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ORIGINAL ARTICLE

FEA-aided design of multi-stage drawing process and tooling for production of a miniature sheet metal component

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Abstract This paper presents the design of multi-stage drawing process and tooling aided by finite element analysis (FEA) for fabrication of a miniature sheet metal component, made of a cold-reduced carbon steel material (SPCC). To design such a tooling, it is essential to figure out how many intermediate drawing steps are needed to produce the final part without deformation defect. First of all, a four-stage drawing process and a set of four-station tooling are designed. This pre-designed process is then analyzed by simulation, and the deformation behavior and formability in each stage is revealed. Based on the revealed deformation behavior and formability, the design of the process and tooling is confirmed. The reasonable drawing ratio and drawing depth in each drawing operation are determined. The size, clearance, and the corner radii of punch and die in each stage are also identified. The designed process and tooling are finally implemented. Through experiment, the "right design in the first time" is realized, and the simulation and experiment are found to have a good agreement. The research further demonstrates that the FEA simulation can be used as an effective tool to aid the design of metal-formed component, tooling, and process in upfront design process.

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1 Introduction

Sheet-metal forming processes have been widely used in many industries. The deep drawing process is one of the processes and widely used in production of small and complex deep drawn components [1, 2]. In the production of a miniature deep drawing component with a diameter of less than $\phi 3$ mm, a multi-stage drawing process is needed. In this process, the blank material sheet undergoes severe plastic deformation. Compared to the conventional single-step deep drawing process, the multi-stage drawing process generally involves additional bending, unbending, stretching, and severe contact in the cup wall with ironing, compression, as well as shearing in each drawing stage with different drawing ratios. Since the deformation mechanism is very complicated and the final product quality and geometry accuracy, which are significantly affected by process route, process parameters, and tooling geometries, are difficult to predict, the design of drawing process and tooling is thus a non-trivial issue in achieving the desired product dimensions, precision, accuracy, and material properties. As the products in the marketplace are getting smaller and smaller, the assembly parts or components inside these products are required to certainly reduce their sizes accordingly. Therefore, the development of sheet-metal deep drawing process and tooling design for production of such miniature products is increasingly important in the current miniaturized product market.

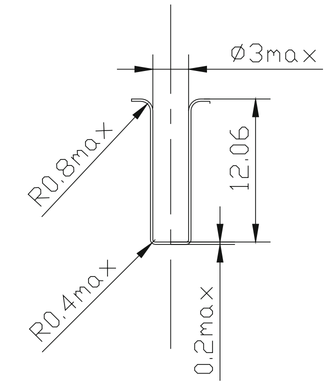
In conventional design paradigm for the development of miniature sheet metal components, experience and know-how play important roles in process and tooling design. Empirical formulae provide the basis for decision making and design solution generation. With the increasing demand on precision and reliability of metal formed parts, the traditional design paradigm is difficult and sometimes handicapped to provide design solutions, much less the optimal solution. With the advent of finite element analysis (FEA), it has become a useful design tool in metal forming industries to predict the formability of materials and determine the drawing ratio distribution in drawing stages, especially in producing a new miniaturized component. This kind of FEA-aided design paradigm is very important in sheet metal forming, as it involves complex physical mechanisms that give rise to a high-order non-linear problem [3].

Apart from the nonlinearity induced by contact, friction, and material properties, a geometrical nonlinearity is also caused by the large plastic deformation along the non-linear die profile in drawing process. These would make the problem even more difficult to be solved analytically. Since the process and tooling design for miniaturized parts is quite different from the conventional one, the FEA simulation is thus employed to support metal formed part design, forming process determination and tooling design before the design solution and actual production are implemented [2, 4–13].

Due to the efficiency of FEA in providing solutions for process and die design in metal-forming industries, efforts from both academia and industry have been provided in using this approach to support forming process design. Kim, Kim, and Huh used FEA to analyze a multi-stage deep drawing and ironing process of a rectangular cup with a large aspect ratio [14]. The research revealed that the difference of drawing ratio within the cross-section would lead to the non-uniform metal flow and cause severe local extension. In this research, the sheet metal blank with a diameter of 51.5 mm and the thickness of 0.5 mm was used. The final part was fabricated by a four-stage drawing process, and the thickness of the final part is 0.41 mm. While in this paper, the desired part is much smaller. The blank diameter is 13 mm, and the thickness is 0.2 mm. The diameter of the final drawn part is only 3 mm. It is thus called a miniature sheet metal component in this research.

In deep drawing of miniature sheet metal parts, the blank holding force is very important as it restricts wrinkling occurrence, controls material flow, and further affects the thickness distribution of final part and the limit drawing ratio (LDR) [15]. Padmanabhan, Oliveira, Alves, and Menezes used FEA to analyze the deep drawing of LPG bottles [16, 17]. Their research used an in-house FE code to perform simulation and revealed that the variable blank holding force and lubrication can be used in deep drawing of axis-symmetric cups to reduce the thinning effect in deep drawing process.

Fig. 1 The miniaturized deep drawn part



Regarding the frictional behavior, Manabe, Shimizu, and Koyama used FEA simulation and experiment to investigate the effect of blank holding force and tooling surface roughness on frictional behavior and found that the tooling surface roughness is closely related to frictional behavior but does not affect the cup surface accuracy for the tooling with less than 0.1 μm surface roughness [2].

In addition, Huang and Chen used the FEA simulation and experiment to study the relationship of clearance between punch and die and LDR [18]. It is found that the largest value LDR is at c=1.15t (c denotes the clearance between punch and die and t designates the initial blank thickness of sheet metal), and the smallest LDR is at c=1.22t. Furthermore, there are many other parameters that influence the LDR. Leu [19] proposed a new and accurate equation for estimating the LDR of cup-drawing process, which is the function of normal anisotropy value, strain-hardening exponent n, friction coefficient, die radius, and yield strength. In FEA simulation, all of these factors can be considered to obtain more accurate results.

To investigate the change of side-wall thickness in deep drawing process, Logue, Dingle, and Duncan [20] conducted the FEA simulation of the process, and it revealed the bending and straightening of sheet metal in drawing process and the relationship of side-wall thinning with die corner radius and the friction between metal sheet and die surface. Furthermore, the FEA simulation helps predict the damage defects in design stage [21–23].

Although many efforts have been provided for exploring how FEA helps the design of metal-forming process and tooling in multi-stage deep drawing process,

Table 1 LDR distribution in each drawing stage

Stage no.	Limiting drawing ratio (LDR)
1	0.55
2	0.77
3	077
4	0.77

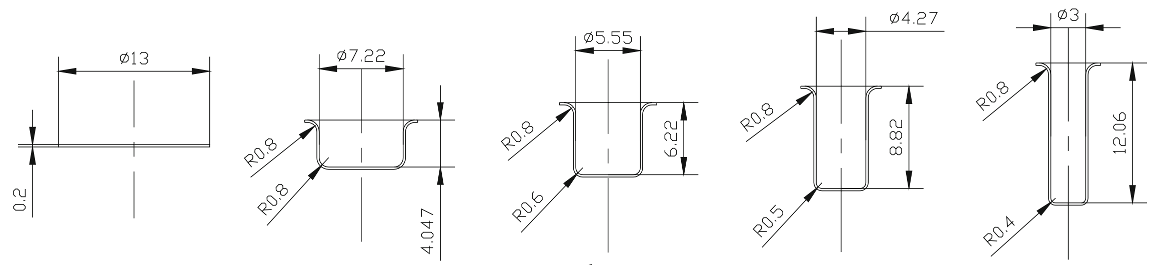


Fig. 2 Schematic of the initial blank and intermediate parts

there are very few publications on the multi-stage deep drawing of miniaturized parts with a diameter of less than a few millimeters. The goal of this paper is to explore the use of FEA simulation to aid the design of process and tooling in deep drawing of such miniaturized sheet metal parts. Through FEA modeling and simulation, a four-stage drawing process and tooling are designed for production of a miniaturized part. The design solutions are verified and validated through physical experiment, and it is found that the FEA-aided design is efficient in fabrication of miniature sheet-metal parts.

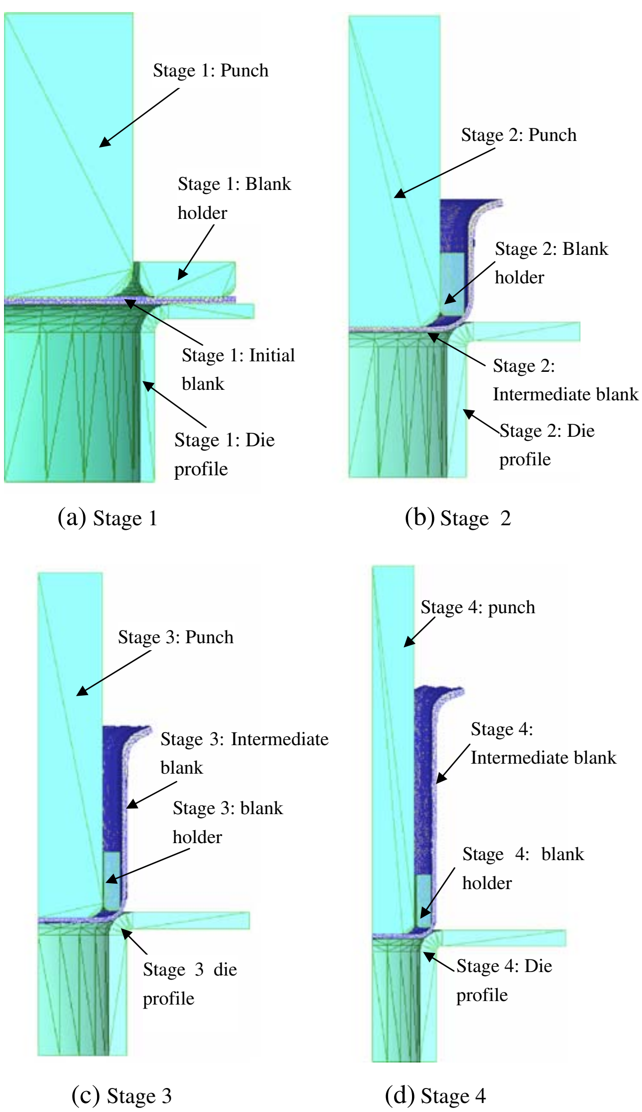


Fig. 3 FEA models in the four-stage drawing process. **a** Stage 1. **b** Stage 2. **c** Stage 3. **d** Stage 4

2 Conceptual design, FEA simulation, and experiment

The miniaturized deep drawn part is shown in Fig. 1. The part thickness is 0.2 mm, the diameter is ϕ3.0 mm, and the height is 12.06 mm. The outer radius is 0.4 mm. Based on this geometry configuration, a multi-stage drawing is needed for the successful fabrication of the final geometry.

2.1 Conceptual design aided by FEA simulation

If the part was drawn in a single operation, the drawing ratio would be around 4. This is much greater than the normal LDR of SPCC material, which is usually less than 2. A multi-stage drawing process is thus needed to successfully fabricate the part via drawing process. Table 1 gives the detailed drawing ratio in each stage. The intermediate preform profile in each stage is shown in Fig. 2. The detailed dimensions of the initial blank are also shown. The original blank diameter is ϕ13.0 mm, which is drawn into a cylindrical cup with the diameter of ϕ7.22 mm and the height of 4.047 mm in the first stage

Table 2 Material properties

	SPCC properties
Density (g/cm^3)	7.6
Young's modulus (GPa)	202
Poisson's ration	0.32
Friction coefficient	0.08
True stain versus true stress	As shown in Fig. 6

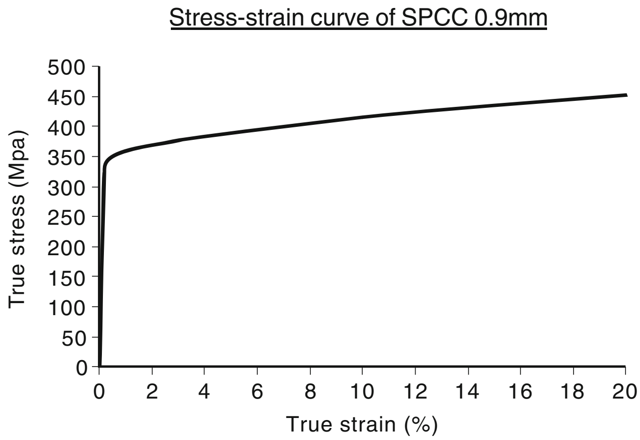


Fig. 4 True strain versus true stress curve of SPCC

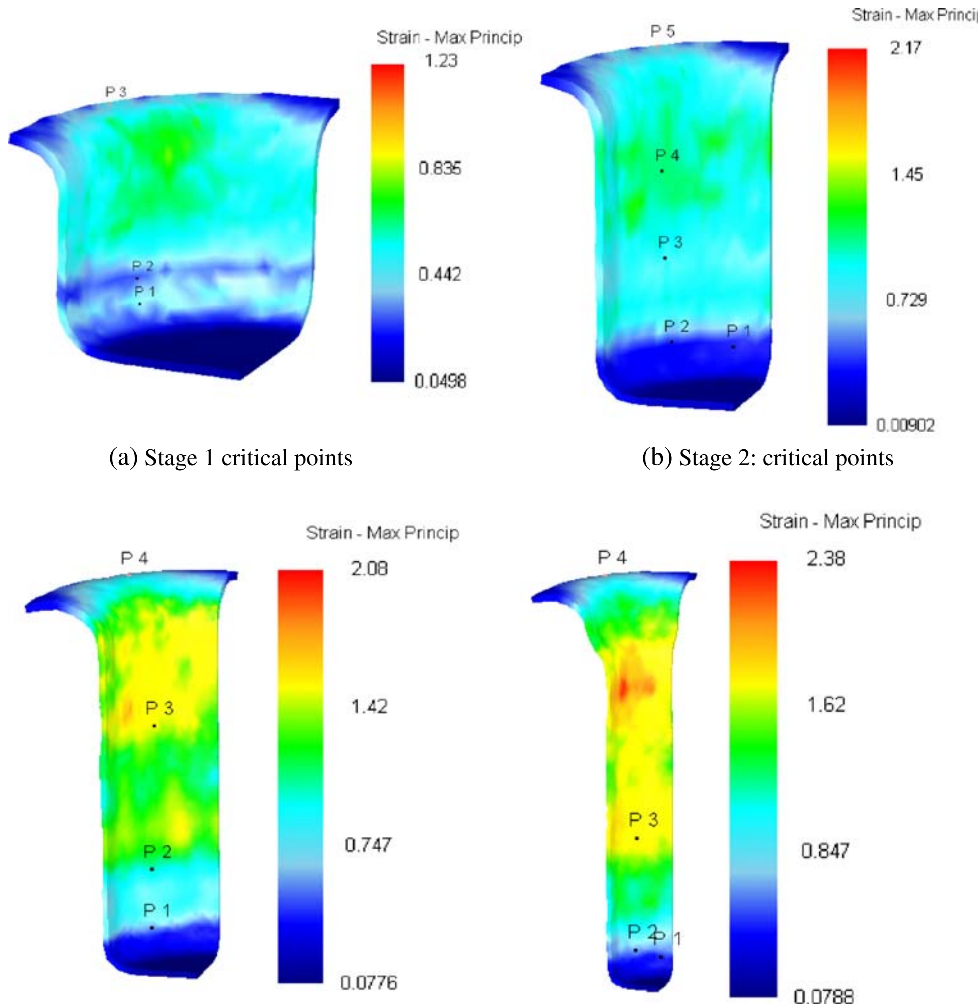
drawing. The drawn part in the first stage will be used as a preform to be further drawn into a cup with the diameter of ϕ5.55 mm and the height of 6.22 mm in stage 2 drawing process. In the third stage, the drawn part in stage 2 is further deformed into the intermediate part with the diameter of ϕ4.27 mm and the height of 8.82 mm, which is eventually drawn into the final part with the diameter of ϕ3.00 mm and the height of 12.06 mm.

To verify these design solutions, the FEA simulation of the four-stage drawing process was carried out in DEFORM-3D system, which is a FEA simulation system for the analysis of highly non-linear deformation problem. The FEA models are presented in Fig. 3. Due to geometrical and material symmetries, a quarter of the drawing forming system was simulated. The blank was meshed into two layers in thickness direction and 27,393 tetrahedral elements for the whole part. In addition, the material properties of the SPCC sheet are determined based on tensile test and shown in Table 2. The stress and strain curve of the material is shown in Fig. 4.

2.2 Experimental setup

The multi-stage deep drawing experiments were carried out using a mechanical press with an adjustable bottom center to perform the various depths of punch stroke. The developed experimental setup, including equipment, tooling, and the deformed sheet metal parts are shown in Fig. 5.

Fig. 5 Experimental set up for multi-stage deep drawing: equipment, tooling, and the drawn parts



(a) Stage 1 critical points (b) Stage 2: critical points

(a) Stage 1 critical points (b) Stage 2: critical points

Fig. 6 Strain distribution at the defined critical points in each stage. **a** Stage 1 critical points. **b** Stage 2: critical points

The blank holding force is 100 N at the first stage. In the subsequent drawing processes, a fixed clearance is used to control the metal flow. In addition, oil lubricant is applied for the drawing in each stage.

3 Results and discussion

3.1 Drawability in each stage

In FEA-aided design of deep drawing process, the distribution of drawing deformation to each drawing stage is critical. How to determine the deformation level and verify its drawability in each stage is a key issue. To address this issue, a few critical tracking points are defined in the deformation body for analysis of their deformation behaviors. Figure 6 shows these tracking points in each stage. The extracted results from FEA simulation show that all the points are in the safe region based on the forming limit diagram, as shown in Fig. 7. In

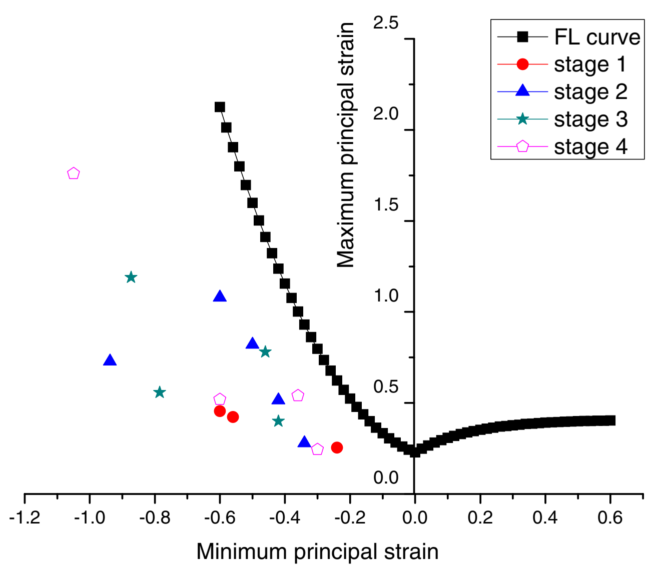


Fig. 7 Forming limit diagram

other words, the maximum and minimum principal strains for the defined tracking points are all located under the forming limit curve, which is the coarse curve in the figure. Therefore, it predicts that the desired parts can be produced through the designed four stages of the deep drawing process.

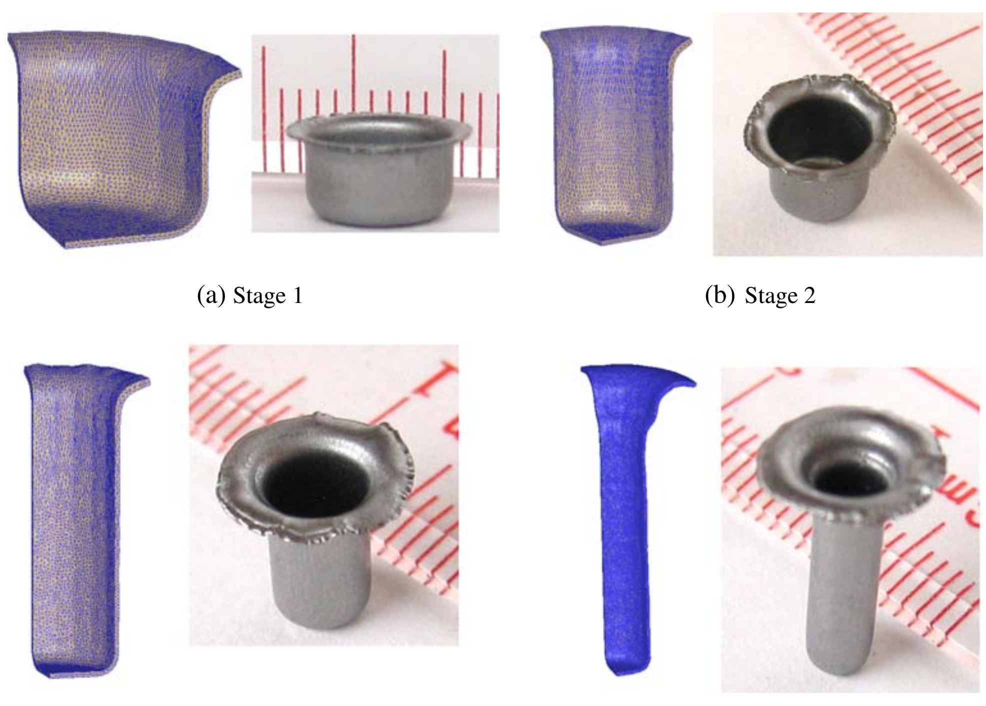
In addition, Fig. 8 shows the deformed parts in each stage predicted by FEA simulation and experiment. Obviously, small wrinkles on the flange of the simulated parts are observed, and the experiment also shows the same results. In fact, the flange will be trimmed away subsequently after the drawing process; the wrinkles on the flange will thus no longer affect the appearance of the ultimate part.

3.2 Thickness distribution

The thickness distributions of the deformed parts in different stages are shown in Fig. 9. The thickness is increased on the flange and reduced at the other portion of the drawn part. In the first stage, the thinnest thickness occurs at the connection area between the punch radius corner and the side wall. In the first stage, there is only one trough on the thickness distribution curve, as shown in Fig. 9a. After the second stage of drawing, the thickness of the deformed part is reduced mainly at the two regions, and there are two troughs in the thickness distribution curve. One is the corner region at the first drawing stage due to bending and unbending. The other is the corner region of the second stage. At the third stage, the thickness distribution of the deformed part shows three reduced regions due to the corner regions in the former stage after bending and unbending as well as the current stage corner. So does the fourth stage of the drawn part. Therefore, it is found that this finding is very interesting in product quality control, and only the FEA simulation can reveal this in-depth deformation behavior and phenomenon. Through the four-stage deep drawing process, the final thickness of the part is increased with 75% on the flange and reduced with 60% at the thinnest portion, which is the combined representation of the thinnest portions of the previous three stages of the deep drawing.

3.3 Punch loading

Due to the geometry and material symmetries, a quarter of the deformed part is simulated in this four-stage deep drawing process. In addition to the revealing of other process parameters, the punch loading in each stage is an important parameter, as it helps determine the machine capacity and design of tooling. The deformation loads of the four stages predicted by FEA simulation are shown in Fig. 10. The peak loads in stages 1, 2, 3, and 4 are 604, 489.89, 339.53, and 167.59 N, respectively. The results show that the peak deformation loads from stages 1 to 4 are decreased. The main reason is that the diameters of punch and the intermediate parts are decreased from stages 1 to 4, generating lower deformation load. Since only one quarter is simulated, the actual loading is four times the predicted value by FEA simulation.



(a) Stage 1 (b) Stage 2 (c) Stage 3 (d) Stage 4

Fig. 8 The formed parts predicted by FEA simulation and experiment. **a** Stage 1. **b** Stage 2. **c** Stage 3. **d** Stage 4

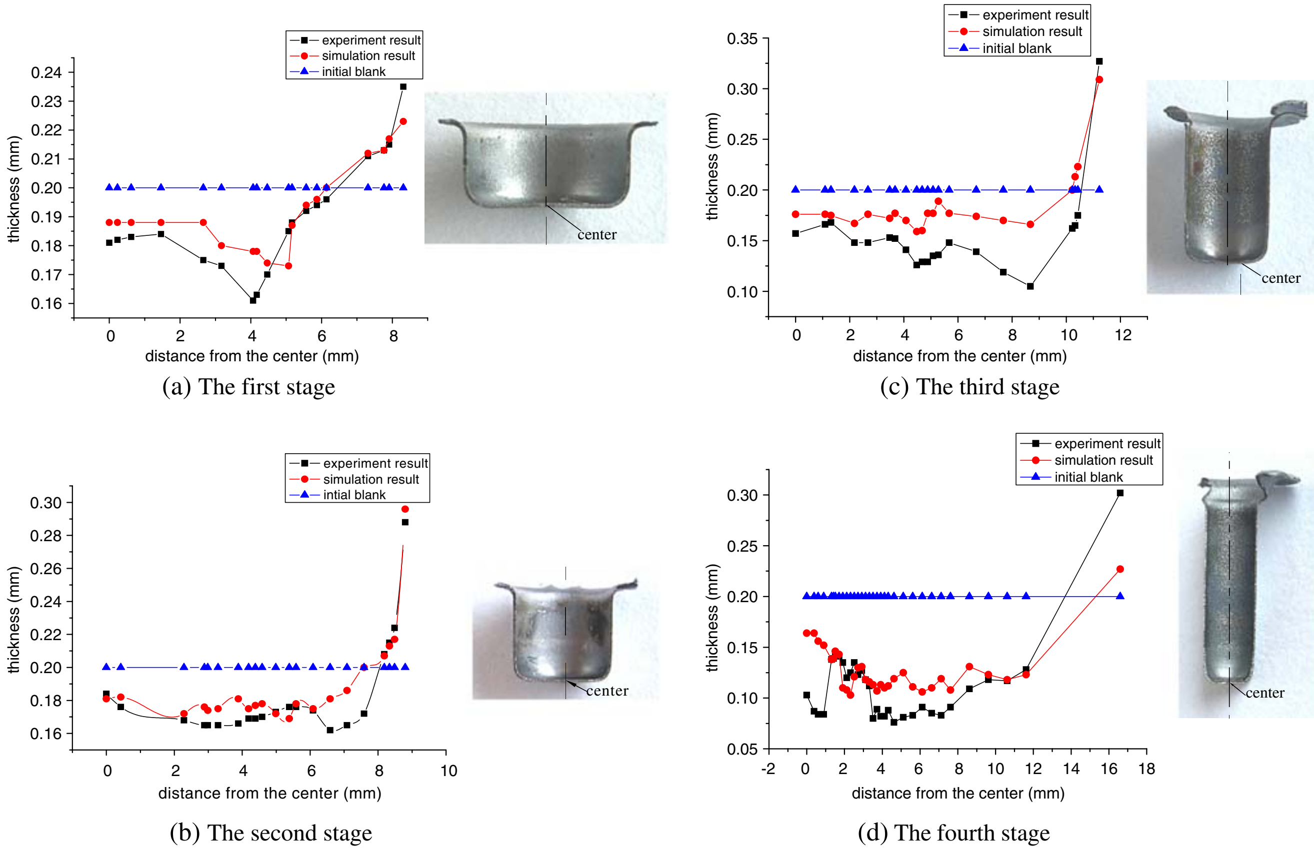
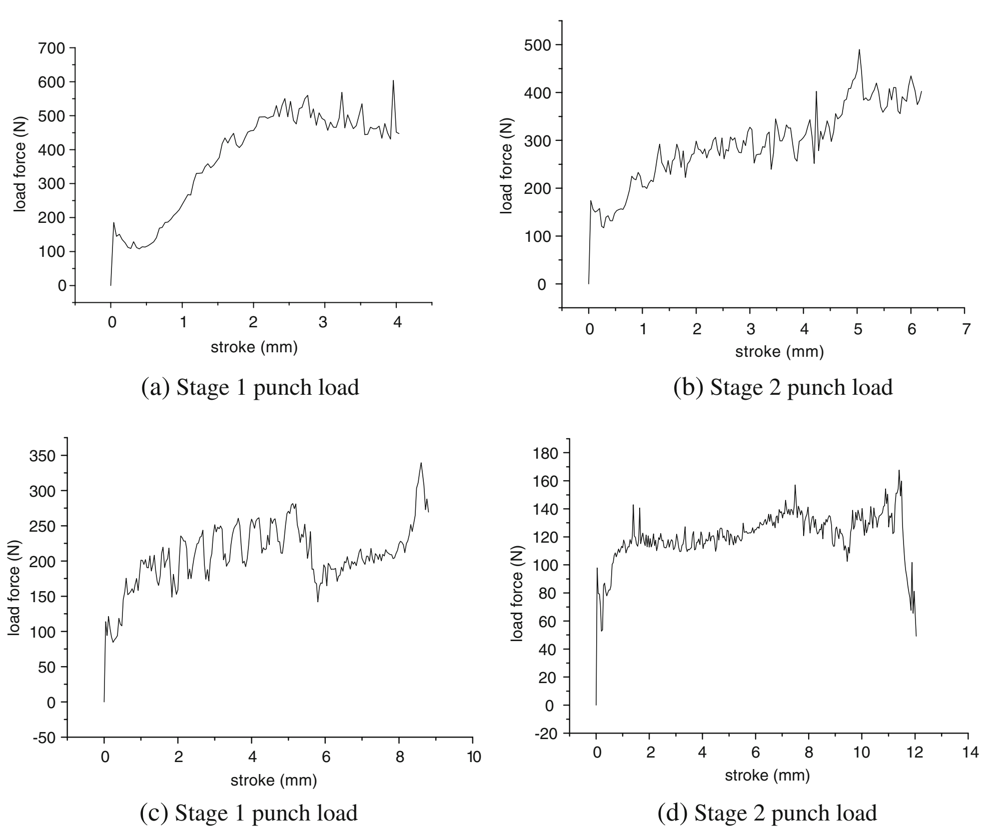


Fig. 9 The thickness distribution of the drawn part in four drawing stages. **a** The first stage. **b** The second stage. **c** The third stage. **d**. The fourth stage

Fig. 10 Deformation loading in each stage. **a** Stage 1 punch load. **b** Stage 2 punch load. **c** Stage 1 punch load. **d** Stage 2 punch load



3.4 Effect of the corner radius of die

In the single-stage drawing, the metal flow is more uniform than that in multi-stage deep drawing, no matter how big the corner radii of the punch and die are. In multi-stage drawing process, however, the sheet metal in the corner region of die undergoes bending and unbending deformation. Therefore, the deformed corner region in the previous stage has a significant effect on the deformation at that region in the subsequent stage. When many such merging regions are formed, the troughs on the thickness distribution curve will be getting closer and closer. Eventually, cracks could occur after the drawing process. Therefore, how the die radius geometries affect the deformation behavior, the thickness distribution of the deformed part, and the deformation load is an interesting issue, which will be extensively studied in future.

4 Conclusions

In the multi-stage deep drawing of miniature sheet metal parts, the design of drawing process, drawing ratio distribution, and die geometries is a critical issue. The traditional design based on experience and know-how needs many times of fine-tunings at production tryout stage, which is time-consuming, error-prone and not cost-effective. The FEA-aided design, however, provides an efficient approach for verification of design solutions in upfront design process and thus reduces time-to-market, shortens design and development lead-times, and cuts product development cost.

For development of the miniaturized sheet metal component with the diameter of ϕ3 mm, the FEA-aided design is employed. Through FEA simulation, the design of drawing stage, drawing ratio, and the drawing depth in each stage are determined based on the deformation behavior and the forming limit diagram. The design solutions verified by FEA simulation are finally implemented, and the physical experiment shows the feasibility of the design solutions via the successful drawing of the intermediate preforms and the final part. All of these systematically illustrate that the FEA-aided design of process and tooling is practical and feasible in production of miniaturized deep drawn sheet metal components.

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