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Thinning Minimization for Forming Aluminum Beverage Can End Shells

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Forming simulations of the can end shell have been implemented based on both of the axisymmetric model and three-dimensional models, for a better understanding of the forming process. The comparison shows that the simulation results agree reasonably well with the experimental observations of the actual forming process. The influence of the loads applied to tools, the clearance between tools, the shape of the tool profile and the position of tools have been investigated, based on the axisymmetric model to save computational time. The design optimization method based on the numerical simulations have been applied to search the optimum design points, in order to reduce the thinning subjected to the constraints of the geometric shape of the shell and the suppression of wrinkles. The optimization results show that the thinning can be improved up to 4% by optimizing the forming route, adjusting the clearance and the load, and modifying the tool shape.

Nomenclature

H_1	=	Unit depth of the shell
H_2	=	Lip height of the shell
H_3	=	Panel depth of the shell
P_1	=	load applied to the upper piston
P_2	=	load applied to the die center
P_3	=	load applied to the lower piston
P_4	=	load applied to the panel punch
E	=	Young's modulus of the blank
ν	=	Poisson's ratio of the blank
σ_0	=	yielding stress of the blank
T_0	=	initial thickness of the blank before forming
T_{min}	=	minimum thickness of the shell after forming
ε_0	=	minimum circumferential plastic strain of the shell
A_{P4}	=	rate of change in the load applied to the panel punch
A_R	=	axial length ratio of the panel punch elliptic curve
ΔL_S	=	change in longitudinal clearance between the die center and upper piston

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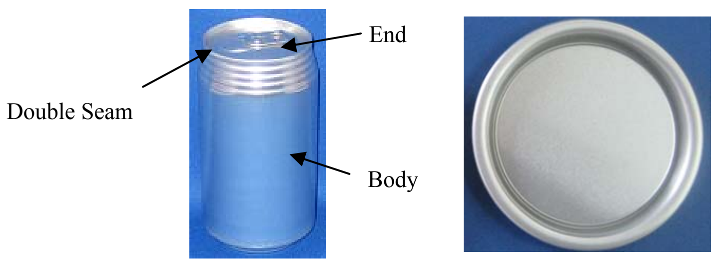
ΔL_A = up moving distance of the die center at initial position

I. Introduction

Sheet metal forming simulation technology has been continuously developed and computer capacity has been greatly improved recent years, which make it more realistic to design and to optimize dies and the forming process based on numerical simulations [1, 2]. 2-Piece aluminum cans (Fig.1a) have been used as beverage containers for more than thirty years because they have many merits such as lightweight, high productivity, high recycle-ability, hence environmentally friendly [3, 4]. Can-makers have never stopped doing research and development to pursue lighter can ends by reducing the end size and gauge while still keeping enough buckling strength by changing the shape of end shell. Since the late 1980s, the Finite Element (FE) method has been applied to predict can performance and to simulate the can forming process [5-14]. Development of functional cans, such as easy crushing cans, finger friendly can body and end, easy drinking bottles have recently been implemented utilizing the FE analyses [10-13]. In our previous study for the end shell development, structural optimization technology based on numerical simulations has been applied to minimize the weight of end shells subject to constraints of the buckling strength, the panel growth suppression and the other design requirements[14]. However, to form the end shell into a new geometrical shape, we also have to design optimum dies and its forming process.

Forming the sheet into the basic end shell needs three processes, namely blanking, shell forming and curling. The blanking operation is to cut the sheet into circular blank, while curling operation is to deform the curl of the shell into the shape required for seaming with the can body. The shell before curling is called “uncurled end shell” (Fig.1b), and its forming process is investigated in this paper. Though a number of shell shapes and forming methods have been developed in the past years, this paper focuses on the uncurled shell of the MF206 end that is the conventional 206 diameter end (outside diameter of the double seam is 2+6/16 = 2.375 inches, approximately 60 mm) for 2-piece beverage cans. The profile and nomenclature of the shell are shown in Fig. 2. After filling the beverage into the can body, the seaming panel radius of the end is contacted with the corresponding part of the can body, then the curl is double seamed with the flange of the can body. The shape and thickness of the shell play an important role in seaming quality as well as structural performance. Three geometrical dimensions of the shell, namely, the unit depth H_1, the lip height H_2 and the panel depth H_3 are adopted for a quick check of the shell forming results.

In this paper, the forming simulation of the end shell is performed using the FE method for a better understanding of the forming process. Simulation results and computational time are compared between an axisymmetric model and a three-dimensional (3D) model. The influences of the load applied to the tools, the clearance between the tools, the shape of tool profile and the tool relative position are then investigated. The design optimization method based on the numerical simulations are finally applied to search optimum design points, in order to minimize thinning subjected to the constraints of the geometrical shape of shell and the wrinkle suppression.



(a) 2-piece can (b) Uncurled end shell

Figure 1. Photos of 2-piece aluminum beverage can

II. Shell Forming Process

A. Tooling System

The axisymmetric cross section of tooling system utilized to form the end shell at its initial position is illustrated in Fig. 3. The system consists of three upper tools and three lower tools. The three upper tools are the Blank & Draw Die (BDD), the upper piston and the die center. Three lower tools are the lower piston, the Die Core Ring (DCR) and the panel punch. During shell forming process, loads of P_1, P_2, P_3, P_4, are applied constantly to the upper piston, the die center, the lower piston and the panel punch, respectively. Movement of the BDD is controlled by the shell press. The shell is formed by moving the BDD down to bottom dead center and then up to top dead center.

B. Shell Forming Simulation Based on Axisymmetric Model

Shell forming simulations using the commercial FE code, MSC.MARC are performed, based on an axisymmetric model. All tools are assumed to be rigid. The cross section of the blank is descritized into axisymmetric elements of four-node quadrilateral cross section. The material model used for the blank is an elasto-plastic von Mises material with isotropic hardening. Young's modulus E = 68.6 GPa, Poisson's ratio ν = 0.33 and the yielding stress σ_0 = 0.3 GPa are assumed. The friction coefficient between die surfaces and the blank is assumed to be 0.05. The initial thickness of the blank is T_0 = 0.260 mm.

Figure 4 shows the history curve of the minimum thickness during the forming process. The sheet profiles at main hinges of the curve are displayed in the same figure and the thinnest locations are indicated by arrows. To understand clearly the movement of metal, color marks are pasted to the blank model. It is observed that the minimum thickness decreases sharply between hinges N_A and N_B when the tip of the die center begins to apply a load to the sheet, and thinning of 4% occurs at the panel radius. The minimum thickness keeps almost constant followed by a little decrease when the die center begins to draw the sheet into the DCR cavity. The thickness decrease ratio increases again between hinges N_C and N_D, and 3% thinning occurs at contact part with the outside of the die center tip. After the sheet edge slides out of the clamp between the BDD and the lower piston, the minimum thickness keeps constant until dies reaching bottom dead center. The minimum thickness increases a little between hinges N_E and N_F and then drastically decreases when the panel punch rises up to form the panel and the panel radius. Between N_F and N_G, 4% thinning occurs in the panel wall. It is noticed that the thinning between N_C and N_G occurs at the same region of the sheet, in the other words, it moves across the round tip of the die center and finally stops in the clearance between the sidewalls of the die center and the panel punch. Figure 5 shows the thickness distribution of the shell in its final profile. The minimum thickness is T_{min} = 0.229 mm, namely, 11.9% thinning occurs. The key part of the shell cross section in its final shape, as shown in Fig.6, is compared to an actual sectioned shell manufactured by the shell press machine. It's confirmed that they matched each other well.

Wrinkling is also one of important factors to evaluate the forming quality. There are several ways to predict the wrinkle from the simulation results. This paper uses the Circumferential Plastic Strain (CPS) to predict the occurrence of wrinkling at the seaming panel radius subjected to a compressive circumferential stress. Figure 7 shows the CPS distribution of the shell. If the minimum CPS ε_0 is smaller than its threshold value, the wrinkle may be expected. The shell formed by the shell press machine does not show wrinkles, so it is confirmed that the minimum value of the CPS ε_0 = –0.17 does not reach its critical limit to cause wrinkling.

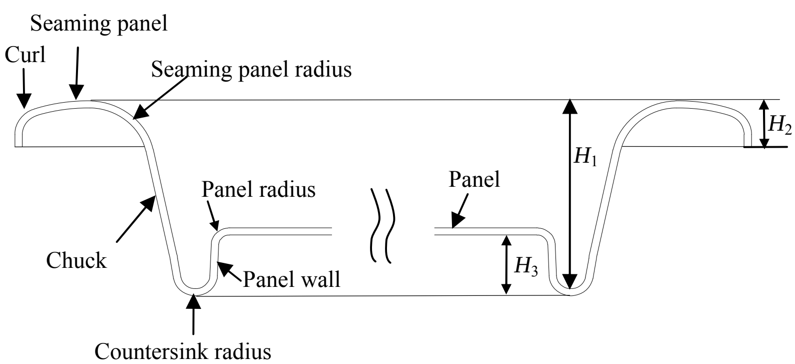


Figure 2. Cross section of uncurled end shell

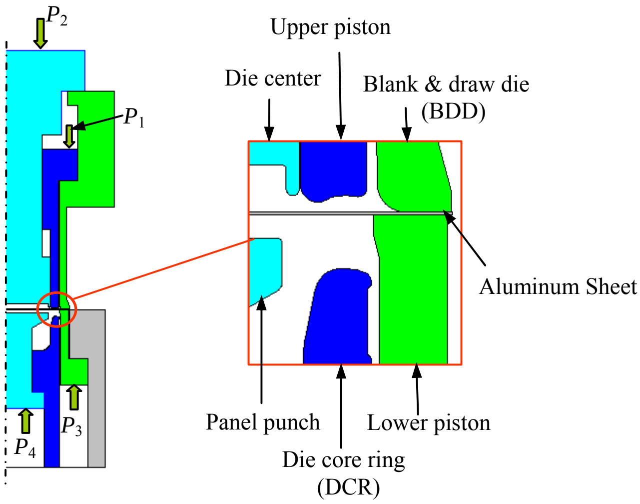


Figure 3. Axisymmetric cross section of tooling system

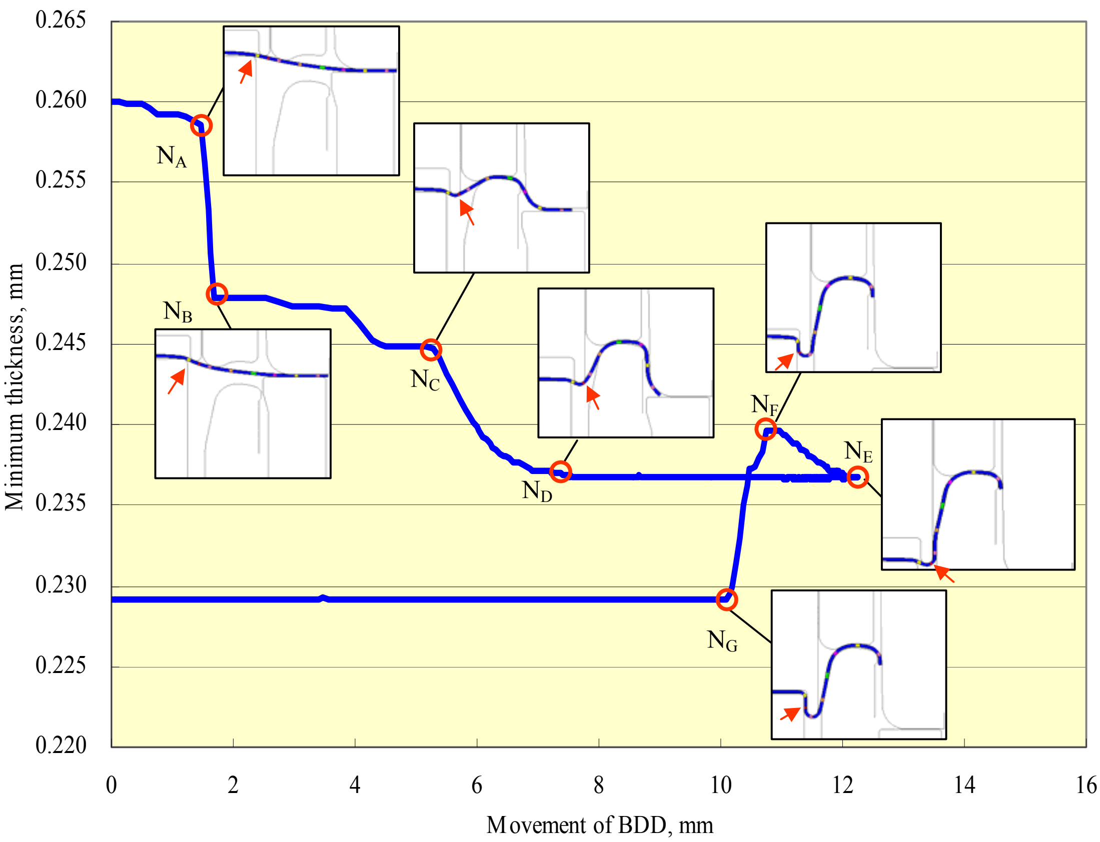


Figure 4. History of minimum thickness and its location.

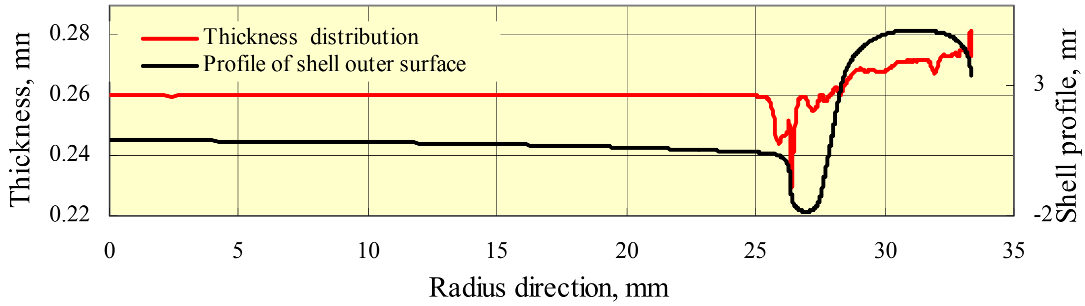


Figure 5. Formed shell thickness distribution obtained by forming simulation based on axisymmetric model.

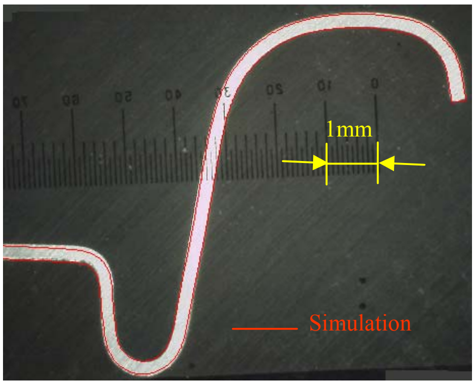


Figure 6. Profile comparison between simulation and an actual sectioned shell

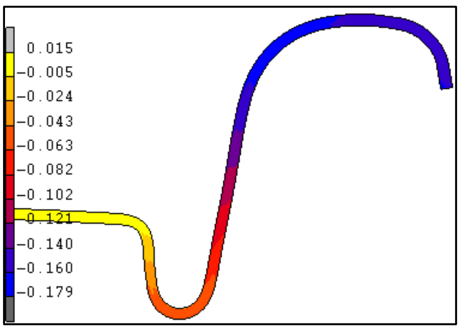
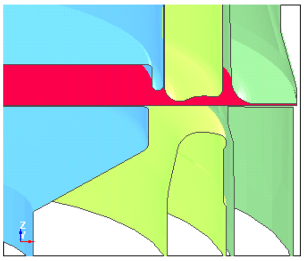


Figure 7. Circumferential plastic strain(CPS) distribution

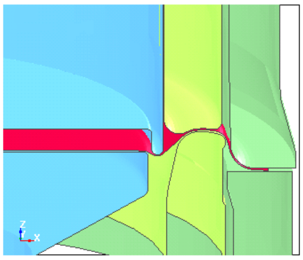
C. Shell Forming Simulation Based on Three-dimensional Model

Shell forming simulations using the FE code, LS-DYNA are also carried out based on a 3D model. In the actual shell forming using the press machine, the blank is designed into a non-circle shape to get earless shells. However, in the forming simulation, the blank is assumed to be a circular sheet with an isotropic material property. A quarter of blank is modeled with Belytschko-Tsay quadrilateral shell elements.

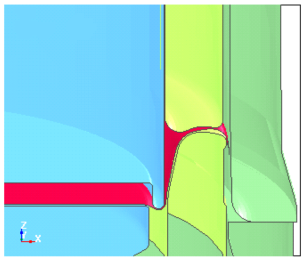
Forming simulation results in Fig.8 shows that forming process simulated by the 3D model is the same as that of the axisymmetric model. Figure 9 shows the thickness distribution of the formed shell. As compared with simulation results of the axisymmetric model, differences in the minimum thickness, geometric dimensions H_1, H_2 and H_3 are -0.02 mm, +0.02mm, -0.16mm and -0.02mm, respectively. These two models indicate thinning in the same locations. Since computational time of the axisymmetric model is much shorter than that of the 3D model, the axisymmetric model is used for further study.



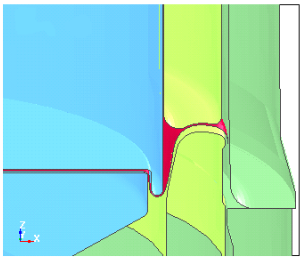
(a) Time = 0 ms



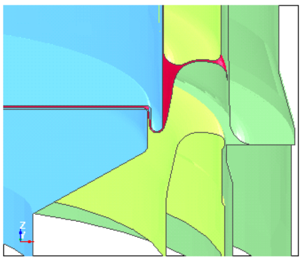
(b) Time = 8 ms



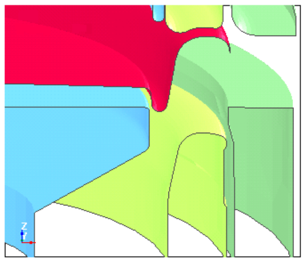
(c) Bottom dead center



(d) Time = 38 ms



(e) Time = 48 ms



(f) Final profile

Figure 8. Shell forming process simulation results

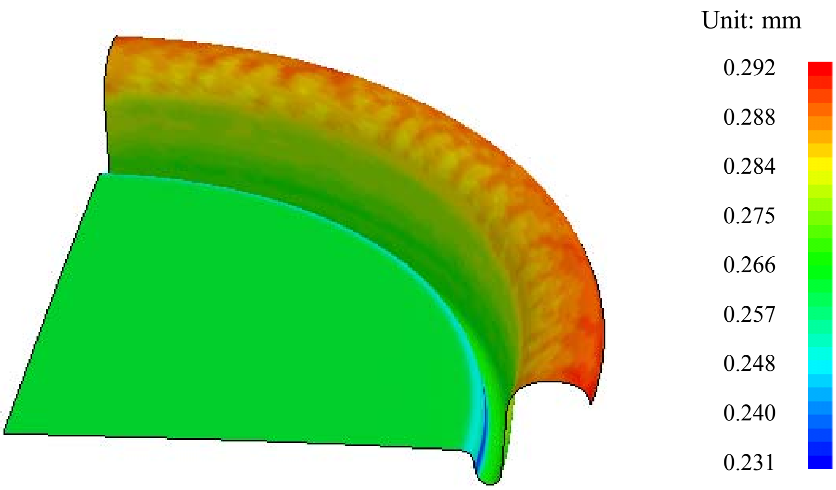


Fig. 9 Formed shell thickness distribution obtained by forming simulation based on a 1/4 model.

D. Influence on Forming Quality

Loads applied to the tools, profile of the tool upmost surface, clearance between tools, the forming route are considered to affect the forming quality, such as the resulting shape of the shell profile, thinning and wrinkling. Considering the restrictions in designing shell products and forming conditions, the simulations are performed to study the influences of loads applied to the upper piston, the die center and the panel punch, the influence of the panel punch profile, the influences of the longitudinal clearance between the die center and the upper piston as well as horizontal clearance between the BDD and the DCR, and the influences of distance at initial position if the die center and the panel punch moving longitudinally, respectively.

For example, it is observed that with the load applied to the panel punch P_4 changing from 90% to 1.2 times of the original value, the unit depth and panel depth of the shell increase and the other evaluation items decrease, especially the lip height decreases about 3.5% as compared with those of the base model. If the load P_4 is reduced to less than 80%, the panel punch is too weak to rise up for forming the panel wall. If the load P_4 is increased to twice, the metal is rolled into the clearance between the panel punch and the die center before reaching bottom dead center, resulting in no enough metal left for forming the curl.

As shown in Fig. 10, influences are also observed by changing the cross section profile of panel punch corner from circular curve to elliptic curve, whereas the length of horizontal axis of the elliptic curve is kept the same as the radius of original circular curve. If the ratio of vertical axis length to the radius, A_R = 0.68, the unit depth and the minimum thickness decrease a little while the lip height increases a little. Moreover, forming simulation results indicate that if reduces the longitudinal clearance ΔL_S = 0.035mm between the die center and the upper piston, the lip height decreases 1.5% and the minimum CPS decreases a little while the unit depth increases a little. It is also confirmed that if the die center is moved up a distance of ΔL_A = 6.25 mm at initial stage, the sheet may be delayed the drawing into the DCR cavity, hence, increase the minimum thickness up to 4%, decrease the lip height about 6% and the minimum CPS about 2%.

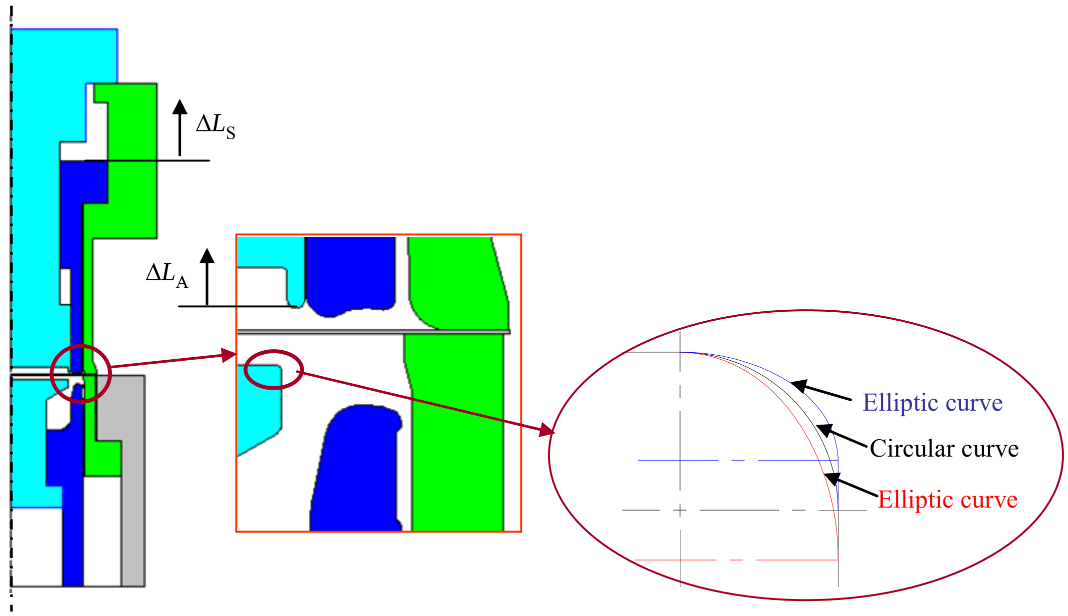


Figure 10 Changes in tooling system

III. Thinning Minimization

On the basis of the shell forming simulation results, it is observed that the thinning can be improved by selecting proper forming route, meanwhile the geometric shape of shell profile can be kept the same by designing the die shape, the clearance and the loads applied to the tools. The deign optimization method is applied to perform optimum design for forming the shell.

A. Formulation of Optimization Problem

The objective of design optimization is to minimize the thinning of end shell, which is equal to maximize the minimum thickness. The unit depth H_1, the lip height H_2 and the panel depth H_3 are restricted within prescribed limits, to ensure the shape of shell profile for the following shell forming process, the seaming operation and for keeping required buckling strength. In order to avoid wrinkling, the minimum CPS ε_0 is also considered to be larger than an allowable minimum bound. The design variables may be selected from the forming conditions, the die shape and the positions. The problem is then posed as:

Find design variables: $\boldsymbol{X} = \{x_i\}$, $i = 1, \ldots, n$ (n: the number of design variables) (1)

maximize $f = T_{\min}(\boldsymbol{X})$, (2)

subject to $g_1 = H_{1\min} / H_1(\boldsymbol{X}) - 1 \le 0$, $g_2 = H_1(\boldsymbol{X}) / H_{1\max} - 1 \le 0$,

$g_3 = H_{2\min} / H_2(\boldsymbol{X}) - 1 \le 0$, $g_4 = H_2(\boldsymbol{X}) / H_{2\max} - 1 \le 0$,

$g_5 = H_{3\min} / H_3(\boldsymbol{X}) - 1 \le 0$, $g_6 = H_3(\boldsymbol{X}) / H_{3\max} - 1 \le 0$,

$g_7 = \varepsilon_{0\min} / \varepsilon_0(\boldsymbol{X}) - 1 \le 0$, (3)

$$x_i^L \le x_i \le x_i^U, \quad i = 1, \ldots, n \tag{4}$$

where $H_{1\min}$ and $H_{1\max}$, $H_{2\min}$ and $H_{2\max}$, $H_{3\min}$ and $H_{3\max}$ are the allowable upper and lower bounds of the unit depth H_1, the lip height H_2, and the panel depth H_3, respectively. $\varepsilon_{0\min}$ is the allowable lower minus bound of the CPS. x_i^U and x_i^L are the upper and lower bounds of design variable i, respectively.

The Response Surface Approximation(RSA) method[15] based on the FE analyses is used to solve the optimization problem. At first, select the design variables and define the design space. Then, an orthogonal array in the design-of-experiment is used to arrange the design points and the FE code is utilized to implement the simulation of forming process. The RSA technique is then applied to generate an approximate response surface in terms of the selected design variables. The numerical optimization program is then used to perform the optimization calculation based on the response surfaces. If it is necessary to move the design space, according to judgment based on the optimization results, then the above steps are repeated.

B. Numerical Examples

As a numerical example, the up moving distance of the die center at initial position ΔL_A, the change in the longitudinal clearance ΔL_S between the die center and the upper piston , the rate of change in the load applied to the panel punch A_{P4}, and the axis length ratio A_R of the panel punch elliptical curve are selected as the design variables. The shell forming simulations are carried out for 9 design points that are arranged using the orthogonal array L_9. On the basis of the numerical simulations, the response surfaces of the minimum thickness, the unit depth, the lip height, the panel depth and the minimum CPS are constructed in terms of the four design variables and the approximated optimization problem is then solved by the mathematical programming method.

If changes in H_1, H_2 and H_3 are restricted within about 0.02mm as compared with those of the baseline and $\varepsilon_{0\min} = -0.17$, in the design space of

$$0 \le \Delta L_A \le 7.0\text{mm}, -0.2\text{mm} \le \Delta L_S \le -0.05\text{mm}, 0.95 \le A_{P4} \le 1.05, \ 0.5 \le A_R \le 1.5 ,$$

the optimum values for the design variables at the optimum point are then obtained as

$$\Delta L_A = 6.45 \text{ mm}, \Delta L_S = -0.07 \text{ mm}, \ A_{P4} = 0.95, A_R = 1.50.$$

The forming simulation results at the optimum design point are $T_{\min}$ = 0.240 mm. The history curve of the minimum thickness at the optimum point is compared with that of baseline, in Fig. 11. The thinning is improved from 11.9% to 7.7%.

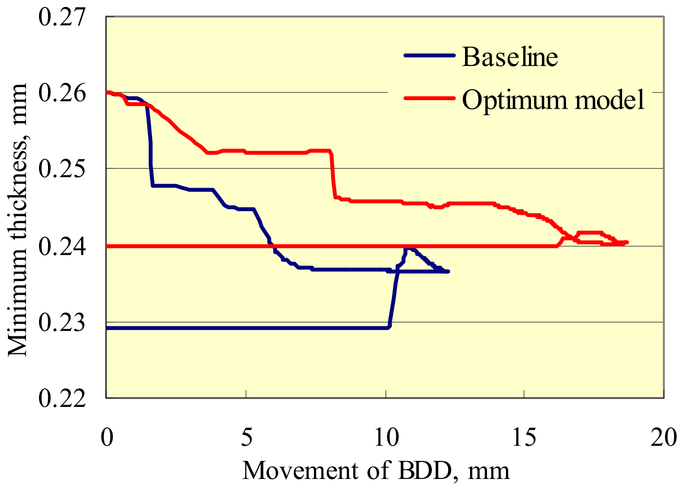


Figure 11. Comparison of minimum thickness history

III. Conclusion

The forming simulation of end shell has been carried out based on both of the axisymmetric model and 3D models, for a better understanding of the forming process. The comparison shows that the simulation results agree reasonably well with the experimental observations of the actual forming process. The influence of the loads applied to the tools, the clearance between the tools, the shape of the tool profile and the position of the tools have also been investigated, based on the axisymmetric model to save computational time. The design optimization method based on the numerical simulations has been applied to search the optimum design points, in order to reduce the thinning subjected to the constraints of the geometric shape of shell and the suppression of wrinkles. The optimization results show that the thinning can be improved from 11.9% to 7.7% by optimizing the forming route, adjusting the longitudinal clearance between the die center and upper piston, adjusting the load applied to the panel punch, and modifying the shape of the panel punch corner.

Furthermore, the optimum design based on shell forming simulations may be performed to develop a new tooling system as well as a new shell profiles.

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