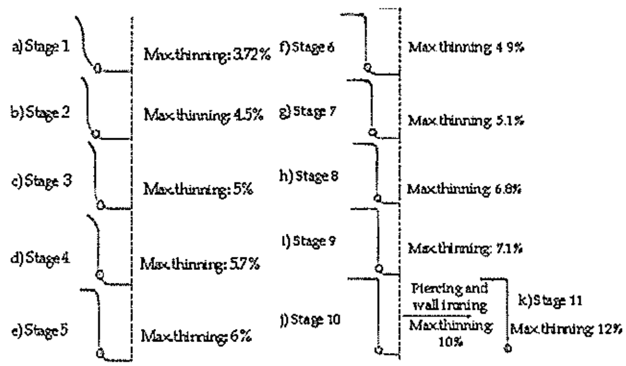

Fig. 7 Shape of deformed part at each stage for progressive die sequence design

the optimum punch diameter for the subsequent stages. Cups were completely drawn for the first four stages and the maximum thinning was restricted below 6%.

3.4 Punch Corner and Die Corner Radii for the First Stage. After the determination of optimum punch diameter, it is necessary to determine the punch corner and die corner radii. Table 2 shows the simulation matrix used for this purpose. Initial values of punch corner and die corner radii were taken from the design handbook [8]. Also, the ratio of punch corner radius to die corner radius was kept to less than 1 based on the guidelines obtained from the investigation of the die design of the example part, A. The last column in Table 2 shows the wall thinning values for different sets of punch corner and die corner radii at the first stage. Punch and die corner radii of 19.5 and 21.5 mm, respectively, were selected to meet the thinning criterion (i.e., to keep wall thinning below 4%) and reduce the number of forming stages. A similar approach was adopted to determine the optimum set of punch and die corner radii for the subsequent stages.

3.5 Final Progressive Die Sequence. The progressive sequence design using FEM simulation consisted of ten forming stages and a final piercing/wall ironing stage. Figure 7 shows the progressive die sequence and the corresponding maximum thinning in percentage for each stage.

Table 1 Simulation matrix for determining the optimum punch diameter

Case No.	d_p (mm)	d_d (mm)	r_p (mm)	r_d (mm)	F_b (kN)	Max wall thinning from FEM
1	100	104	19.5	21.5	50	3.3%
2	97	101.5	19.5	21.5	50	3.7%
3	95	99.5	19.5	21.5	50	4.1%

Table 2 Simulation matrix for determining the optimum punch corner and die corner radii

Case No.	d_p (mm)	d_d (mm)	r_p (mm)	r_d (mm)	r_p/r_d	F_b (*kN*)	Max Wall thinning from FEM
1	97	101.5	18	20	0.9	50	4.3%
2	97	101.5	19.5	21.5	0.9	50	3.7%
3	97	101.5	22	25	0.88	50	3.5%

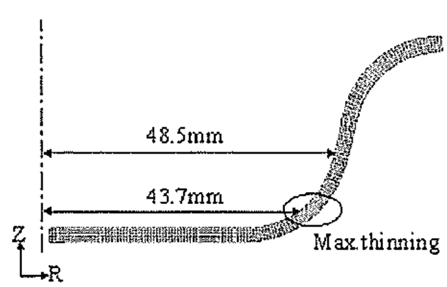

Fig. 6 Location of maximum thinning at the first stage (determines the upper limit of the punch diameter for the next stage)

4 Progressive Die Design - Comparison Between FEM and Experience Based Methods

Figure 8 shows the comparison of punch diameters obtained from FE assisted and experience based approaches. FEM predicted ten forming stages while experience based approach predicted nine forming stages. As observed from the slope of two curves, punch diameter change in FEM assisted approach is gradual. However, larger draw ratios were used for the first five stages in the experience based approach. Figure 9 shows the comparison of thickness distributions obtained from FEM assisted approach and experience based approach. Thickness distributions obtained from these two designs show that gradual change in punch diameter would result in a more uniform wall thickness distribution in the final part. Figure 10 shows the comparison of punch corner for FEM assisted and experience based approaches. Similar trends were observed for corner radii as well.

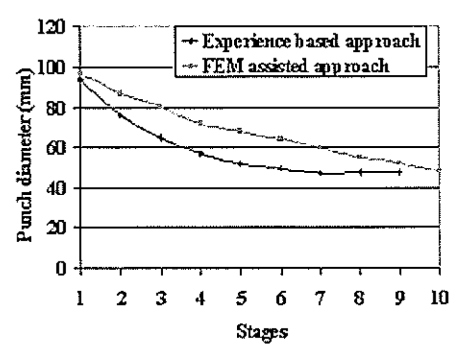

Fig. 8 Comparison of punch diameters predicted by experience based and FEM assisted approaches

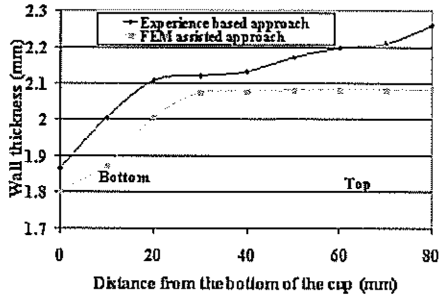

Fig. 9 Thickness distribution in the final part predicted by experienced based and FEM assisted approaches

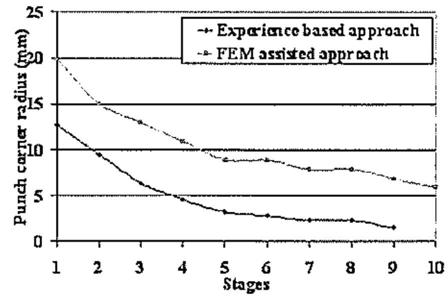

Fig. 10 Comparison of punch corner radii predicted by experience based and FEM assisted approaches

5 Conclusions

In this study, FEM has been used to design progressive die sequence for a deep drawn round cup. The die design obtained from FEM simulations was compared with that obtained from experience based approach. The study has demonstrated that integration of computer aided engineering (CAE) capability and the experience of process from tool designers can reduce the progressive die development time. Furthermore, CAE can also help in designing geometrically more complex parts that would require increased manual design effort as well as more trial and error. With process simulation via FEM, field variables such as strain distribution, stress distribution, material flow, and forming defects can also be estimated. This information will enhance the design capability and know-how of an experienced process designer. The major conclusions drawn from this study are:

- Integration of FEM and past experience can reduce the number of die-tryout tests and associated time and cost.
- The use of FEM can allow further refinement and optimization of the die design so that product properties, i.e., wall thickness tolerances, can be improved.
- To make FEM a practical tool for designing progressive and transfer dies in the stamping industry, close cooperation between the experienced die designers and the FEM engineers is necessary. Alternatively, the experienced designer can be trained in the use of FEM codes.

References

[1] Choi, J. C., Kim, M., and Kim, C., 1999, "An Automated Progressive Process Planning and Die Design and Working System for Blanking or Piercing and Bending of a Sheet Metal Product," Int. J. Adv. Manuf., 14, pp. 485–497.
[2] Esche, S. K., Khamitkar, S., Kinzel, S., and Altan, T., 1996, "Process and Die Design for Multi-Step Forming of Round Parts from Sheet Metal," J. Mater. Process. Technol., 59, pp. 24–33.
[3] Eshel, G., Barash, M., and Johnson, W., 1986, "Rule Based Modeling for Planning Axisymmetric Deep-Drawing," J. Mech. Work. Technol., 14, pp. 1–115.
[4] Kang, S. S., and Park, D. H., 2002, "Application of Computer-Aided Process Planning System for Non-Axisymmetric Deep Drawing Products," J. Mater. Process. Technol., 124, pp. 36–48.
[5] Sitaraman, S. K., Kinzel, G. L., and T. Altan, 1991, "A Knowledge-Based System for Process Sequence Design in Axisymmetric Sheet-Metal Forming," J. Mater. Process. Technol., 25, pp. 247–271.
[6] Cao, J., Li, S., Xia, Z., and Tang, S., 2001, "Analysis of an Axisymmetric Deep Drawn Part Forming Using Reduced Forming Steps," J. Mater. Process. Technol., 117, pp. 193–200.
[7] Kim, S.-H., Kim, S.-H., and H. Huh, 2002, "Tool Design in a Multi-Stage Drawing and Ironing Process of a Rectangular Cup with a Large Aspect Ratio Using Finite Element Analysis," Int. J. Mach. Tools Manuf., 42, pp. 863–875.
[8] Lange, K., 1985, *Handbook of Metal Forming*, McGraw-Hill, New York.