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Tool design in a multi-stage drawing and ironing process of a rectangular cup with a large aspect ratio using finite element analysis

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Abstract

Tool design is carried out for a multi-stage deep drawing and ironing process of a rectangular cup with the large aspect ratio using the result of the finite element analysis. The analysis incorporates three-dimensional continuum elements for an elasto-plastic finite element method with the explicit time integration scheme using LS-DYNA3D. The analysis simulates the five-stage deep drawing and ironing process with the thickness control of the cup wall. Simulation is performed in order to investigate the failure by tearing during the forming process at the initial state of tool design. The analysis reveals that the difference of the drawing ratio within the cross section induces non-uniform metal flow which causes severe local extension. The irregular contact condition between the blank and the die also induces non-uniform metal flow which causes local wrinkling. This paper identifies such unfavorable mechanism in the rectangular cup drawing with ironing and proposes a new tool design with the guideline for modification in the design of the process and the sequential tool shape. The finite element analysis result with the improved tool design confirms that the proposed design not only reduces the possibility of failure but also improves the quality of a deep-drawn product. The numerical result shows fair coincidence with the experimental result.

Keywords: Tool design; Multi-stage rectangular cup deep drawing and ironing process; Large aspect ratio; Finite element analysis

1. Introduction

Rectangular and elliptic cups with the large aspect ratio are widely used for electric parts such as the battery case, the semiconductor case, the crystal vibrator and the motor case in the industry. While the demand of such cups increases rapidly, the technology for design and manufacturing of such cups still needs more development in order to reduce the lead-time and improve the productivity and the product quality. Such products are manufactured by a multi-stage deep drawing process with ironing by the transfer press without interruption for additional processing such as annealing and trimming. The continuous multi-stage forming is desirable from the viewpoint of the productivity and the cost saving. The ironing process is used in most can manufacturing processes since it controls the wall thickness, the strength and the height of the drawn cup easily with an additional advantage of saving blank material.

In the multi-stage drawing process, the blank material experiences additional complex deformation in each stage compared to the conventional single-step deep drawing process. The process generally involves the additional bending, unbending, stretching and severe contact in the cup wall with ironing as well as compression and shear by the different drawing ratio during the subsequent drawing stage. Since the deformation mechanism is very complicated and the final mechanical properties are difficult to predict, the process design is not easy to manufacture successfully the product for a desired shape and material properties. The deformation inherently proceeds with the irregular shapes of the cross section and contact conditions that cause failure. Success or failure of the forming process is influenced by many process parameters such as the drawing ratio in each stage, the difference of the drawing ratio within the cross section, the shape of the die including the die radius, the

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amount of the die clearance, the strain hardening coefficient, formability, the lubrication condition, the degree of ironing and so forth.

Many researches on the multi-stage deep drawing process of the non-circular cup was carried out with trial-and-error-based experimental works in the manufacturing industry without the fundamental understanding of the complicated deformation mechanism. Recently, the finite element method has been introduced to the analysis of the forming process and provided useful information to the manufacturing process design. The finite element analysis of the forming process with the shell element has advantages of obtaining deformed shapes and contact conditions with moderate computing time. The shell element analysis, however, is unable to consider the thickness reduction in the cup wall when the clearance between the punch and the die is smaller than the sheet thickness since the shell element cannot offer correct solution in the compression loading state along the thickness direction. Continuum element is preferable to the shell element in the multi-stage forming process with ironing since the normal compression force and the friction force by the contact constraint in the blank are large and very important at the punch–blank–die contact condition in the cup wall.

The multi-stage deep drawing process was studied by Swift in the 1940s. Chung and Swift [1] carried out experimental studies on the multi-stage deep drawing process of the cylindrical cup. Parsa *et al*. [2] carried out rigid-plastic finite element analysis of the two-stage forward and reverse redrawing process. The success or the failure of the forming process was affected by many process parameters such as the drawing ratio of the first and the second stage, the strain hardening coefficient, the shape of the die and the annealing condition. Chung *et al*. [3] developed the three-dimensional finite element code for simulation of the multi-stage sheet metal forming process and applied in the four-stage drawing process of an axisymmetric yoke. Almost all researches done so far have been focused on the multi-stage analysis of the axisymmetric cup with the small aspect ratio because it was rather easy to estimate the deformed shape and the strain distribution. Since the elliptic and rectangular cups in the present study are formed with the gradual change of the cross section shape at each stage, the successful forming needs the adequate design of the tool shapes, the amount of the tool clearance and the accurate estimation of the thickness distribution. Recently, Huh *et al*. analyzed the four stage deep drawing process of an elliptic cup using a finite element inverse method with membrane elements [4] and an elasto-plastic finite element method with shell elements [5]. They have revealed that the non-uniform drawing ratio in the cross section induced non-uniform metal flow to cause failures such as wrinkling and tearing. Although the analyses clarified the deforming mechanism, they could not predict the thinning in the cup wall by ironing because the elements used could not calculate the through-thickness deformation.

Studies on the ironing process in the can manufacturing process have been focused on experimental researches because the numerical analysis needed a lot of computation cost and time. Saito *et al*. [6] measured the punch force and the friction force in the cup ironing process. They carried out ironing experiments of aluminum cups and discussed the effect of the lubrication on the quality of the product. A few researchers carried out basic numerical analyses such as the upper bound method [7] and the slab method [8]. They investigated the effect of process parameters such as the die angle and the friction force on the success or failure of the ironing process. Their researches had limitations because the plastic hardening effect and the contact mechanism were not considered exactly. In order to clarify the deformation mechanism and the contact phenomena, finite element analysis is indispensable to simulation of the multi-stage ironing process. Odell [9] and Delarbre and Montmitonnet [10] analyzed the cup ironing process by the finite element method with continuum elements in two dimensions. The effect of the friction and the intake angle was studied. Takeuchi [11] pursued finite element simulation in order to optimize the tool shape and the process condition. Baillet *et al*. [12] used an explicit finite element method in the analysis of the aluminum can ironing process. They studied the influence of the ironing speed, the friction coefficient and the reduction rate on the quality of ironed products. They commented that a dynamic projection method produces better solutions than the penalty method for the contact scheme in order to inspect the fracture during the ironing process.

In this paper, simulation-based design modification is introduced to the multi-stage deep drawing with ironing of a rectangular cup. This paper provides the initial design criterion and proposes the guideline on the design modification from the finite element analysis result. The analysis is carried out by a commercial code LS-DYNA3D [13] with continuum elements in the three dimensions. The simulation confirms the real deformation mechanism and inspects contact conditions at the tool–blank interface. The analysis is concerned with the five-stage deep drawing process of a rectangular cup with the large aspect ratio. The original design is examined by the finite element analysis and the reason of the unfavorable result is explained. Then, the modification guideline for the new tool design is proposed according to the finite element analysis result in order to lessen the possibility of failure during the forming process. The result from the numerical analysis shows fairly good agreement with the experimental results. After the slight modification of the tool shape, the rectangular cup is produced without failure such as tearing or wrinkling and uniform deformation of the whole domain is achieved even in the sharp corner.

2. Elasto-plastic finite element method

A finite element simulation of a multi-stage rectangular cup forming is carried out with an explicit elasto-plastic finite element method using LS-DYNA3D. The governing equations of motion at a material point are given as follows:

$$\sigma_{ij,j} + \rho b_i = \rho a_i \quad (1)$$

$$\sigma_{ij} n_j = t_i(t) \text{ on } \partial D_\mathrm{f} \quad (2)$$

$$u_i = g_i(t) \text{ on } \partial D_\mathrm{d} \quad (3)$$

where σ_{ij} is Cauchy stress, ρ is the current density, b_i is the body force density, a_i is the acceleration, the comma denotes covariant differentiation, ∂D_f is the traction boundary where the traction vector $t_i(t)$ is specified and ∂D_d is the displacement boundary where the displacement $g_i(t)$ is prescribed. n_i denotes the unit outward normal to the boundary surface.

The variational formulation from the principle of virtual work can be written as follows:

$$\delta\pi = \int_\Omega \rho a_i \delta u_i \, \mathrm{d}D + \int_\Omega \sigma_{ij} \delta u_{i,j} \, \mathrm{d}D - \int_\Omega \rho b_i \delta u_i \, \mathrm{d}D - \int_{\partial D_\mathrm{f}} t_i \delta u_i \, \mathrm{d}\Gamma = 0 \quad (4)$$

where δu_i is an arbitrary variation of the displacement field compatible with the boundary condition. The finite element equation is derived as the following equation with the spatial discretization using the iso-parametric shape function $N_\alpha(\alpha=1\sim8)$ for the eight-node brick element.

$$\sum_{nel=1}^{n} \left\{ \int_{\Omega_{nel}} \rho \mathbf{N}^T \mathbf{N} \mathbf{a} \, \mathrm{d}D + \int_{\Omega_{nel}} \mathbf{B} \boldsymbol{\sigma} \, \mathrm{d}D - \int_{\Omega_{nel}} \rho \mathbf{N}^T \mathbf{b} \, \mathrm{d}D - \int_{\partial D_\mathrm{f}} \mathbf{N}^T \mathbf{t} \, \mathrm{d}\Gamma \right\} = 0 \quad (5)$$

where $\mathbf{B}$ is the strain-displacement matrix, and $\mathbf{a}$, $\boldsymbol{\sigma}$, $\mathbf{b}$ and $\mathbf{t}$ denote the discretized values of the acceleration, the stress component, the body force density and the traction vector, respectively.

The dynamic force balance equation can be rearranged to the following matrix form after mass lumping:

$$\mathbf{Ma} = \mathbf{F}_\mathrm{ext} - \mathbf{F}_\mathrm{int} \quad (6)$$

where, $\mathbf{M}$, $\mathbf{F}_\mathrm{ext}$ and $\mathbf{F}_\mathrm{int}$ are the lumped mass matrix, the external force vector and the internal force vector, respectively.

The analysis scheme adopts the eight-node brick element with the selective reduced integration scheme. The reduced integration scheme often induces hourglass modes although it is effectively used in the conventional forming process. The severe contact condition in the cup wall generates so large contact forces and friction forces at contact nodes that elements undergo unfavorable deformation in the ironing analysis. In order to treat the severe contact phenomena between the tool and the blank, the Lagrangian multiplier method is adopted in spite of the much consumption of the computing time since the non-penetration condition at the contact region is not satisfied by the penalty method due to the severe contact problem. The tool shape at each stage is discretized with the four-node shell element and the material properties of the tools are assumed to be rigid. Contact searching is carried out between the outer surface of the tool and the blank and the appropriate contact forces are imposed to the contact nodes in order to prevent oscillation of nodes due to the dynamic effect. The contact constraint is imposed at the outer and inner surface of the blank since accurate contact treatment is an important factor especially at the contact interface between the blank, the cup holder and the die in the multi-stage deep drawing process.

3. Analysis condition

The rectangular cup in the present analysis is formed by a five-stage deep drawing process from a flat blank. Ironing is pursued at each forming stage in order to achieve the gradual reduction and uniformity of blank thickness. The shaping and the bottoming processes are carried out after the drawing and the ironing processes. The ratio of the height to the minor axis of the cross section, that is called the aspect ratio in this paper, is over 7.6 after the bottoming process. In the initial design, the first and the second stage of the drawing processes are performed with the cylindrical punch to impose uniform deformation while the third and the fourth stages are performed with the elliptic punch to form the desired shape. After the fourth stage, the cross section of the punch is changed to be a rectangular shape gradually. The elliptic and rectangular cross section of the punch after the second stage is constructed by folding of two circular arcs that have different origins and radii in the initial design. The cross sectional shape of the punch and the die cavity at each stage is shown in Fig. 1. The finite element mesh system for the blank consists of 3093 nodes and 1950 elements for one quarter of the domain as shown in Fig. 2. The blank is discretized by two layers of brick elements in the thickness direction in order to consider the plastic bending deformation and ironing

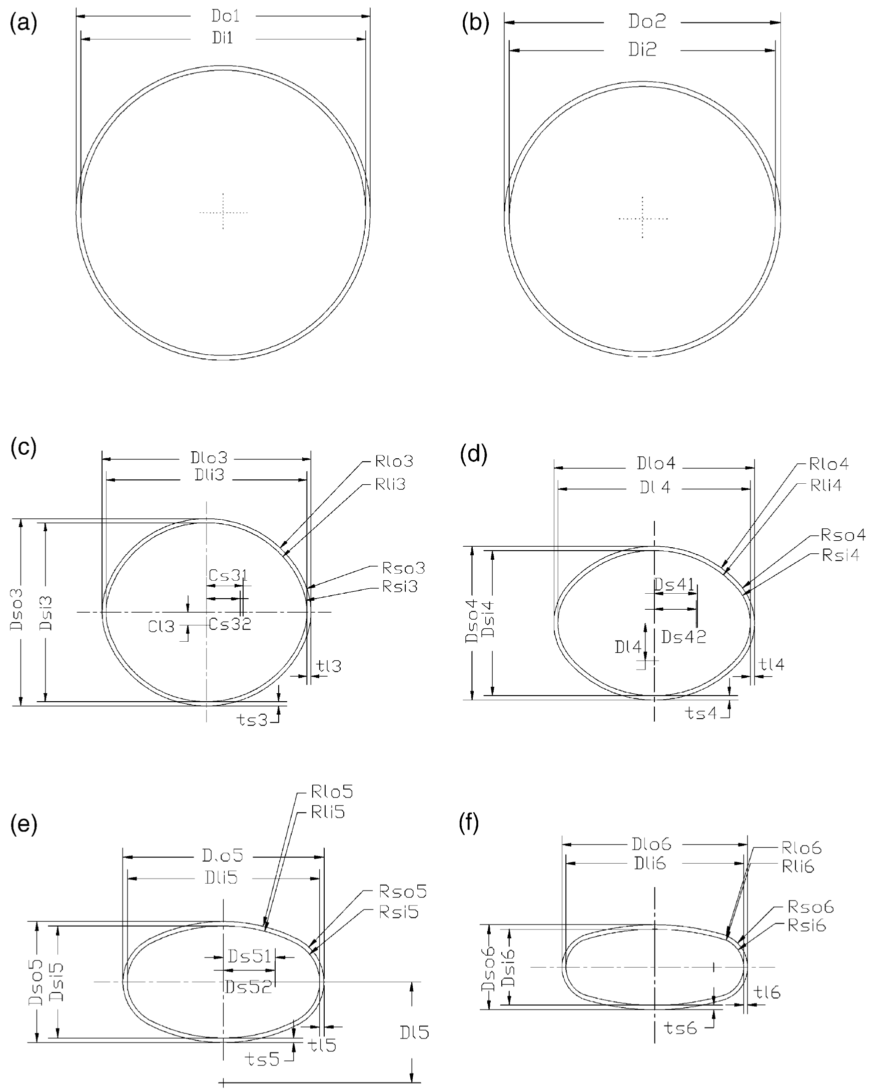

Fig. 1. Punch profiles at each forming stage in the initial design: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 5; and (e) stage 6.

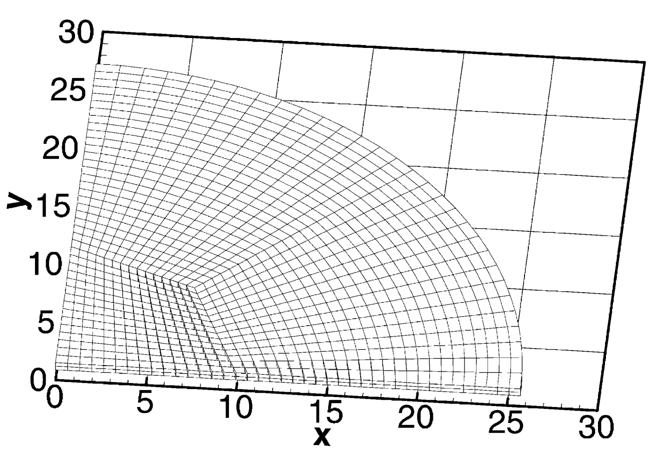

Fig. 2. Initial mesh system for the blank discretized by continuum elements.

effectively with moderate computation time. The forming tools consist of the punch, the blank holder and the die. Fig. 3 shows the finite element models of the tool and the blank from the first to the fourth stage in the initial design. Table 1 shows the reduction ratio of ironing at each stage.

The material properties are determined from the tensile test and relevant experiments for numerical simulation. The material used in the analysis is the SPCE-SB cold-rolled steel whose flow stress is expressed as $\bar{\sigma} = 521.86(0.014834 + \bar{\varepsilon}^{p})^{0.23373}$MPa. The initial sheet thickness is 0.5 mm and the initial blank diameter is 51.5 mm. The Coulomb friction coefficient at the contact interface is 0.1. The density is 7.98×10^{-6} kg/mm^3. The material properties obtained from the tensile test are as follows: Young's modulus of 201 GPa; Poisson's ratio of 0.3; and the initial yield stress of 194.72 MPa.

The blank material is assumed to be isotropic to sim-

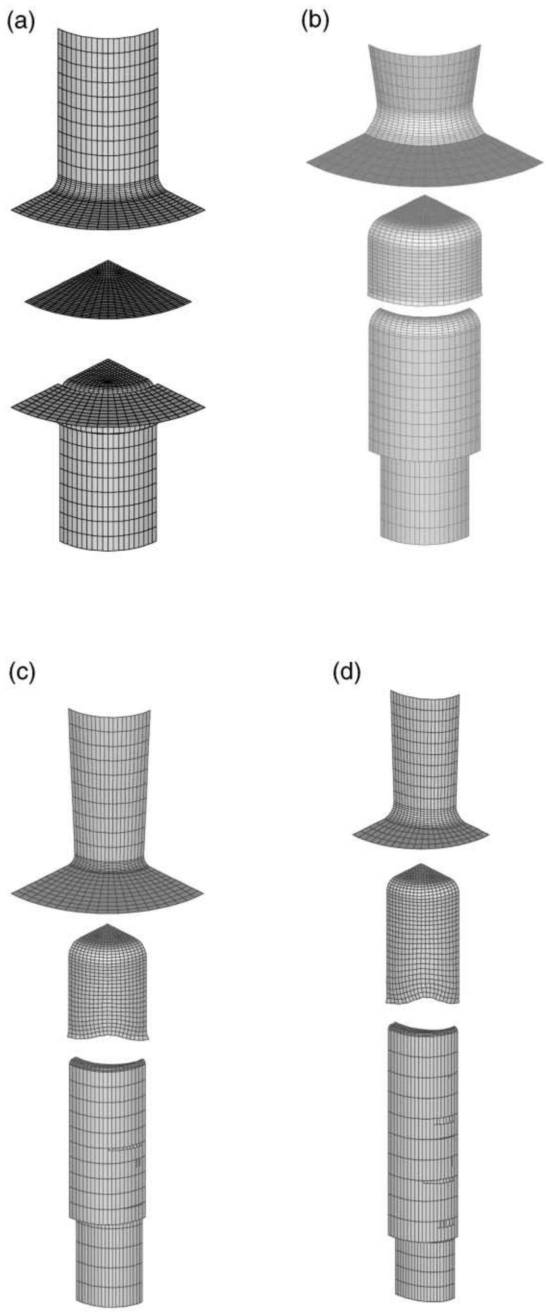

Fig. 3. Shape of tools and the blank in the initial design: (a) stage 1; (b) stage 2; (c) stage 3; and (d) stage 4.

plify the simulation. In the explicit simulation, the step size for the analysis is determined from the elastic modulus, the density and the mesh size of the blank. In the present analysis, a mass scaling scheme is used to increase the density of the blank to ten times of the original density, which increases the time step size about 3.3 times. The mass scaling scheme produces no problem of excessive kinetic energy during the simulation. The punch speed is fixed to 1 m/s. The analysis is carried out until the blank is fully drawn from the binder. The blank holding force of 5 kN is applied at the first stage and removed thereafter. Instead of the blank holder, a fixed cup holder is utilized instead of the blank holder in order to control metal flow and to prevent formation of wrinkling at the flange.

4. Analysis results of the initial design

Finite element simulation using explicit time integration is performed with the analysis conditions described in the previous section. The simulation result reveals that ill-forming problems cause failure in the initial design with the information about the contact condition as well as the deformed shape and the strain distribution during forming.

Fig. 4 shows deformed shapes at each stage when the blank is fully drawn from the binder. The figures confirm that the simulation has been performed successfully. At the fifth stage, severe stretching is observed along the minor axis in the deformed shape. This is due to the high drawing ratio in the direction of the minor axis compared to that of the major axis. At the third stage, the shape of the cross section of the punch and the die cavity is changed from a circle to a near-ellipse, called merged arcs, which causes non-uniform metal flow into the cavity. From possibility of tearing, it is predicted that the process design of the drawing ratios in the initial design fails to produce the rectangular cup successfully. The simulation result suggests that the design of the drawing ratio and the cross section should be carried out very carefully although the different drawing ratio in the cross section is inevitable.

Fig. 5 shows the thickness distribution in the fully drawn cups with the desired thickness by the ironing process in the cup wall at each forming stage in the

Table 1
Desired thickness reduction of the cup wall by the ironing process

Thickness (mm)	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Major axis	0.4925	0.46	0.43	0.42	0.41
Minor axis	0.4925	0.46	0.45	0.44	0.43

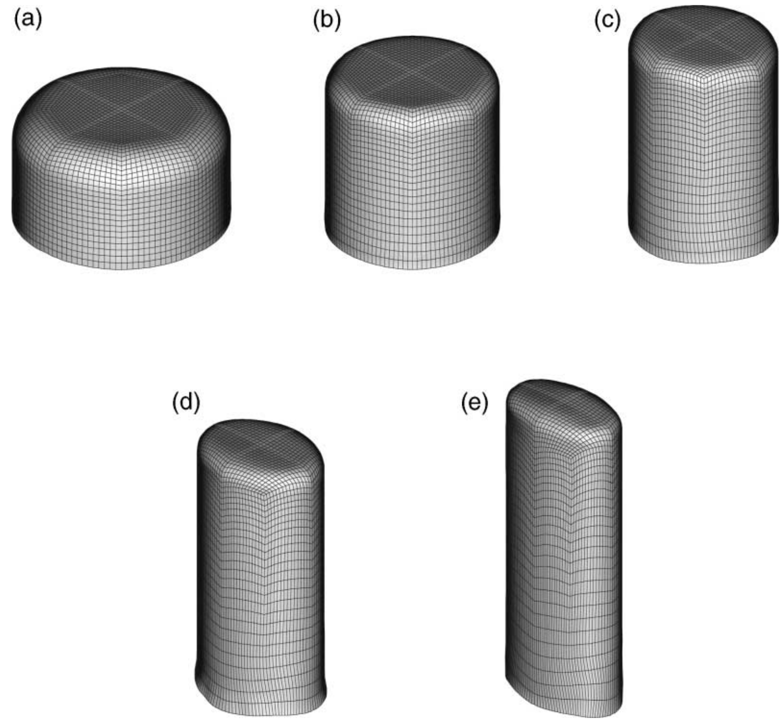

Fig. 4. Deformed shapes of the blank at each forming stage with the initial design: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 4; and (e) stage 5.

initial design. Distributions of the thickness strain explain thinning at the shoulder region of the punch along the major axis. The amount of the maximum thickness reduction is 28% after the fifth stage, which means that the possibility of tearing is very high in the initial design. Fig. 6 shows that the blank thickness near the shoulder region is reduced in the cup wall below the ironing reference thickness slightly because additional tension force is applied to the drawn cup by the severe contact in the cup wall. Fig. 7 shows the shape of the cup wall after the first and the second stage. The figure shows that the flange part of the cup loses straightness by the springback after the forming process and the element near the flange is thickened even though it is passed through the ironing process. While the blank far from the flange is bent and unbent by the drawing into the die and it is straightened sufficiently in the cup wall by the ironing process, the blank near the flange is ironed slightly and it is not straightened sufficiently. The deviation also results from the simulation error by the dynamic effect involved in the explicit dynamic analysis. The relatively coarse mesh with respect to the blank thickness also produces the error in contact constraints.

Severe stretching near the major axis can be explained by the irregular contact condition during the forming process. Fig. 8 shows the contact condition between the blank and the tools at the major axis and the minor axis at the fourth stage before forming. The figure shows that severe stretch occurs along the major axis because of the tight contact between the punch and the blank especially at the punch shoulder region. The material along the major axis deforms with stretching because of the tight contact between the punch and the blank. On the other hand, the material along the minor axis deforms mainly with bending because of the loose contact. The irregular contact condition is originated from the initial tool design when the shoulder radius is designed uniform. The figure reveals the problem of the initial contact when the blank is mounted on the die. The blank at the major axis is not in contact with the die face while the blank at the minor axis contacts with the die face. The contact and positioning condition among the die, the cup holder and the blank at the minor axis controls the metal flow so that the blank can deform with bending and unbending deformation. Such deformation mode at the minor axis produces relatively moderate reduction of the blank thickness. The tool positioning condition at the major axis, however, does not impose the sufficient holding force to control the metal flow, which results in the stretch dominated deformation of the blank. Since the die and the blank shape is not in favor of the smooth contact and the uniform metal flow, the initial design requires modification of the tools that could improve the uniform contact and metal flow.

5. Design modification

The previous section explains phenomenological reasons of unfavorable deformation mechanisms in the

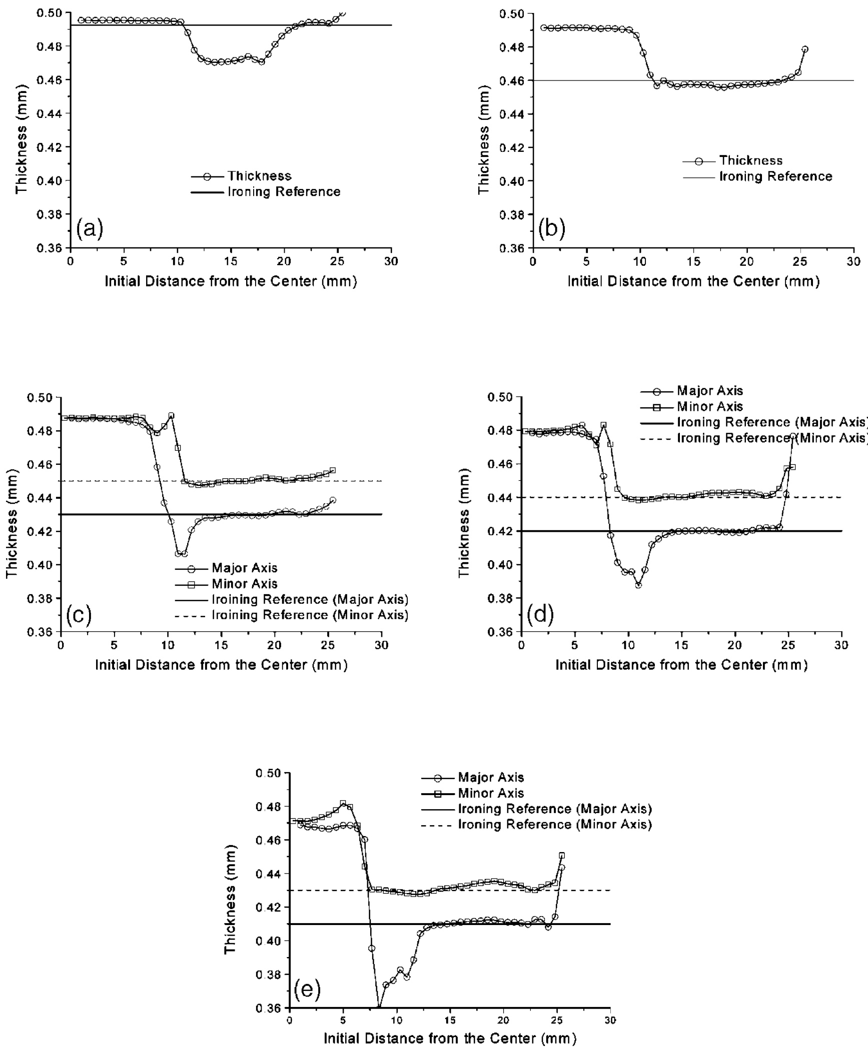

Fig. 5. Thickness distribution in each forming stage with the initial design: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 4; and (e) stage 5.

initial design with the finite element analysis result. The failure by tearing occurs from the non-uniform metal flow due to the different drawing ratio in the cross section and the irregular contact condition with the initial tool positioning. Essential points to be considered for a new design of tools are as follows:

1. uniform change of the drawing ratio between the neighboring stages;
2. uniform contact between the tool and the blank; and
3. accurate bottom shape of the rectangular cup.

The difference of the drawing ratio between the neighboring stages is reduced so as to achieve more uniform deformation in the cross section than that with the initial design. The thickness reduction at each stage is kept up the same value as that of the initial design in order to achieve gradual changes of blank thickness. The elliptic and rectangular cross section of the punch after the third stage is constructed by folding of three circular arcs, which was constructed by two circular arcs in the initial design, in order to reduce the stress concentration at the intersection region of the merged arc. The changed shape of the folded arc is explained in Fig. 9. The modified design also alters dimensions of the flat punch head in order to improve the accuracy of dimensions of the bottom part of a cup. The cross section shape modified is near rectangular while the cross section shape was near elliptic in the initial design. In the earlier stage, the rectangular cross section is expected to produce more strain because the corner part of the rectangular cross section produces more strain, which was the smooth elliptic shape in the initial design. The modified design is expected to prevent abrupt change in the cross section shape as the stage proceeds.

The curvature at the punch shoulder is modified to improve the uniform contact between the blank and the die. Since the initial design does not make the blank at the major axis contact with the die face, the blank shape needs modification so that the blank keeps in contact

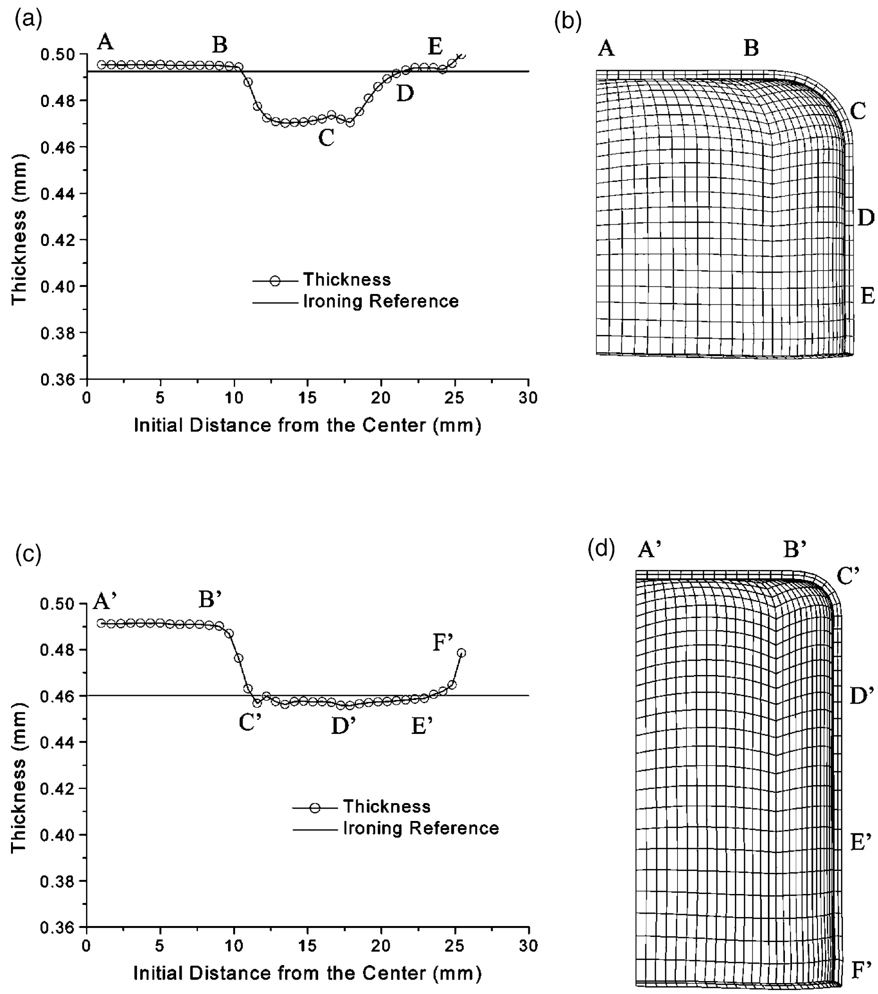

Fig. 6. Thickness distributions with the location of measuring points: (a) thickness distribution at the stage 1; (b) position of measuring points at the stage 1; (c) thickness distribution at the stage 2; and (d) position of measuring points at the stage 2.

with the die face both at the minor axis and the major axis simultaneously. The blank shape can be changed from the modification of the punch at the previous stage. The punch shape at the previous stage is modified in order to make the blank contact the die face simultaneously. Mismatching of the blank and the tool is corrected by enlarging the curvature of the punch shoulder at the minor axis. Fig. 10 explains the modification procedure of the shoulder part of the punch. The modification of the punch shape is imposed after the second stage.

This result also suggests that the die shape be modified by adding the intake angle as shown in Fig. 11 after the second stage in order to prevent the shock line which could occur in the conventional redrawing process. In order to improve the contact condition at the initial mounting of the blank on the die face, the curvature at the shoulder part along the minor axis is enlarged, which guarantees the smooth deformation of the blank at the intake part of the die at the subsequent stage. The smooth angle of the shoulder part near the minor axis also lessens the possibility of wrinkling. The tool is redesigned using the three-dimensional CAD software to satisfy the above mentioned guideline because the tool shape becomes so complex that it cannot be described with respect to the simple analytic function in three dimensions. Fig. 12 shows the three-dimensional punch shapes in the initial and modified design, respectively.

Finite element analysis is carried out again with the modified tool shapes to investigate the effect of the design change. Fig. 13 shows deformed shapes with the experimental results at all stages except the first stage that is the same as the initial design. The figure shows that the numerical result can predict the deformed shapes well. As the stage proceeds, the rectangular cross section is successfully formed by changing the drawing ratio and by enlarging the curvature of the shoulder part at the minor axis in the modified design. Shock marks are slightly shown after the fourth stage both in the numerical and the experimental results. It can be eliminated when the curvature of the punch is reduced slightly near the minor axis in the try-out procedure of the punch.

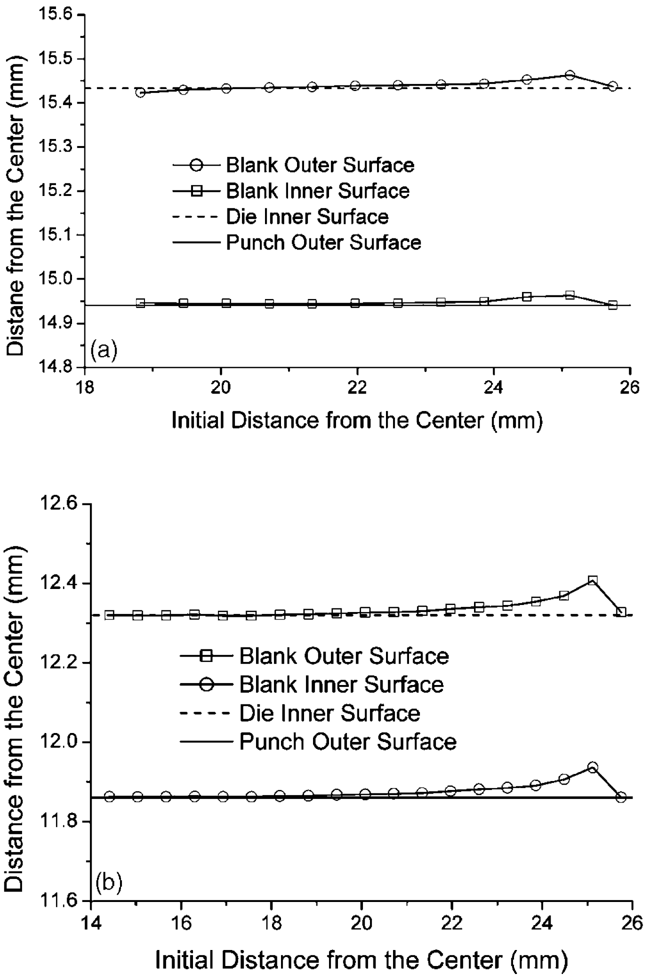

Fig. 7. Shape of the cup wall after the forming process: (a) stage 1 and (b) stage 2.

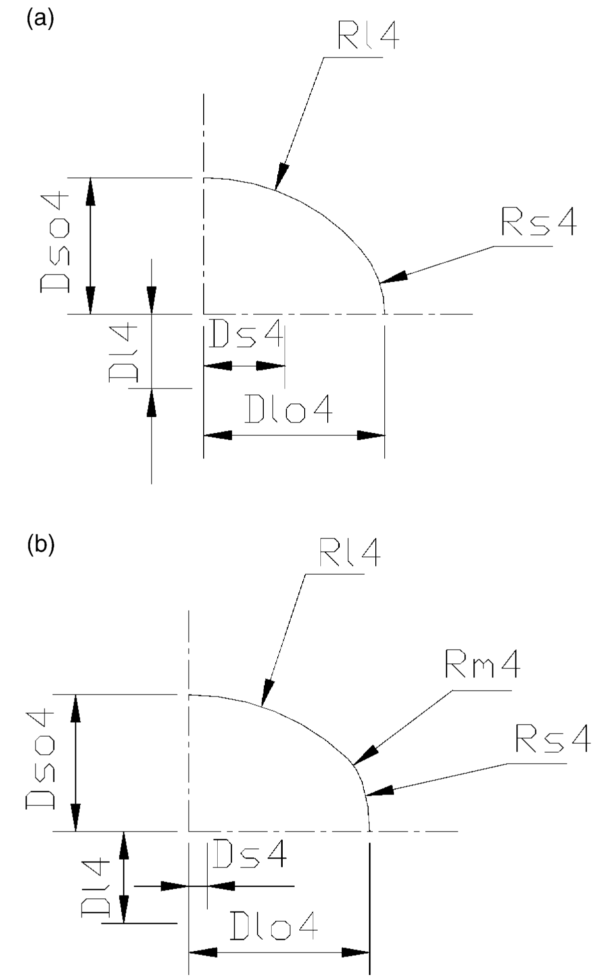

Fig. 9. Modification procedure for the cross section of the punch head at stage 4 (a quarter model) : (a) initial design; and (b) modified design.

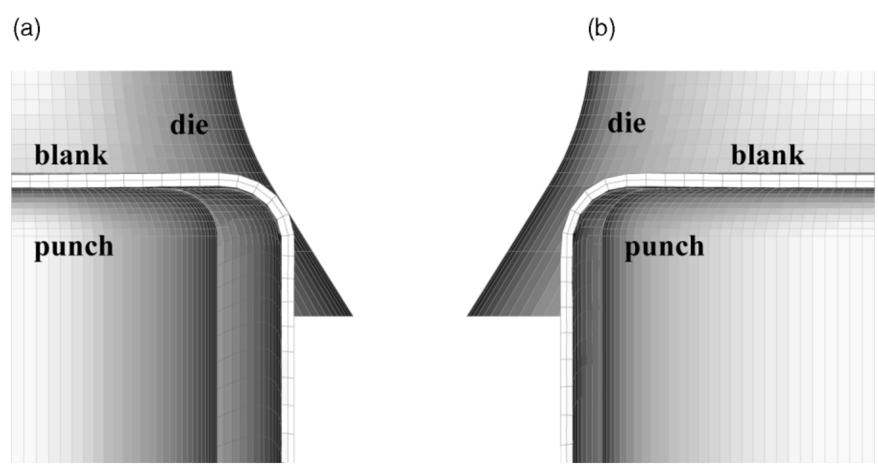

Fig. 8. Initial shape of tool positioning at stage 4 with the initial design: (a) minor axis; and (b) major axis.

Fig. 14 represents thickness strain distributions in the numerical and the experimental results at each stage with the modified tool. At the second and the third stage, the blank near the minor axis becomes thicker and the blank becomes thinner than that in the initial design. Both results show good agreements with each other especially in the punch head and the shoulder parts. The thickness distributions in the cup wall become close near the target thickness of the ironing process in the numerical result while those in the experimental result deviate from the

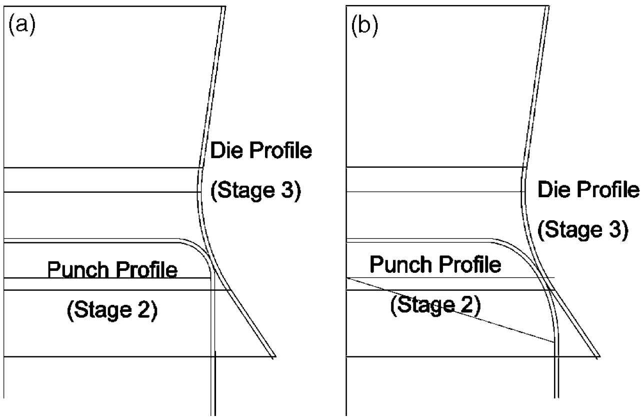

Fig. 10. Modifying procedure for the shoulder part of the punch at the minor axis at stage 2: (a) major axis; and (b) minor axis.

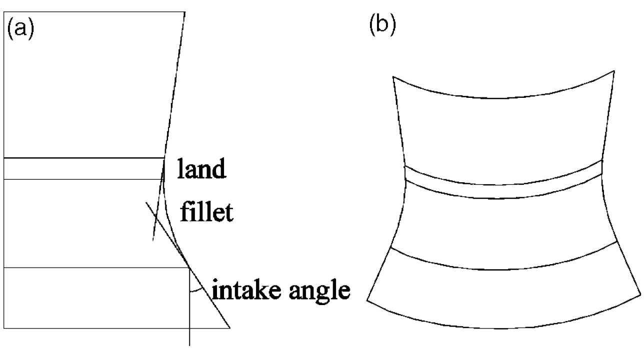

Fig. 11. Intake angle of the die with the modified design at stage 3: (a) side view; and (b) isometric view.

target thickness. This phenomenon is caused by the mistake that the center of the tool is not fixed up. The figure shows that the thickness distribution becomes non-uniform in the modified design, which is inevitable to achieve the final rectangular cross section. The thickness distributions at the fourth and the fifth stage show that the localized thinning at the major axis is reduced. The thickening at the minor axis is also reduced at the fifth stage. Comparing at the fifth stage, the amount of maximum thickness reduction is 23%, which means that the possibility of failure of the shoulder part at the major axis is decreased and the thickness at the minor axis shows almost the same behavior as that in the initial design. The modified design is shown to be more effective than the initial design from the viewpoint of shaping the accurate rectangular cross section and reducing the possibility of failure. The modified design also ensures the uniform contact condition between the blank and die interface. Fig. 15 shows that the initial contact condition before the fourth stage is remarkably improved. The blank is in touch with the die face at the major axis and the minor axis simultaneously, which results in more uniform deformation than before.

6. Conclusions

Tool design for the multi-stage deep drawing with ironing is carried out to obtain the rectangular cup with the large aspect ratio with the aid of the finite element analysis. Explicit elasto-plastic finite element analysis

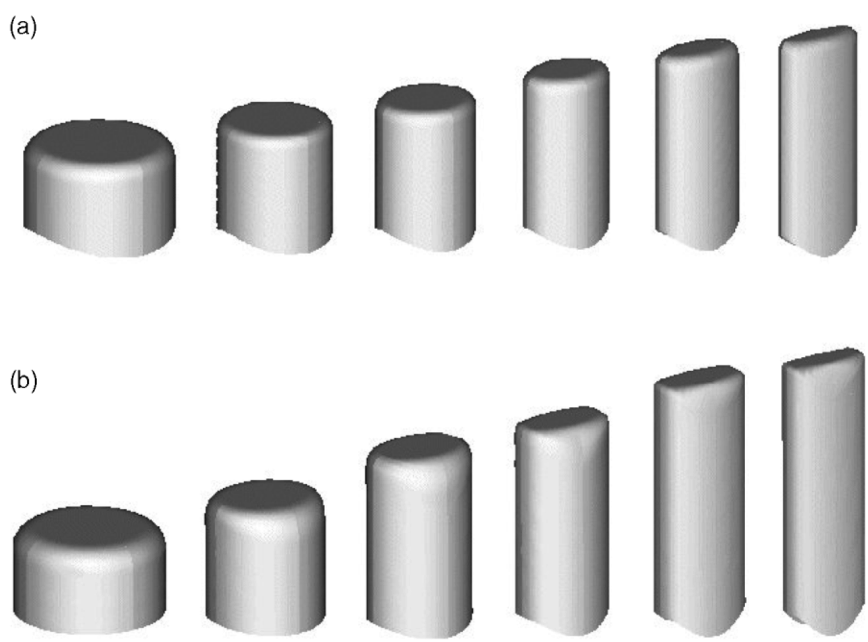

Fig. 12. Intermediate punch shapes in each forming stage: (a) initial design; and (b) modified design.

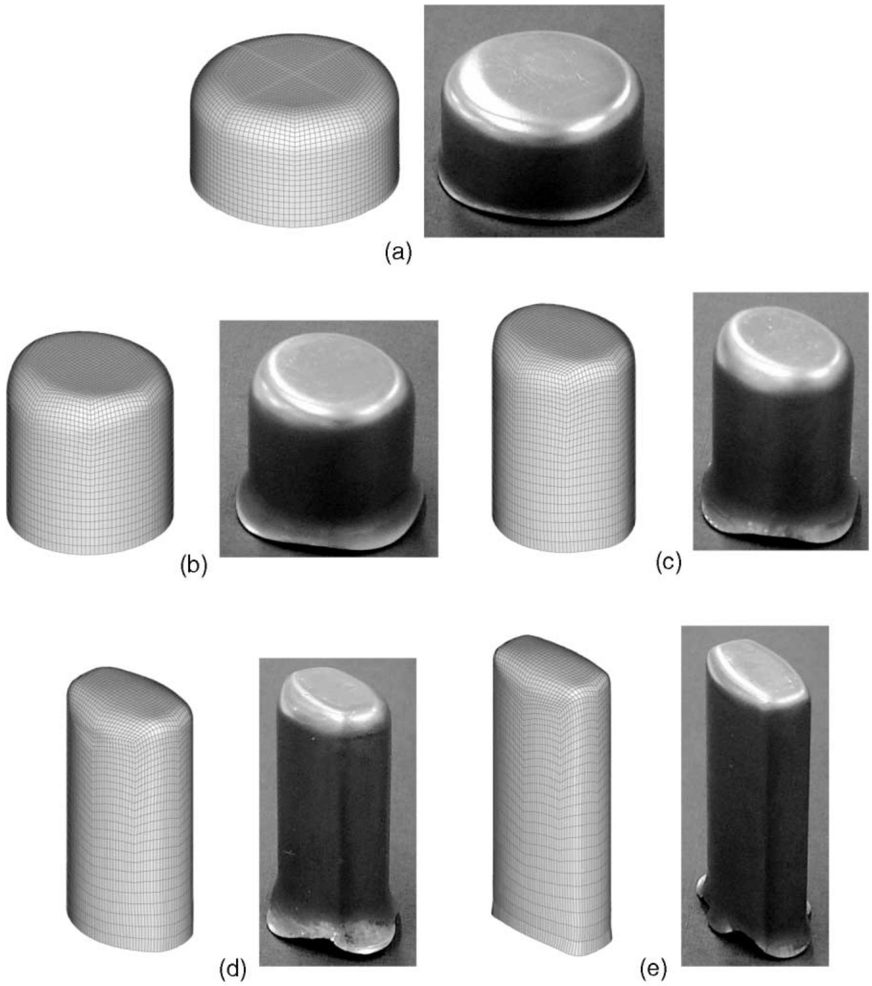

Fig. 13. Deformed shapes of the blank at each forming stage with the modified design: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 4; and (e) stage 5.

with continuum elements is carried out in order to seek the reason of failure in the initial design during the forming process including the ironing process. Finite element results show that the localized deformation occurs along the major axis. Reasons are mainly due to the non-uniform drawing ratio in the non-circular cross section and the irregular contact condition between the blank and the tool during the forming process. Guideline of the process design modification is proposed in order to reduce the possibility of failure. The modified design proposes change of the subsequent drawing ratios between the adjacent stages in order to achieve smooth deformation. The punch shape of the shoulder part at the minor axis is modified so that the blank keeps in contact with the die face both at the major and minor axis simultaneously. The design modification proposed is examined by the finite element analysis. The analysis result confirms that the modified design guarantees more uniform deformation and reduces the possibility of failure in the initial design. With the aid of the design modification from the finite element analysis, the rectangular cup with the high aspect ratio was able to be successfully produced without defects such as wrinkle or tear from the design in the real forming process. The proposed modification method can be a good reference in the forming of the non-circular cup with the large aspect ratio.

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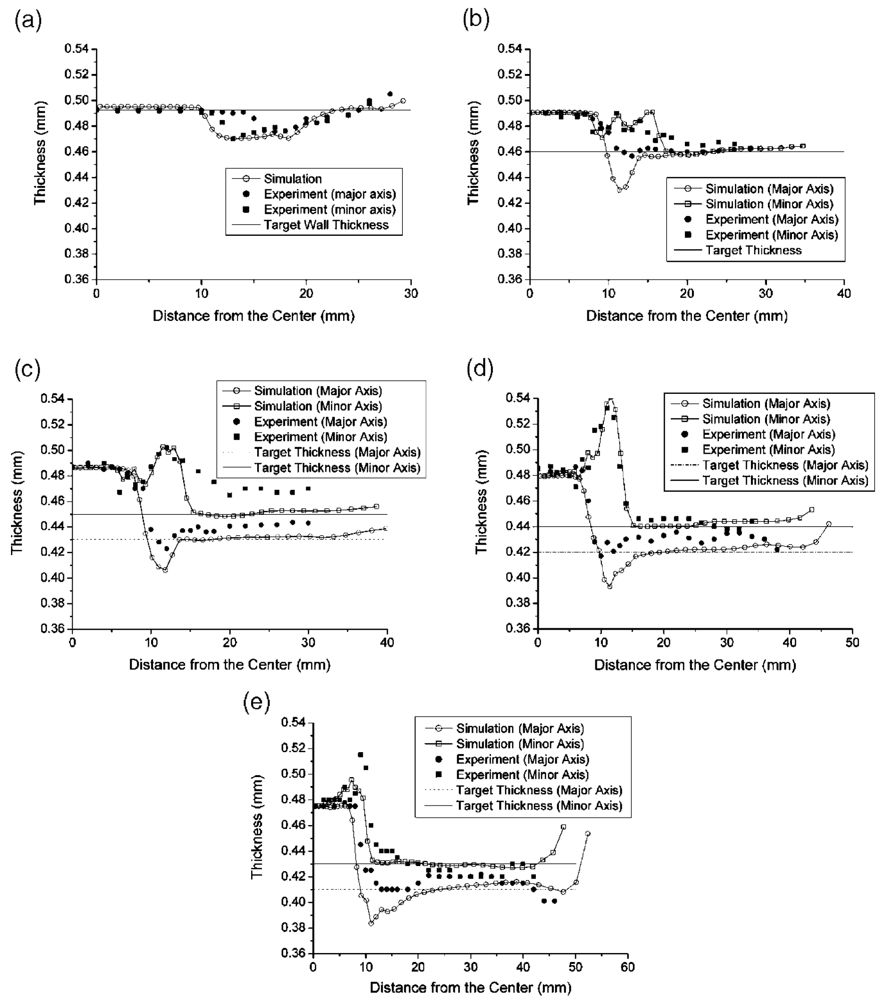

Fig. 14. Thickness distribution in each forming stage with the modified design: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 4; and (e) stage 5.

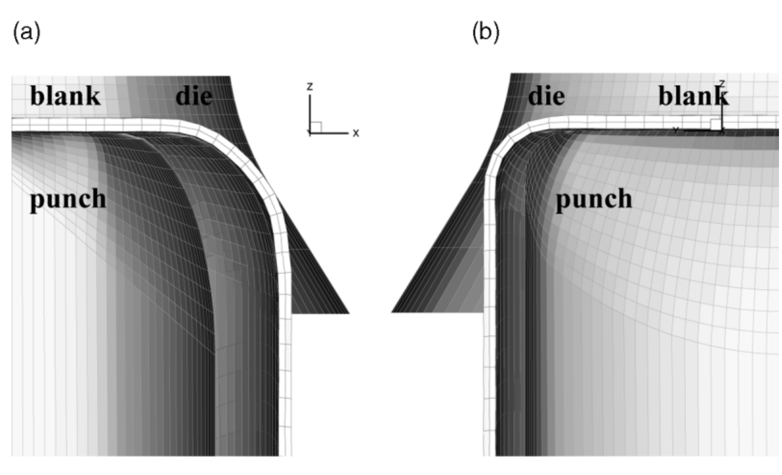

Fig. 15. Initial shape of tool positioning at stage 4 with the modified design: (a) minor axis; and (b) major axis.

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