Analysis of an Axisymmetric Deep Drawn Part Forming Using Reduced Forming Steps

Jian Cao, Shunping Li

Department of Mechanical Engineering

Northwestern University

Evanston, IL 60208-3111

Tel: 847-467-1032

Fax: 847-491-3915

Email: jcao@northwestern.edu

Z. Cedric Xia and Sing C. Tang

MD 3135

FORD Scientific Research Laboratory

Dearborn, MI 48121

Submitted to the *Journal of Materials Processing Technology*

ABSTRACT

Numerical simulations have been widely used to assist part and process design. In this paper, deep drawing processes of an axisymmetric part with a complex geometry are analyzed with the aim of reducing possible forming steps. The existing practice requires 10-step drawing. Our approach combines optimization scheme, design rules and numerical tests using finite element analysis incorporated with a damage model. As a result, the 10-step drawing is reduced to 6-step drawing. Additionally, the new process design yields a lower maximum void volume fraction in the sheet, meaning a more formable process, and a slightly higher press load.

INTRODUCTION

Sheet metal forming possesses great design flexibility, high productivity and the ability to offer high strength and lightweight products. Multi-step drawing processes are usually applied to forming parts that have geometrical complexity or formability problem and cannot be formed by one-step forming. In these cases, one of the most critical and challenging issues is to determine minimum required forming steps and the corresponding tooling shapes as tooling cost is the major expense. Design of multi-step drawing process has been heavily relying on experience-based technology as it is not trivial to systematically analyze the effects of all the design parameters on the quality of parts drawn.

Recently, sensitivity analysis combined with incremental FEM has been widely studied by many researchers to automatically identify optimal conditions [1-8]. Badrinarayanan and Zabaras [1] calculated an optimum die shape of an extrusion problem. Chenot and co-workers [3,4], Zhao and colleagues [5,6] calculated an intermediate tool shape of two-step forging problems. Badrinarayanan[1], Chenot [4] and Zhao [6] used 6, 3 and 20 design variables to define a tool shape, respectively. These works were focused on the design of a single target tool shape with only a limited number of design variables, whereas multiple tool shapes involve much more design variables. The multi-step drawing problem needs the determination of the minimum required forming steps as well as the optimum tool shapes for each step.

Inverse finite element method using the deformation theory has been developed for sheet metal forming process [9-15] to optimize initial blank shapes and process parameters with the promise of obtaining reasonable accuracy in a very short time period. Most inverse finite element methods have been focused on only thin sheet metal forming problem. Recently, Lee and Cao [15] developed a multi-step inverse method using shell element to solve both thin and thick metal forming problems with increased accuracy. The change of strain path in a drawing process and the bending effect were considered, which led to 1% discrepancy in predicting the original blank diameter and 12% discrepancy in radial strain prediction. The accuracy of these predictions were considerably improved from the corresponding 5% and 46% discrepancies when membrane elements were used in one-step inverse analysis. However, no sensitivity analysis incorporated with the inverse FEM has been developed to find the optimum tooling shapes automatically.

Alternatively, knowledge-based system has been explored to design intermediate tooling conditions and to determine minimum required drawing steps of axisymmetric deep drawing problems and two-dimensional forging problems [16-19]. The approach has shown some success, however, it cannot handle the process conditions beyond given knowledge rules. The knowledge for thick sheet metal drawing has not been systematically documented.

The objective of this paper is to find a new forming process that will reduce forming steps of an axisymmetric thick metal drawing problem. Systematic approach, which consists of finite element code with sensitivity analysis, optimization method, damage model for assessing failure potential and knowledge rules, are being investigated here to find an optimum condition. Side by side comparisons of formability and press load will be presented to demonstrate the feasibility of the approach.

PROBLEM DESCRIPTION

An automotive part illustrated in Fig.1 has an axisymmetric shape and was formed by a 10-step drawing process due to difficulties in forming Zone I with an initial blank thickness of 5 mm. This initial blank is thicker than most of common sheet forming products with that dimension. The final shape after multi-step drawings and springback should satisfy the geometric requirements as shown in Fig.1 without physical defects.

The material properties of a mild-steel and the initial blank size used in FEM analysis are as follows:

Stress-strain relation : $\bar{\sigma} = 533.3(0.0018 + \bar{\varepsilon})^{0.1908}$ MPa

Young's modulus : E= 210 GPa

Poisson's ratio : υ= 0.34

Lankford value : r = 1.0

Friction coefficient : μ= 0.1

Initial blank thickness : t_o = 5.0 mm

Initial blank diameter : ϕ_B = 330 mm

ANALYSIS OF ORIGINAL DRAWING PROCESS

The existing forming process consists of 10 steps, that is, 7-step, 2-step and 1-step drawing to form Zone I, Zone II and Zone III, respectively. The process was simulated by Finite Element analysis using a commercial implicit FEM package ABAQUS/Standard to establish the base for our following analysis. The finite element model in Fig.2a has 8 layers (4 layers in the flat areas) through the thickness direction, and 140 8-node solid elements with reduced integration (ABAQUS type CAX8R) along the radial direction. The entire 10-step drawings have been solved including springback after each drawing step. The initial geometry and deformed shapes for each step are shown in Fig.2. The distribution of void volume fraction using the Gurson-Tvergaard damage model associated with the von-Mises yield criterion and the tooling reaction forces were recorded. These data will be presented later with those of new proposed drawing processes for comparison.

DETERMINATION OF NEW DRAWING PROCESS

It is worth noticing that the most difficult forming area is in Zone 1 and the first draw is deeper than the final desired height in order to form the extremely tight radius (R/t=0.24) (see Fig.2*l*). The existing process plan requires 7-step drawing to form Zone 1. Here, in this section, we will utilize a combination of optimization scheme, inverse analysis and forward analysis to reduce the step number to 4. The 1st step will be the drawing stage to move material to the center region. The 2nd and 3rd steps are the transition stages. Finally, the 4th step is the shaping stage that makes the final shape of Zone I. The 8th to 10th steps in the original process will be consolidated to 2 steps, which results in a total of 6-step drawing instead of the original 10-step drawing.

<u>STEP 1</u>

The objective of this forming step is to draw enough material into Zone I for the subsequent drawing and to have the punch diameter as close as possible to the final dimension.

The thinning should be kept below a reasonable level (i.e. 20% for steel alloy) so that it would not cause tearing problems in the following forming steps. Wrinkling is not a major concern in this problem as the sheet thickness is very thick [20]. Similar to Step 1 in the existing process, only straight wall tooling with a circular radius is considered. Therefore, possible tooling variables are the punch diameter, d, the punch profile radius, r_1, and the die profile radius, r_2, (see Fig.2b and Fig.6a). The gap between the punch and the die is set to be 2* t_0 more than the punch diameter, where t_0 is the initial sheet thickness. The drawing depth is kept to 48mm as described in Lee et al. [21][1] to avoid collapse in the subsequent forming step. Other process parameters, including a binder force of 80 KN and a friction coefficient of 0.1 between the tooling and the blank, are used in this step.

The optimization problem can then be formulated as to find a possible set of (d, r_1, r_2) within the design domain R, i.e., $(d, r_1, r_2) \in R$, so that the objective function, F,

$$F(r_1,r_2,d)= t_{diff}/t_0+0.03(d-d_f)/d_f \qquad (1)$$

is minimized, where t_{diff} is the maximum thickness reduction after forming and d_f is the final inner diameter of Zone I in Fig. 1. The factor of *0.03* is determined by test runs to balance the contributions of two parts in the objective function. It should be pointed out that the formulation of the objective function is problem dependent and test runs are needed to verify the behavior of the objective function and the effectiveness of available optimization algorithms.

The design domain of the punch and die profile radii is set to be $(2\sim12)t_o$ based on the experience, whereas the thickness reduction is calculated by the inverse analysis as described in Lee and Cao [15]. The computation cost is much smaller than the forward incremental FEM analysis. A typical one step inverse analysis takes less than 15 seconds on a PentiumII 400 PC for this problem, and reasonable results can be obtained., while a forward analysis using ABAQUS may take several hours. Therefore, inverse analysis is preferable in optimization procedure since a large number of simulations are needed to find the minimum of the objective function. The optimization algorithm used, direction method, is shown in Fig. 3, which searches each variable direction (using line-search method) within the prescribed range for each iteration [22]. Although other sophisticated algorithms such as conjugate gradient, BFGS can be used in

[1] In that work, the same tooling design problem was attempted using knowledge based design approach.

the program, the present one provides the best results and performance. It is advisable to try different algorithms for practical engineering problems and different initial values to test the effectiveness of an optimization process. The convergence criterion for optimization is as follows:

$$\| X_{k+1} - X_k \| \leq \varepsilon \qquad (2)$$

where X_k , X_{k+1} are the variable vectors before and after one iteration, and ε is the convergence tolerance, the value of 0.1 is used in this study.

Various initial values in the design domain (r_1,r_2 = 10~60 mm, d = 100~130 mm) are used to test the robustness of the algorithm and very close values are obtained as shown in Table 1. The final optimized punch and die parameters are:

r_1=30.00mm r_2=60.00mm d=117.60mm

The total computation time to finish this particular optimization was less than 5 minutes on a PentiumII 400 PC.

STEPS 2 AND 3

Inverse analysis is very efficient in designing the first draw as shown above. However, it has not been able to handle a non-flat initial blank shape. This limitation prevents us from using the same approach developed above to design following forming steps. Instead, knowledge-based design approach will be used.

- Basic Design Rules of Steps 2 and 3
  - At the end of steps 2 and 3, the center region should be drawn to an adequate height. Shallow height can cause necking problem at step 4 and severe depth can yield high tooling pressure and folding problem since the excessive material needs to be shrunk to the final geometry.
  - At the end of steps 2 and 3, the diameter of wall region should be as close to the final specification as possible while the thickness reduction of this region should be as small as possible.

- Feasible Process Conditions of Step 2
    - The feasible die shape is shown in Fig.4(a). The straight slant-line shape is used to force the material more close to the final geometry than that the tooling used in [21]. This helps to relieve the excessive bending at the punch corner in the following forming step.

- Feasible Process Conditions of Step 3
    - The die shape of step 3 is similar to that of step 4.
    - - The die diameter and radius of step 3 should be smaller than those of step 2 and should be larger than those of step 4. Die Diameter=32mm
    - ABAQUS analyses have been performed using the above die shapes of step 3 and the best feasible tooling conditions of steps 1 and 2 until 4th step forming. The major problem in step 3 is the excessive bending at the final stage of forming when the material at the punch corner are forced to bend severely. A solution to this problem is to change the die shape in Fig.2e to that shown in Fig.4b. The slanted part in the proposed punch profile serves the purpose of forcing more material down to the die shape.

STEP 4

The tooling shapes of step 4 can be obtained from the deformed shape of Fig.1. The 13mm die radius leads to a folding problem at the end of step 4 as shown in Fig5(a). The 15mm die radius has the same problem with less folding. Under the same process conditions of steps 1, 2 and 4, 17mm die radius of step 3 provides the best results with no folding.

In the modification procedure, the entire 6-step drawing processes were solved to find a better condition by small modifications. For example, the tool movements of step 5 were modified to compensate springback effect of the final product. Springback in these forming processes was not significant due to the usage of thick blank and the axisymmetric geometry. The amount of springback in the Z direction was 1.25 mm for region A and 0.35 mm for region B of Fig. 6g. These amounts of springback were simply added to the tool movements of step 5. The blank size could be modified after the analysis of all the steps considering the height of Zone III. As a result, a new reduced forming process is found and the deformed shapes of each step are shown in Fig.6. The final deformed shape of Fig. 6g satisfies the geometric requirement of Fig.1

within the tolerance limit. The formability of this sequence needs to be examined and will be presented below.

COMPARISON BETWEEN THE ORIGINAL AND PROPOSED PROCESSES

FORMABILITY

During the forming processes, the possible failure modes can be classified as necking, folding and wrinkling. In this application, wrinkling is not of our concern due to the usage of a very thick blank. The folding problem could occur in the case of inappropriate combination of tooling conditions and this problem can be easily detected by examining the deformed shapes. Consequently, necking and subsequent ductile fracture are the major challenges for a successful design. In order to avoid these kinds of phenomena, the Gurson-Tvergaard damage model [23,24] is applied in the present work to examine the formability. Based on the experimental observation, the micro-scale defects in the form of voids is taken into account and considered as damage. The voids nucleation, growth, and coalescence determine the failure process during metal deformation. Thus, the volume fraction of voids works as a damage parameter in the constitutive relation derived with this damage model. The yield surface of Gurson-Tvergaard damage model based on von-Mises material is defined by

$$\Phi = \left(\frac{\sigma_{eq}}{\sigma_y} \right)^2 + 2q_1 \, f \cosh\left(q_2 \frac{3\sigma_m}{2\sigma_y} \right) - \left(1 + q_3 f^2 \right) = 0$$

where σ_{eq}, σ_y, σ_m are the equivalent, yield and hydrostatic stresses, respectively. f is the void volume fraction and q_1 , q_2 and q_3 are material parameters. The initial void volume faction was assumed 0.005. q_1, q_2 were assumed 1.5 and 1 respectively. q_3 is equal to q_1^2.

In order to evaluate the possible failure during the forming analysis, ABAQUS analysis with the damage model has been performed. Fig.7 shows the distributions of void volume fraction obtained from the original (10-step) and proposed (6-step) processes. Two comparisons are presented here. One corresponds to the most severe forming stage, that is, after the 4th step in the original process (see Fig.7a) and the 3rd step in the new process (see Fig.7b). The other comparison is at the end of all the forming steps. It can be seen that the maximum void volume fractions in the new process are lower than those in the original process in both cases, 0.0896 (3rd step new) vs. 0.0928 (4th step old) and 0.0952 (final, new) vs. 0.0998 (final, old). These results imply that the designed forming procedure is not beyond the allowance from the formability of the metal.

PRESS LOAD

The forming load in each of the forming step is monitored in the simulations and presented in Fig.8. The total press load is plotted against the increment numbers in the simulation as no effective normalization can be found. Notice that the high peaks of the load curve is due to the striking of the moving punch/die on the blank at the final forming stage. In practical forming, this should be avoided by adjusting the tooling movement.

SUMMARY

A reduced multi-step drawing process has been designed using a combined approach of optimization method, inverse FEM analysis and forward finite element analysis. Inverse FEM and optimization method were used for the tooling design of first draw. Additional design rules for subsequent drawing steps were useful to construct new tooling shapes. The maximum void volume fraction in the new process, a measurement of tearing potential, is about 5% lower than that in the original one, while the press loads are almost identical. These numbers indicate that the proposed new approach is a valid alternative design.

ACKNOWLEDGEMENT

The support from Ford Motor Company is gratefully acknowledged.

REFERENCES

1. S. Badrinarayanan and N. Zabaras, 1996, “A sensitivity analysis for the optimal design of metal forming processes”, *Comput. Methods Appl. Mech. Engrg.*, Vol.129, pp.319-348.
2. S. Badrinarayanan and N. Zabaras, 1995, “Preform design in metal forming”, in S.F. Shen

and P.R. Dawson (eds.), *Proc. Int. Conf. on NUMIFORM'95*, Balkema, Ithaca, NY, pp.533-538.

3. L. Fourment and J.L. Chenot, 1996, "Optimal design for non-steady state metal forming process - I. Shape Optimization Method", *Int. J. Numer. Methods Eng.*, Vol.39, pp.33-50.
4. L. Fourment and J.L. Chenot, 1996, "Optimal design for non-steady state metal forming process - II. application of shape optimization in forging", *Int. J. Numer. Methods Eng.*, Vol.39, pp.51-65.
5. G. Zhao, E. Wright and R.V. Grandhi, 1997, "Preform die shape design in metal forming using an optimization method", *Int. J. Numer. Methods Eng.*, Vol.40, pp.1213-1230.
6. G. Zhao, E. Wright and R.V. Grandhi, 1997, "Sensitivity analysis based preform die shape design for net-shape forming", *Int. J. Mach. Tools Manufacturing.*, Vol.37, pp.1251-1271.
7. H.J. Antunez and M. Kleiber, 1996, "Sensitivity of forming processes to shape parameters", *Comput. Methods Appl. Mech. Engrg.*, Vol.137, pp.395-409.
8. M.S. Joun and S.M. Hwang, 1998, "Die shape optimal design in three-dimensional shape metal extrusion by the finite element method", *Int. J. Numer. Methods Eng.*, Vol.41, pp.311-335.
9. S. Levy, C.F. Shinh, J.P.D. Wilkinson, P. Stine and R.C. McWilson, 1978, "Analysis of sheet metal forming to axisymmetric shapes", in B.A. Niemeier, A.K. Schmieder and J.R. Newby (eds.), *Formability Topics- Metallic Materials*, STP 647, ASTM, pp.238-260.
10. S.A. Majlessi and D. Lee, 1988, "Development of multistage sheet metal forming analysis method", *J. Mater. Shaping Technol.*, Vol.6, pp.41-54.
11. Y.Q. Guo, J.L. Batoz, J.M. Detraux and P. Duroux, 1990, "Finite element procedures for strain estimations of sheet metal forming parts", *Int. J. Numer. Methods Eng.*, Vol.30, pp.1385-1401.
12. K. Chung and O. Richmond, 1992, "Ideal forming- II. sheet forming with optimum deformation", *Int. J. Mech. Sci.*, Vol.34, pp.617-633.
13. K. Chung, F. Barlat, J.C. Brem, D.J. Lege and O. Richmond, 1997, "Blank shape design for a planar anisotropic sheet based on ideal forming design theory and FEM analysis", *Int. J. Mech. Sci.*, Vol.39, pp.105-120.
14. C.H. Lee and H. Huh, 1998, "Three dimensional multi-step inverse analysis for the optimum blank design in sheet metal forming processes", *J. of Mater. Process. Technol.*, Vol.80,

pp.76-82.

15. C.H. Lee and J. Cao, 2000, “Shell element formulation of multi-step inverse analysis for the design of axisymmetric deep drawing process”, to appear *Int. J. Numer. Methods Eng.*, Vol.50.
16. G. Eshel, M. Barash and W. Johnson, 1986, “Rule Based Modeling for Planning Axisymmetrical Deep-Drawing”, *J. Mechanical Working Technology*, Vol.14, pp.1-115.
17. S.K. Sitaraman, G.L. Kinzel and T. Altan, 1991, “A Knowledge-based Ststem for Process-sequence Design in Axisymmetric Sheet-metal Forming”, *J. Materials Processing Technology*, Vol.25, pp.247-271.
18. S.K. Esche, S. Khamitkar, G.L. Kinzel and T. Altan, 1996, “Process and die design for multi-step forming of round parts from sheet metal”, *J. Materials Processing Technology*, Vol.59, pp.24-33.
19. K. Sevenler, 1986, “Knowledge-based systems approach to forming sequence design for cold forging”, *Ph.D. dissertation*, Ohio state university, Columbus, OH.
20. William H. Press, Brian P.Flannery, Saul A. Teukolsky, William T. Vetterling, 1989, *Numerrical Recipes*, Cambridge University Press,New York.
21. Wang, X. and Cao, J., 2000, “On the prediction of side-wall wrinkling in sheet metal forming processes”, *International Journal of Mechanical Science*, Vol. 42/12, pp.2369-2394.
22. Lee, L.H., Cao, J., Xia, Z.C. and Tang, S.C. (2000) "Reduction of Forming Steps of an Axisymmetric Multi-step Drawing Problem via Numerical Modeling", SAE Paper No. 2000-01-1104, *2000 Society of Automotive Engineers International Congress & Exposition*, Detroit, MI.
23. A.L. Gurson, 1977, “Continuum theory of ductile rupture by void nucleation and growth: Part I – Yield criteria and flow rules for porous ductile materials”, *J. Engineering Materials and Technology*, Vol.99, pp.2-15.
24. V. Tvergaard, 1981, “Influence of voids on shear band instabilities under plane strain condition”, *Int. J. Fracture Mechanics*, Vol.17, pp.389-407.
25. S. Hao, W.K. Liu and C.T. Chang, 1999,”Computer implementation of damage models by finite element and meshfree methods”, to appear *Comput. Methods Appl. Mech. Engrg*.

Table 1: Results of optimization using various initial guesses.

Initial Value(mm)			Final Value(mm)		
r_1	r_2	d	r_1	r_2	d
33.0	28.5	110.0	30.0	60.0	117.6
30.0	37.5	110.0	27.6	60.0	114.0
18.0	28.5	98.0	27.3	60.0	114.0
18.0	51.0	126.	28.2	60.0	113.9

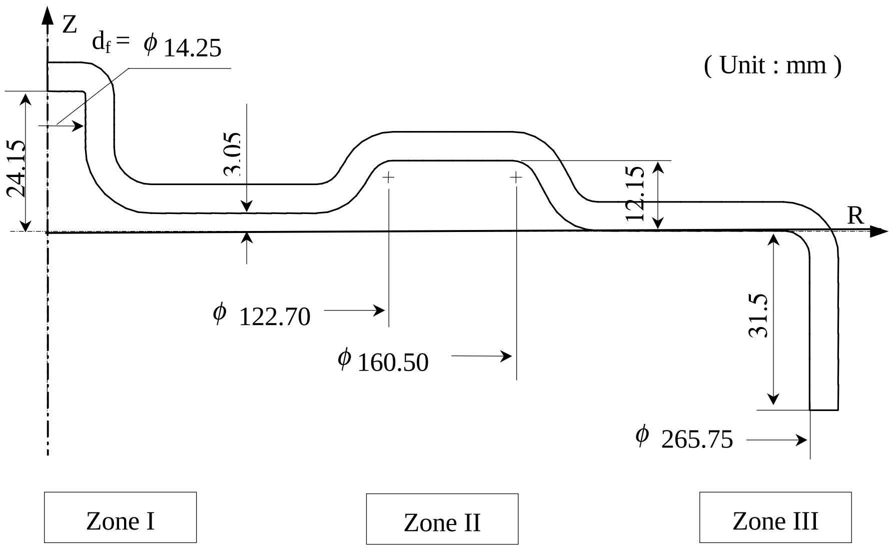


Fig.1 An automotive part of axisymmetric shape formed by multi-step drawing.

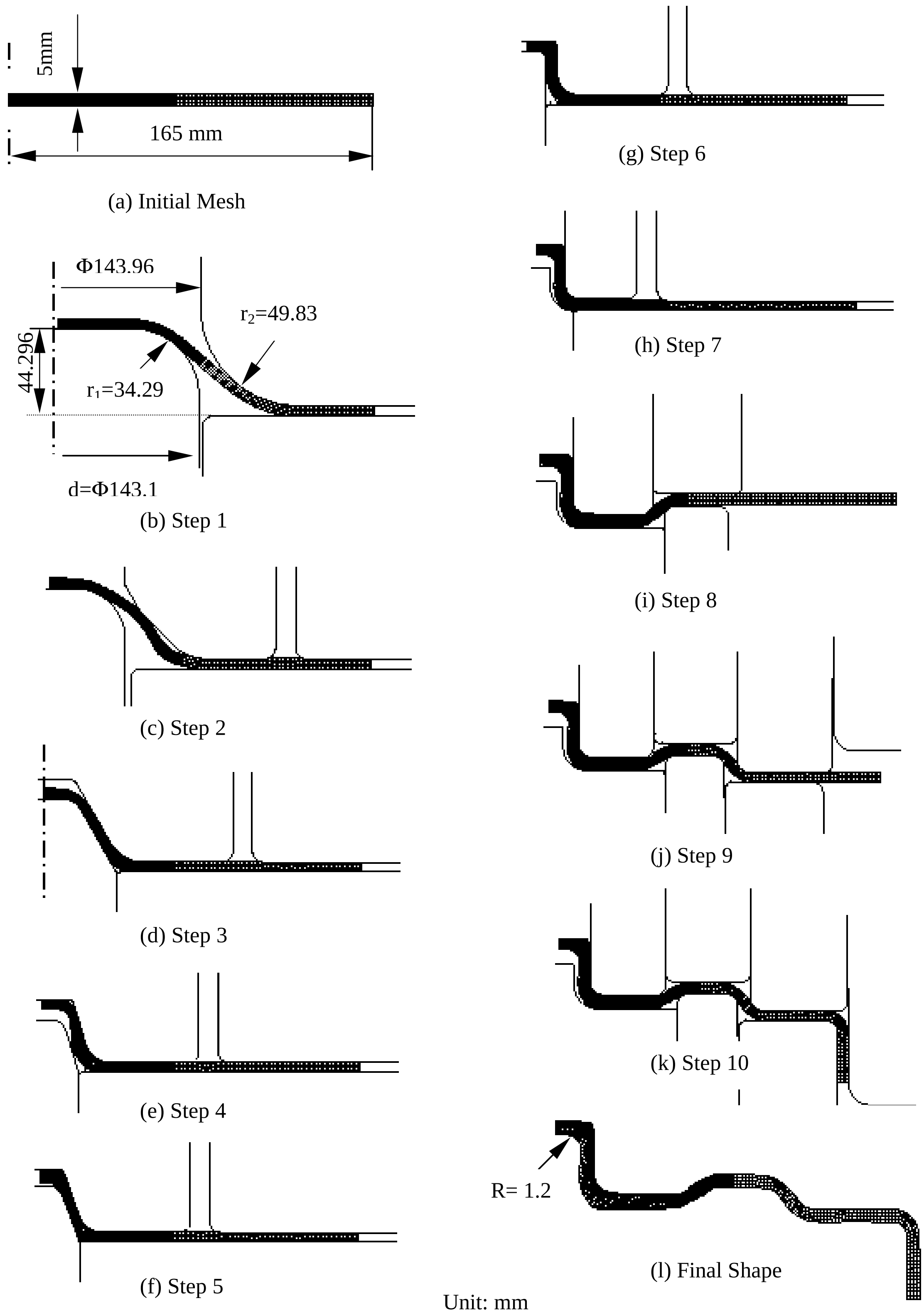


Fig.2 Initial geometry and deformed shapes for each drawing step in the original process.

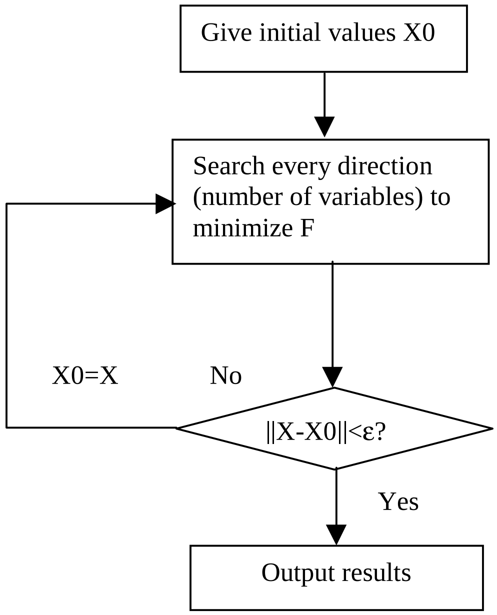
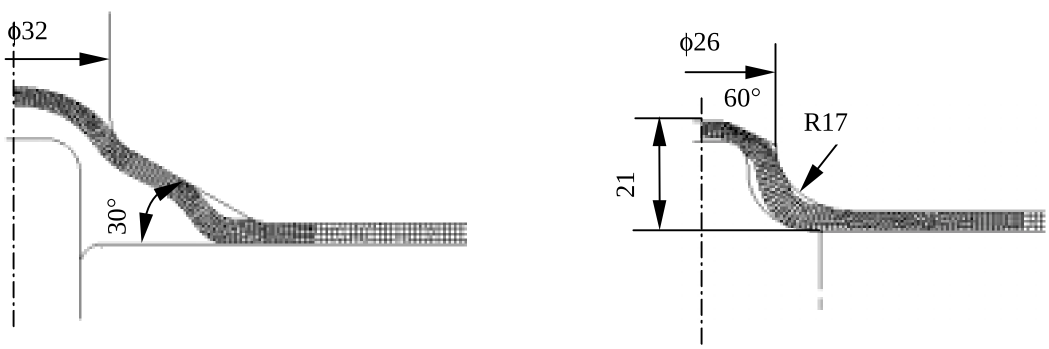
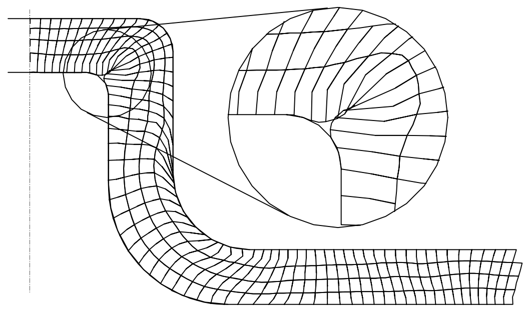


Fig.3 Optimization algorithm used in determining the tooling shape of Step 1.

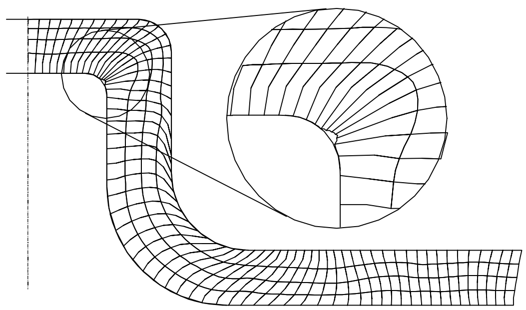


(a) Step2 (b) Step 3

Fig. 4 New tooling geometries of steps 2 and 3.



(a)



(b)

Fig.5 Comparison of deformed shapes at the end of step 4 with different die radii of step 3:

(a) Die radius = 13mm, (b) Die radius = 17mm.

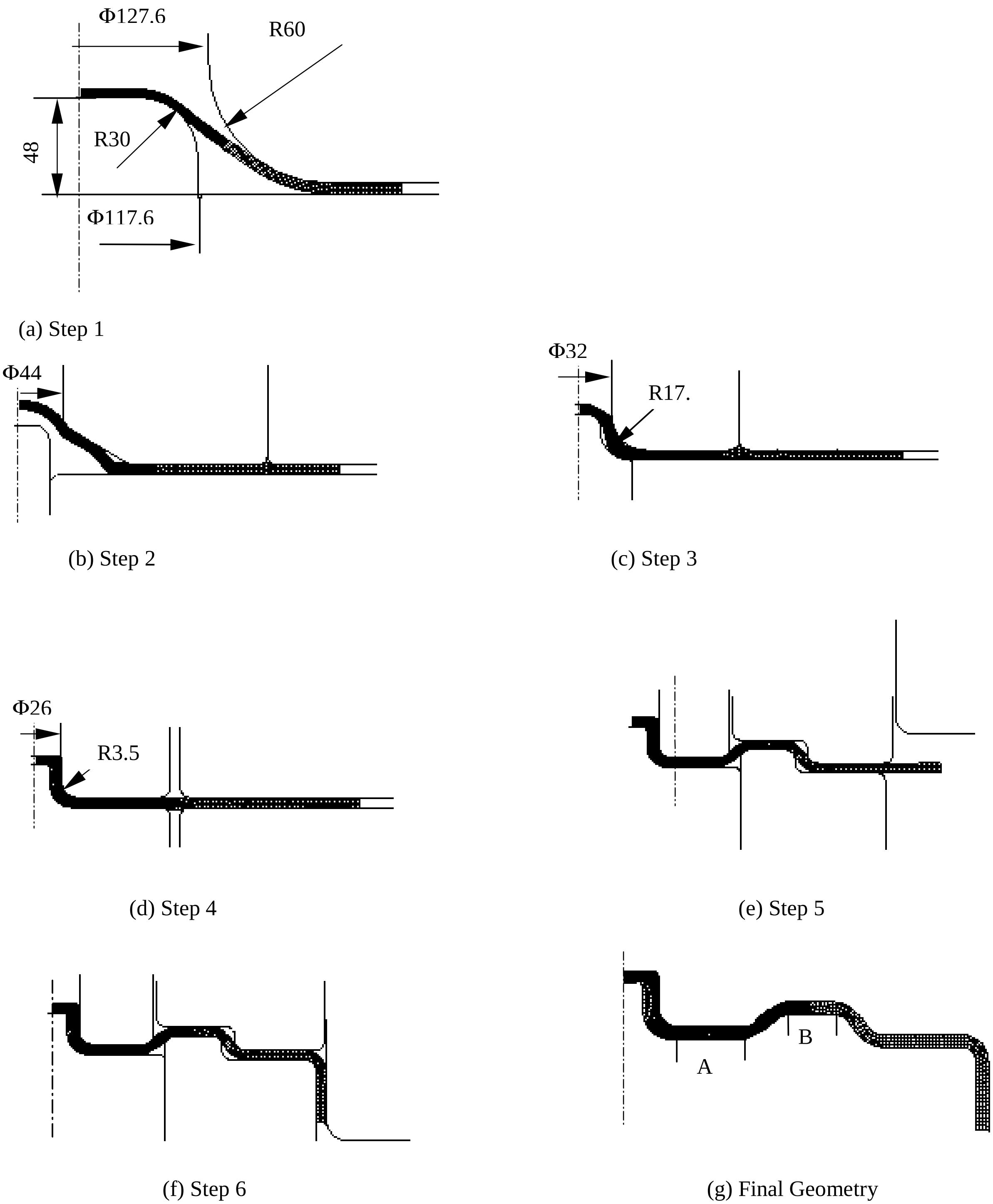
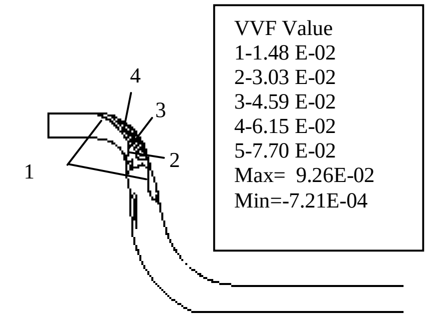
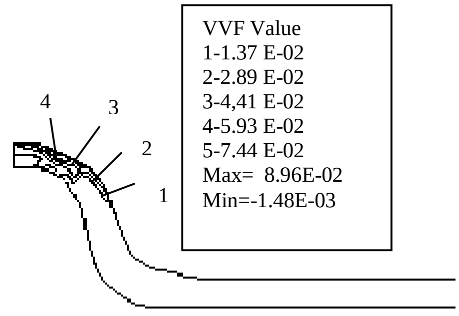


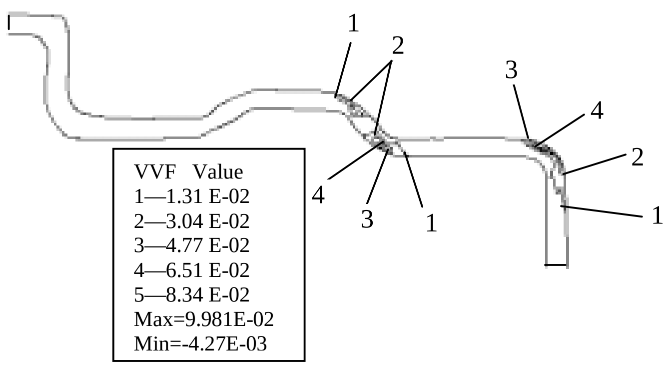
Fig.6 Deformed shapes of each drawing step in the new process



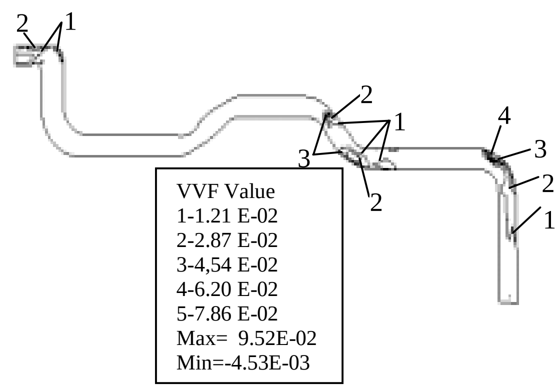
(a) contour of step 4 of old process



(b) contour of step 3 of new process



(c) contour of last step in old process



(d) contour of last step in new process.

Figure 7. Distributions of void volume fraction

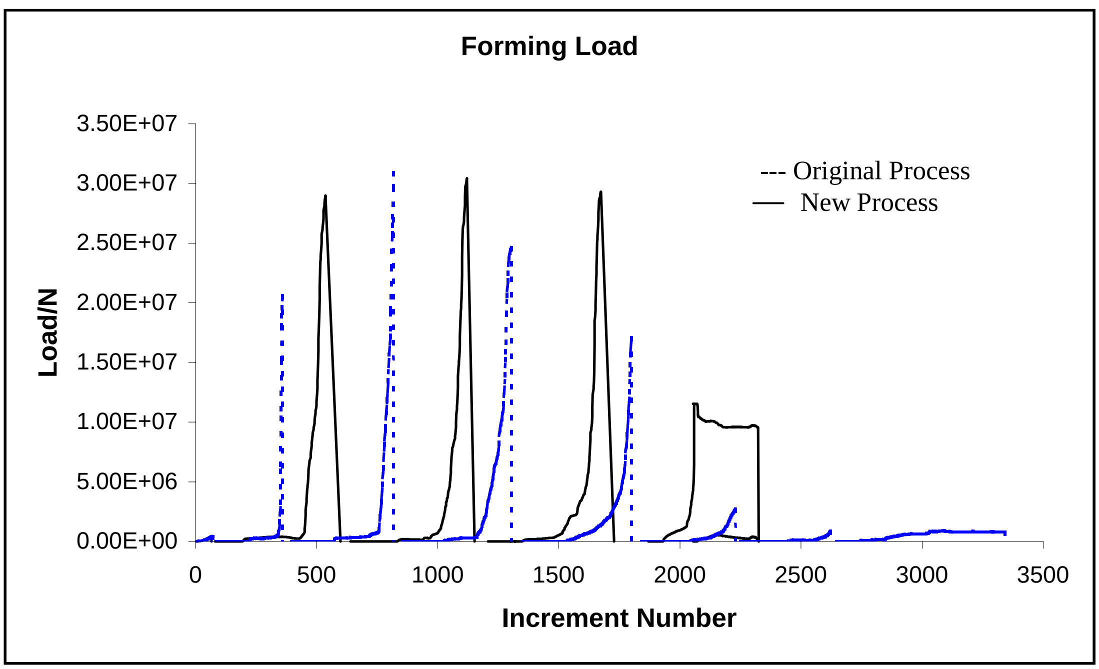


Figure 8 Forming Load of new & original processes