Finite Element Analysis of Multi-Stage Deep Drawing Process for High Precision Rectangular Case with Extreme Aspect Ratio

T.W. Ku, B.K. Ha, W.J. Song, and B.S. Kang

Abstract

Deep drawing process for rectangular drawn section is different with that for axisymmetric circular one. Therefore deep drawing process for rectangular drawn section requires several intermediate steps to generate the final configuration without any significant defect. In this study, finite element analysis for multi-stage deep drawing process for high precision rectangular cases is carried out especially for an extreme aspect ratio. The analysis is performed using rigid-plastic finite element method with an explicit time integration scheme of the commercial program, LS-DYNA3D. The sheet blank is modeled using eight-node continuum brick elements. The results of analysis show that the irregular contact condition between blank and die affects the occurrence of failure, and the difference of aspect ratio in the drawn section leads to non-uniform metal flow, which may cause failure. A series of experiments for multi-stage deep drawing process for the rectangular cases are conducted, and the deformation configuration and the thickness distribution of the drawn rectangular cases are investigated by comparing with the results of the numerical analysis. The numerical analysis with an explicit time integration scheme shows good agreement with the experimental observation.

Key Words : Milli-structure, Grain Element, Grain Boundary Element, Finite Element Method, Strip Bending

1. Introduction

The sheet metal forming process is used widely in a variety of industrial fields. It is required for automotive applications, consumer products, aerospace parts, as well as a wealth of other products. Especially, rectangular and elliptic drawn cups with large aspect ratio are widely used for electrical parts such as a battery container, semi-conductor case, and crystal vibrator in industry[1-3]. Most of the research for the sheet metal deep drawing process has been performed on the formability of an axisymmetric shape, but there are a few concrete reports on the formability of a non-axisymmetric shape. Here, this study will introduce the multi-stage deep drawing process for rectangular cup with extreme aspect ratio. In the multi-stage deep drawing process, the blank material experiences additional complex deformation in each stage compared to the conventional drawing process. The process generally involves bending, drawing, stretching, ironing and various combinations of these modes of deformation. Since the deformation mechanism is very complicated and the mechanical properties for the final product are difficult to predict, the process design is not easy for the manufacturing of a product of desired shape[4-5].

Min et al. analyzed an axisymmetric multi-stage deep drawing operation by a rigid-plastic FEM using bilinear quadrilateral elements[6]. Kim et al. proposed a finite element inverse technique for the multi-stage axisymmetric deep drawing process. The analysis determined the number and the shapes of the intermediate stages by estimating the blank shapes and the strain distribution at each stage[7]. Kim et al. analyzed the four-stage deep drawing process of an elliptical cup using a finite element inverse method and an elasto-plastic finite element method. They have revealed that the non-uniform drawing ratio in the cross-section cause non-uniform metal flow to produce failure such as wrinkling and tearing[8].

In this study, finite element analysis for multi-stage deep drawing process for high precision rectangular cases is carried out especially for an extreme aspect ratio. The analysis is performed using rigid-plastic finite element method with an explicit time integration scheme of the commercial program, LS-DYNA3D. The sheet blank is modeled using eight-node continuum brick elements. The results of analysis show that the irregular contact condition between blank and die affects the occurrence of failure, and the difference of aspect ratio in the drawn section leads to non-uniform metal flow, which may cause failure.

A series of experiments for multi-stage deep drawing process for the rectangular cases are conducted, and the deformation configuration and the thickness distribution of the drawn rectangular cases are investigated by comparing with the results of the numerical analysis. The numerical analysis with an explicit time integration scheme shows good agreement with the experimental observation.

2. Analysis of Multi-stage Deep Drawing Process

2.1 Theoretical Background

The finite element analysis is carried out with an explicit rigid-plastic finite element code, LS-DYNA3D. The analysis scheme adopts the Belytschko-Tsay brick element with reduced integration so that the drawn cup of a rectangular shape with extreme aspect ratio produces reasonable deformation conditions such as bending and twisting in moderate computation time even when the amount of element warpages is severe. The reduced integration incorporates the hourglass control scheme proposed by Flanagan [9]. The variational formulation from the principle of virtual work can be written as follows:

$$\delta\Pi = \int_V \rho \dot{x}\, \delta x_i dV + \int_V \sigma_{ij} \delta x_{i,j} dV - \int_\rho f_i \delta x_i dV - \int_{S_t} t_i \delta x_i ds \qquad (1)$$

where x_i is the current coordinate system, σ_{ij} is Cauchy stress, ρ is the current density, f_i is the body force density, the comma denotes covariant differentiation, and S_t is the traction boundary where the traction vector t_i is specified.

2.2 FE-Analysis Condition

Simulations using the commercial explicit finite element analysis program, LS-DYNA3D, were performed. An explicit finite-element technique is fundamentally a dynamic procedure employing the central difference method[10]. To solve quasi-static problems, it is conventional to convert the real problem to a virtual problem with a different mass density and processing time by means of mass and time scaling[11-13]. Since sheet metal forming is a low speed processing operation, the dynamic effects that are associated with the analysis must be minimized by either applying the loads slowly or decreasing the density of the deforming material being simulated. Here, a suitable punch speed for minimizing dynamic effect was achieved from several simulations.

The total processes for the rectangular battery container are consisted of 14 stages. This study considered a six stage drawing process and one trimming process because the other processes have a mere difference from the rectangular cup shape after the process. The first and the second stage of the drawing process are performed with an elliptical punch and the cross-section of the punch is changed to a rectangular shape gradually. The elliptical cross-section of the die is modeled by the folding of two circular arcs that have different origins and radii. The punch and the blank-holder surface are obtained by offset relative to the corresponding die parts.

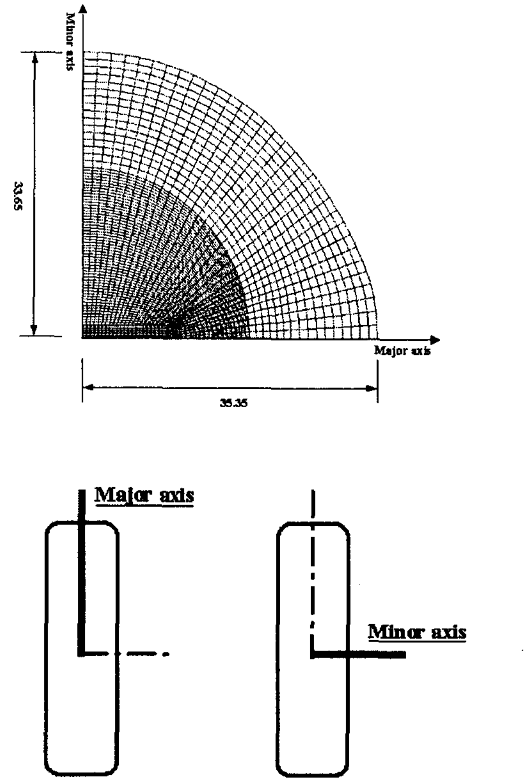


Fig.2 Initial mesh system for the blank (unit:mm)

The cross-sectional shape of the punch and the die at each stage are shown in Fig. 1. The finite element mesh configuration for the blank

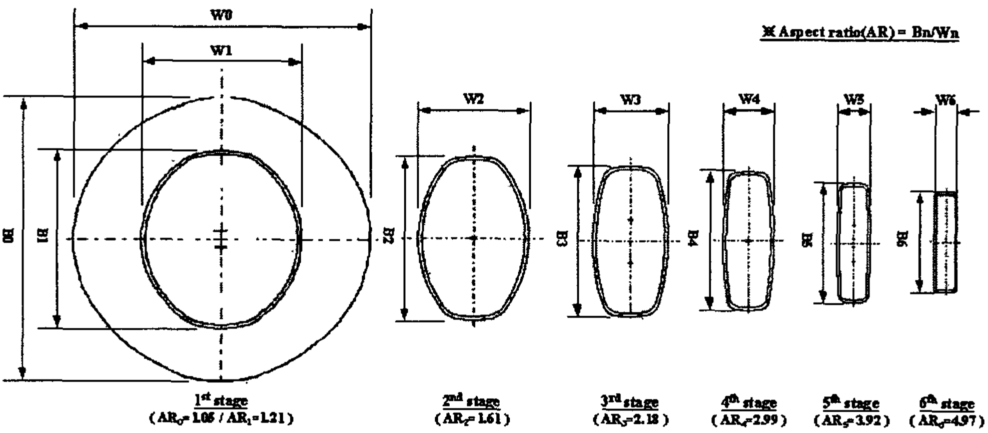


Fig.1 The cross-sectional shape of the punch and the die at each stage(unit:mm)

is constructed with 7788 nodes and 4984 eight-node brick elements as shown in Fig. 2. And the initial thickness for the blank is 0.8mm. The minor axis of the cross-section in the cup coincides with the rolling direction of the blank in the simulation. The use of solid finite elements considers the sheet as a three-dimensional domain, which is the more realistic way to model the process. The simultaneous contact on both sides of the sheet is naturally solved without any particular strategy. Further to this, it is possible to calculate accurately the stress gradients over the thickness of the sheet as well as the evaluation of the sheet thickness during the simulation with these elements. The tool models for the punch, lower-die, and knockout device are constructed by the four-node quadrilateral shell element. The elements of the tool are assumed perfectly rigid. To save computing time, the symmetry of the product has been used by simulating only a quarter of the model.

The material used in the simulation is aluminum alloy AA3003-H16 whose flow stress is expressed as, $\bar{\sigma}=358\,\bar{\varepsilon}^{0.21}$ MPa in Fig. 3 obtained from tensile tests. The elastic properties such as Young's modulus, Poisson's ratio and density are 70GPa, 0.33, $2.73\times10^{-6}kg/mm^3$, respectively.

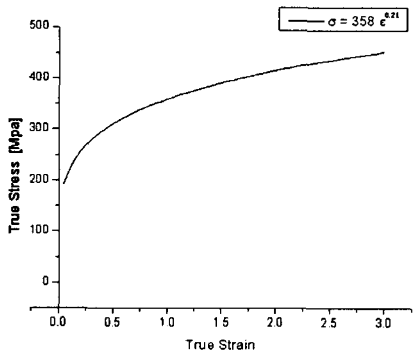


Fig.3 True Stress-strain curve for AA3003-H16

The blank-holding force of 500N is applied in the first stage and removed thereafter. Instead of the blank holder, a knockout device is utilized in order to pull out the product from the die cavity. The initial blank-holder force was determined in the minimum force that could prevent the wrinkling of the blank. And the time scaling factor is taken as 200, i.e. the artificial speed is 20m/s (the actual punch speed is 0.1m/s), in order to minimize the CPU time cost. From several trials and errors, it could be selected the punch speed for simulation, so that the dynamic effects are negligible and the result is valid as a quasi-static solution. Note that interface phenomena at the contact between the blank-holder and workpiece, the die and workpiece, and the punch and workpiece encountered in deep drawing were analyzed using the sliding with separation and friction interface model from the sliding interface DYNA3D code library.

Some limit conditions can be neglected because of their insignificant influences on the deep drawing process. The major simplifications and assumptions are given as follows: The materials are isotropic and homogeneous. The thermal effect during the manufacturing process is neglected. For sheet metal forming processes, the frictional behavior depends on several parameters such as the contact pressure, sliding speed, material of blank and tools, surface roughness, lubricant and concurrent deformation. Especially when the ratio of blank thickness over blank area is small, the friction influences the material flow and the final strain distribution. The constant friction condition is assumed at the die-workpiece interface. The coefficients of friction at the interfaces among the blank, the punch, and the dies are 0.1.

Here, even if anisotropic properties in sheet metal forming are dominant factor causing earing phenomenon, it is assumed that the material for the blank is isotropic. Because a trimming process is added during total

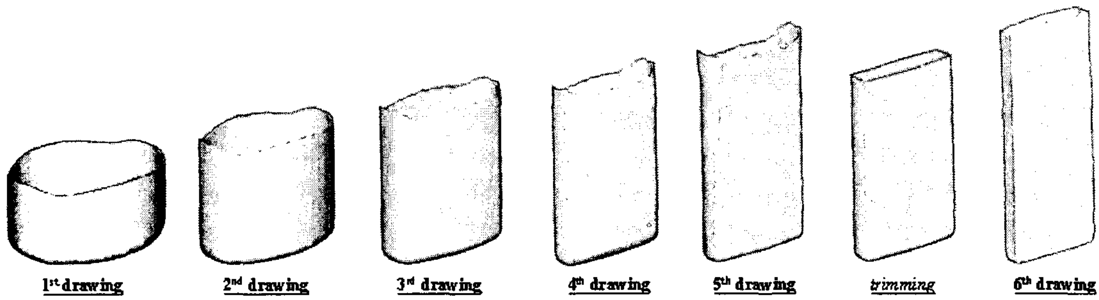


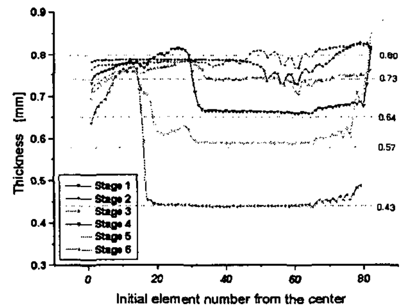
Fig.4 Deformed shapes of the blank at each forming stage

processes for rectangular cup drawing, the flange parts appeared an earing could be trimmed. Also, the selection of a solid element for the simulation makes a decision of the assumption of isotropic material. After the drawing simulation for one stage, the deformed blank was combined with the tools of next stage and the stress distribution of the previous result and the deformed geometry were joined to the next stage simulation.

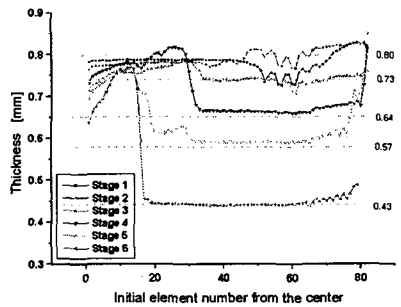
2.3 Result of FE-Analysis

The finite element analysis using explicit time integration is performed with the conditions described in the previous section. All simulations for drawing process are carried out successfully until six stages. Figure 4 shows the deformed configurations of each stage. The figure indicates that the deformation analysis is performed successfully.

The predicted thickness distributions displayed in Fig.5 show that severe thinning takes place around the punch profile at all stage and the maximum value is about 40% of the initial blank thickness at the 6th stage. Some thickening takes place on the edge of the flange. Figure 5 shows the thickness distribution at all stage along the major axis and the minor axis respectively. The wall surface at the major axis is ironed four times, while at the minor axis, three ironing operations are performed during six-stage drawing process. The sudden decrease of thickness in the region of upper wall reveals that the localized thinning at the punch corner in the previous process is not perfectly compensated during ironing process. At each drawing stage, thickness distribution of the wall is similar with clearance between die and punch within the error range.



(a) major axis



(b) minor axis

Fig.5 Thickness distribution in each stage

The forming process is influenced by many kinds of process parameters. For rectangular cup drawing, the intake angle is more important process parameter than others for a good formability. Here, the fourth stage drawing process is a rectangular-shape drawing with variable intake angle. And the previous processes are elliptical-shape drawing process with the same intake angle. To check the effect of intake angle at the fourth stage, four cases under different forming condition in Table 1 are discussed here. The α_1 indicates the intake angle of the minor axis, and the α_2 means that of the major axis as shown in Fig. 6. The die profile of Case I is modeled with a various section shape from minor axis to major axis. Other cases are modeled for a constant section shape with different angle 8° to 16° .

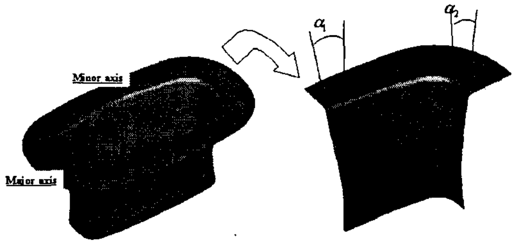
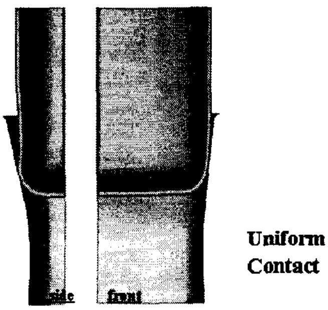


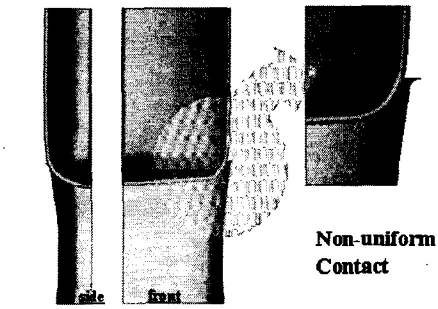
Fig.6 Intake angle of the die

Table 1 FE-Analysis condition for cases of several intake angle(unit:degree)

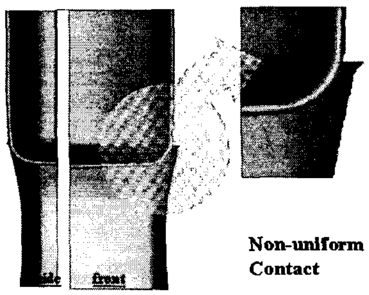
	Case I	Case II	Case III	CaseIV
α_1	16	8	12	16
α_2	8	8	12	16



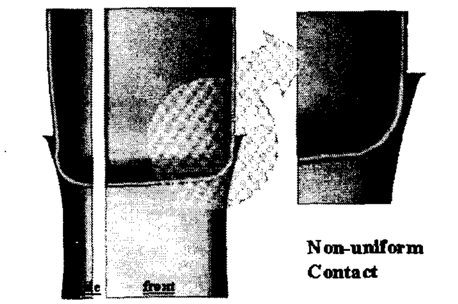
(a) case I



(b) case II



(c) case III



(d) case IV

Fig.7 The contact shape of blank and lower die(14% strike)

Figure 7 shows the contact conditions between blank and die for the four different cases of intake angle combination. For case I of the intake angles of 16° to 8° , the blank is in contact with the die face at the major axis and the minor axis simultaneously as shown in Fig. 7(a). But the other three cases, the blank at the major axis is not in contact with the die face while the blank at the minor axis is in contact with the die face. The Case I with variable section shape is in uniform contact between the tool and the blank during forming process. Others with constant section shape are in non-uniform contact condition.

Figure 8 shows curves for punch load versus punch stroke at each case. Figure 8 indicates that the punch load at variable section shaped die of the Case I is approximately the half of that of other cases with constant section shape, because the tool design in Case I reduces the contact force, and thus the blank deforms uniformly. The oscillation of the curve for punch load may be attributed to non-physical inertia effects due to the up-speeded technique.

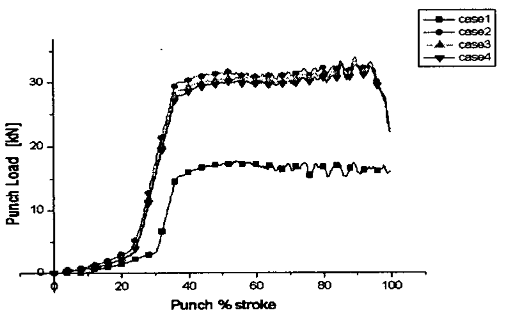


Fig.8 Punch load versus % stroke at each case

3. Experiments of Rectangular Cup Drawing

The experiments were carried out using a 65ton transfer press. The press with sheet metal tooling is noticed in Table 2 lists its specification. All processes for rectangular cup battery case are consisted of 14 stages, which are drawing, ironing, blanking, and trimming stages. The aluminum alloy AA3003-H16 with the thickness of 0.8mm was used in the experiments. The final cup height, width and length were chosen to be 63.4mm, 29.55mm and 5.95mm, respectively. The ratio of the height to the minor axis of the cross-section, called the aspect ratio, is over 10.6.

Table 2 Specification of transfer press

Item	Unit	Amount
Rated capacity	[ton]	65
Recommended capacity	[ton]	45
Standard ram stroke	[mm]	177.8
Max. ram stroke	[mm]	203.2
Shut Height	[mm]	508.0
Main motor	[kW]	15.0
Operating speed	[spm]	25~100

Lower dies were made of P/M high-speed steel to keep the high-strength and precise die shape. Titanium alloy materials were selected for drawing punch, in order to prevent the rod with large aspect ratio from buckling or torsion. Initial blank shape is obtained from several experimental modifications. It can be decided the die and punch profile by trial-and-error to achieve the uniform deformation and the contact condition. The blank can be in contact with the die face at the major axis and the minor axis simultaneously. In rectangular cup drawing, non-uniform drawing ratio in the non-circular cross-section and the irregular contact conditions between the blank and the tool during the forming process are the dominant reason for failure.

The drawing oil was selected for its good lubrication to reduce the occurrence of defects, such as scratches and cracks, and to have sound heat transfer characteristic. Deep drawing

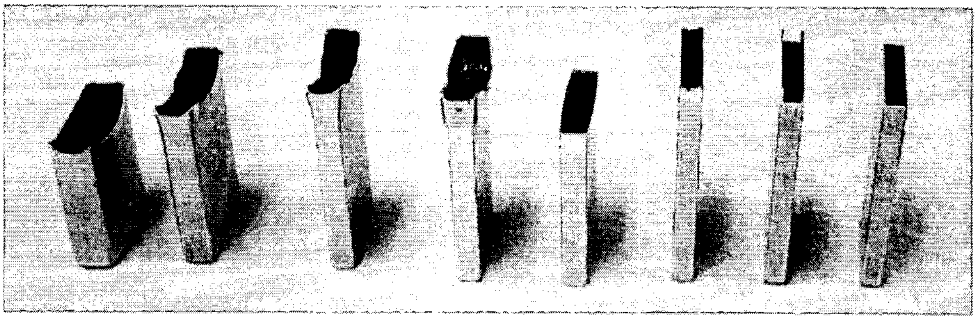


Fig.9 Experimental results for rectangular cup drawing(from 3rd to 10th stages)

processes were performed to manufacture the rectangular cup successfully.

The products of each stage forming are shown in Fig. 9. Figure 10 shows examples of failure in deep drawing process. This surface cracks and shock waves mainly result from property change in materials due to large deformation and surface pressure that cause scratches, shock waves, and cracks[14].

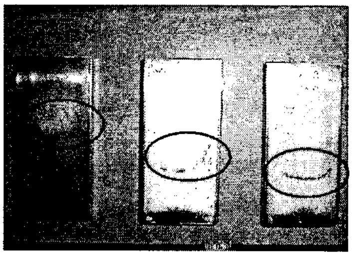


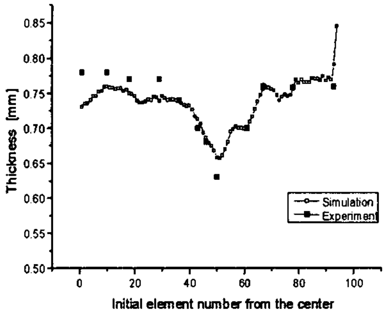
Fig.10 Surface failure in the deep drawing process

4. Discussion about the Result of Analyses and Experiments

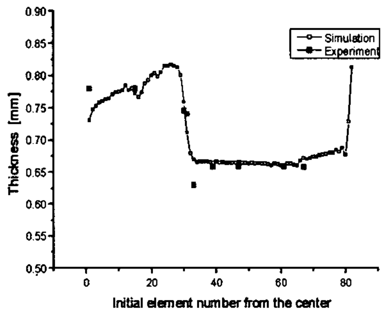
The comparison at each forming stage is conducted for the finite element analysis and experiment for multi-stage rectangular cup drawing. The mesh system of initial blank must have a good quality in order to show the deformed shape accurately. If the number of element is not enough to represent the complex deformed shape of the curvature, the mesh system at the punch radius can not illustrate the curvature of the deformed blank. After the fourth stage of forming, severe wrinkling phenomenon is found along the minor axis, but complex wrinkle shape is not observed in the numerical simulation result due to the coarse mesh system. Finer mesh may produce wrinkling in the forming operation even though significant computational time is required. However, this part does not need to consider the wrinkling, because the flange edge will be trimmed off at the following process.

Figures 11 and 12 indicate the comparison of thickness distribution obtained from the numerical simulation and experiment. The experimental prototypes at each forming stage were mounted with a powder in order to cut the cross-section along the major axis and minor axis. Due to the capacity of the mounting equipment, the prototype was cut into two or three parts for the measurement of the thickness.

As shown in Figs. 11 and 12, the FE analysis shows that the thickness distributions are in good agreement with the experimental result. Figure 13 shows the cross-sectional shape of the simulation and the experiment. The trend in the deformation of cross-section in simulation result is similar with that of the experiment. The severe thinning around the punch corner radius is observed in experiment. Also the numerical result shows the same phenomenon as shown in Fig. 13(b).



(a) major axis



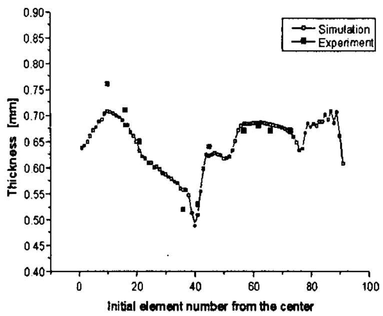
(b) minor axis

Fig.11 Thickness distribution at the 4th stage

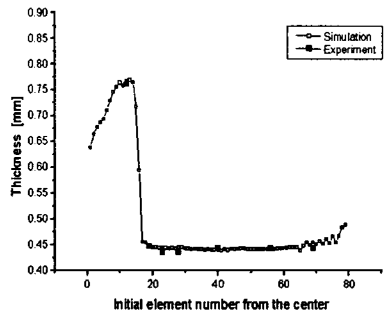
5. Concluding Remarks

The rectangular and elliptical drawn cups with an extreme aspect ratio are widely used for electrical parts such as battery container and semi-conductor. It is important to determine the influence of the process parameters for the design of sheet metal working processes. Recently, the finite element method has been introduced to the analysis of the forming process and has provided useful information for manufacturing process design. Here, the finite element analysis and a series of experiment were carried out for multi-stage rectangular cup drawing process with an extreme aspect ratio.

Explicit finite element simulation using

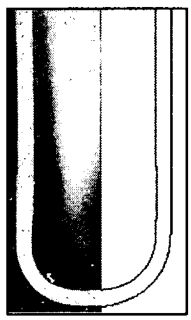


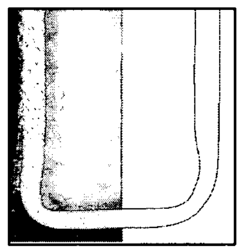
(a) major axis



(b) minor axis

Fig.12 Thickness distribution at the 6th stage





(a) 2nd stage (b) 5th stage

Fig.13 Comaprison of cross-section of FEA and experiment

8-node brick element was performed for rectangular cup forming processes, which include drawing, redrawing, ironing, and trimming. Several experiments were performed to confirm the validation of the FE analysis. The thickness distributions obtained from the simulation and the experimental results were compared at each forming stage. The numerical results show in good agreement with the experimental results.

The effect of the process parameter, intake angle, has been investigated. The uniform contact is an important factor to get a sound final product. Also, it is found that the contact condition and drawing ratio affect the metal flow and material distribution. The die with variable sections can avoid the possibility of failure due to non-uniform contact between tool and blank during forming analysis.

In this study, the reliability of the finite element analysis for multi-stage rectangular deep-drawing process could be confirmed by comparing the results obtained from the simulation with the experiment.

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