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The design of blank's initial shape in the near net-shape deep drawing of square cup

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Abstract

Deep drawing process is very useful in industrial field because of its efficiency. The deep drawing is affected by many process variables, such as blank shapes, profile radii of punch and die, formability of materials and so on. Especially, in order to obtain the optimal products in deep drawing process, blank shape is very important formability factor. In this paper, the finite element method is used to investigate the cup height of the square cup drawing process. In order to verify the prediction of FEM simulation of the product's height and forming load in the square cup drawing process, the experimental data are compared with the results of the current simulation. A finite element analysis is also utilized to acquire the designed profile of the drawn products, a reverse forming method for obtaining the initial blank's shape according to the forward square cup drawing simulation is proposed. The design of initial blank's shape is also certified to obtain the designed profile of drawn cups by experiment. The influences of the blank's shape on the height of product, the forming load, the maximum effective stress and the maximum effective strain are also examined.

Keywords: Near net-shape deep drawing; Finite element analysis; Initial blank's shape

1. Introduction

In deep drawing a metal sheet is used to form the cup components by a process in which the central portion of the sheet is pressed into die opening to draw the metal into desired shape without folding of the corners. Deep drawing process has taken an important role in such industries as automobiles, airplanes and electric appliances due to its advantages in reducing development time and final cost of the products. So many researches on the process variables of cylindrical products have been carried out into the fundamentals of deep drawing process. Thus, many shapes, such as square, rectangular, elliptical and non-axisymmetrical have been produced. Deep drawing is affected by many process variables, such as blank shapes, profile radii of punch and die, formability of materials and so on. The top edges of a cup formed by deep drawing are not usually even, often having crests and valleys. The choppy of the top edges is undesirable, as it requires some metal to be trimmed from the top of the cup, which consumes money and time. A problem that has attracted some attention in the recent past is optimal blank shape design for the deep drawing process. One approach to avoid this is to modify the initial blank shape and thereby produce a final cup shape with uniform top edges. Since an experimental trial and error process to determine the best blank shape for making a defect-free cup is very expensive and time consuming, numerical simulation tools present an attractive and effective alternative.

An important aspect of numerical simulation is the use of an effective model for the anisotropic plastic

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flow of sheet metal. A lot of researches have been devoted to characterizing anisotropy of sheet metal and in particular on developing a useful yield function for plastic flow. The quadratic anisotropic yield criterion of Hill [1] has been widely used. However, the model can not predict the behavior of certain metals, including some aluminum alloys. A number of non-quadratic yield criteria were subsequently developed including Gotoh [2], Bassani [3], and Logan and Hosford [4]. None of these criteria are effective for modeling planar anisotropy in sheet metal under general loading conditions. Barlat and Lian [5] proposed a non-quadratic planar anisotropy yield function where three parameters describe the anisotropy in sheet metal. This yield function is suitable for plane stress condition. Barlat et al. [6] proposed a six-component model for planar in sheet metal that is applicable to three-dimensional deformations. Liu et al. [7] use the Barlat and Lian's [5] anisotropy yield function and a quasi-flow corner theory to predict the earing, the numerical results agree well with the experimental results of the cylindrical deep drawing. Moreover, the effects of different combination of anisotropic coefficients R_0, R_{45} and R_{90} on flange earing are also discussed in square-punch stretching, as shown in Fig. 1.

A number of approaches have been used to determine the optimum blank shape that could be deformed to get the desired cup shape without ears. Early approaches were based on the slip line field method. Liu and Sowerby [8] proposed a method based on potential flow to establish the optimum blank shape for prismatic cup drawing. They assumed that the flow of material in cup drawing is comparable to irrotational flow of an inviscid fluid. Chung and Richmond [9] proposed a method of designing an optimum blank shape. A finite element code was developed to obtain the initial size of the blank, the input being the final shape of the product and material properties. Realistic forming conditions including friction and blank holder force were not considered

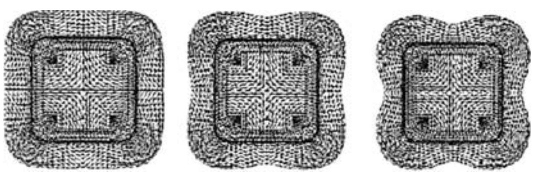

Fig. 1. Effects of different combination of anisotropic coefficient on flange earings [7] (a) R_0=R_{90}=3.0, R_{45}=1.0; (b) R_0=R_{90}=R_{45}=2.0; (c) R_0=R_{90}=1.0, R_{45}=3.0.

and hence optimum blank shapes obtained from this method had shape error. Chung and Richmond [10] optimize the initial blank shape to minimize the earing. They proposed the ideal forming processes based on the ideal forming theories. Chung et al. [11] developed a sequential design procedure to optimize sheet-forming processes based on the ideal design theory, FEM analysis and experimental trials. They used this procedure to design a blank shape for a highly anisotropic aluminum alloy sheet that resulted in a deep drawn circular cup with minimum earing. Zaky et al. [12] determine the optimum shape of a blank for the deep drawing of a cylindrical cup without ears. The modified blank is used to reduce the ear configuration. Comparison between the experimental results of circular and modified blanks is included. Kishor and Kumar [13] used the software LS/DYNA to observe the earing and compared with the experimental data with reasonably good accuracy. To optimize the initial blank shape to minimize earing, the flow of material was observed at various steps during the process. Park et al. [14] suggested a new blank design method as an effective tool combining the ideal forming theory with a deformation path iteration method based on the FE analysis. Shim et al. [15] proposed a method of blank shape design based on the sensitivity analysis for the non-circular deep drawing process. By assuming the final deformation shape to be a drawn cup with a uniform trimming allowance at the flange, the corresponding initial blank which gives the final shape after deformation has been found. Son and Shim [16] proposed a new method of optimal blank shape design using the initial nodal velocity (INOV) for the drawings of arbitrary shaped cups. With the given information of tool shape and the final product shape, corresponding initial blank shape has been found from the motion of boundary nodes. The deformed shape with predicted optimal blank almost coincides with the target shape at every case.

In this paper, a finite element method is used to investigate the cup height of the square cup drawing process. In order to verify the predicted FEM simulation of the product's height and forming load in the square cup drawing process, the experimental data are compared with the results of the current simulation. Finite element analysis is also utilized to acquire the designed profile of the drawn products, and a reverse forming method for obtaining the initial blank's shape according to the forward square cup drawing simulation is proposed. The design of initial blank's shape is also certified to obtain the even top edges of drawn cups by experiment. The influences of the blank's shape on the height of product, the forming load, the maximum effective stress and the maximum effective strain are also examined.

2. Finite element modeling

A finite element method has been applied to simulate the plastic flow of materials during the forming process. For the square cup drawing process of a plastic deformation problem, the governing equations for the solution of the mechanics in plastic deformation for materials involve equilibrium equations, yield criterion, constitutive equations and compatibility conditions. The duality of the boundary value problem and the variation problem can be seen clearly by considering the construction of the function [17]:

$$\pi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\,dv - \int_S F_i u_i ds \tag{1}$$

where $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain-rate, F_i represents the surface tractions and, u_i is the velocity components. The variational form for finite-element discretization is given by:

$$\delta\pi = \int_V \bar{\sigma}\delta\dot{\bar{\varepsilon}}\,dv + k\int_V \dot{\varepsilon}_v\delta\dot{\varepsilon}_v\,dv - \int_S F_i\delta u_i ds = 0 \tag{2}$$

where $\dot{\varepsilon}_V = \dot{\varepsilon}_{ii}$ is the volumetric strain rate, π is functional of the total energy and work, and k, a penalty constant, is a very large positive constant. $\delta\dot{\bar{\varepsilon}}$ and $\delta\dot{\varepsilon}_V$ are the variations in effective strain rate and volumetric strain rate. Eq. (1) and Eq. (2) are the basic equations for the finite element formulation.

A commercial FE code DEFORM-3D [18] that can analyze the effects of blank's anisotropic property is adopted to analyze the plastic deformation of the deep drawing process from a circular workpiece. The iteration methods adopted for solving the nonlinear equations are Newton-Raphson and the direct iteration methods. The direct iteration method is used to generate a good initial guess for Newton-Raphson method, whereas Newton-Raphson method is used for speedy final convergence. The convergence criteria for the iteration are the velocity error norm $\|\Delta v\|/\|v\| \le 0.01$ and the force error norm $\|\Delta F\|/\|F\| \le 0.1$, where $\|v\|$ is defined as $\left(v^T v\right)^{1/2}$.

The most important and crucial part of simulation in software is the selection of appropriate material model. DEFORM-3D contains various material models (for elastic-plastic, rigid-plastic and porous material), and each model has different suitability, so selection of correct material model as per the requirement is the prime necessity to get the accurate output or simulated results. Most of the material models require detailed material properties such as young's modulus of elasticity, strain hardening exponent, anisotropy coefficient (R_0, R_{45} and R_{90}) and strength coefficient, etc., as input to preprocessor before running the solver. In addition to material properties, preprocessor also require input of detailed process parameters such as friction coefficient, punch velocity, blank holding force, sheet thickness, etc.

3. Results and discussion

A schematic diagram of the square cup drawing process is shown in Fig. 2. An initially flat thin circular metal workpiece is placed onto a drawing die and an adequate pressure is applied to the blank holder. The punch moves down to make contact with the sheet and to draw it into a square cup. In order to verify the FEM simulation results of DEFORM-3D software for the square cup drawing processes, experimental data such as punch load and final cup height are compared with the results of the current simulation. The experimental conditions are adopted as the input parameters of the simulation. The punch width punch is 50.8 mm × 50.8 mm, the punch and die radius are 8 mm, and the size of die throat is 62 mm × 62 mm. The blank is SPCC steel with a radius of 125 mm and thickness of 0.95 mm; the Young's modulus is 210 GPa; the poison ratio is 0.3; and the anisotropy of material is $R_0 = 2.04$, $R_{90} = 2.16$, $R_{45} = 1.3$, and the flow stress of material is expressed as:

$$\sigma = 514.734(0.006309 + \varepsilon_P)^{0.227}$$

where σ is effective stress and ε_p is effective strain. The blank holder force is 5000 *N*, the friction coefficient is 0.17, and the punch velocity is 1.2 *mm/s*. The values of the material properties and the process parameters are given in table 1 and table 2. Fig. 3 and Fig. 4 compare the current simulation and the experimental results for the punch load and cup height. The results show that the calculated punch load and cup height agree well with the measured values. The difference for the punch load and cup height between the simulation and experiment are attributed to the strain rate sensitivities are not introduced in the current simulation. Fig. 5 shows the final shape of square cup drawing with the circular shape of blank for the current simulation. The final shape of square cup drawn with circular shape of blank for the current experiment is shown in Fig. 6. The maximum cup height occurs at the four corners of the square cup; while the minimum cup height occurs at about the centers of the sides of square cup. The square cup shape of the simulation is similar to that of the experimental results. The top edges of a cup formed by deep drawing are not even with the crests and valleys. The choppy profile of the top edges is undesirable since it requires some metal to be trimmed from the top of the cup to obtain a uniform cup height. Figs. 7(a) and 7(b) show the effective stress and effective strain distributions in the final square cup. When the workpiece is formed into the die completely, the maximum effective stress and effective strain occur at the top edges of the product. The values of maximum effective stress and maximum effective strain are about 718 MPa and 5.14, respectively.

Table 1. The material's property of blank.

Material of blank	SPCC steel
Flow stress	$\sigma = 514.734(0.006309 + \varepsilon_p)^{0.227}\ MPa$
Young's modulus	210000 MPa
Poisson ratio	0.3
Speed of punch	1.2 mm/s
Anisotrpy	R_0 =2.04, R_{45} =1.3, R_{90} =2.16

Table 2. The process parameters of square cup deep drawing process.

The size of square punch	59.5 mm × 59.5 mm
The punch radius	8 mm
The punch corner radius	8 mm
The die radius	8 mm
The size of die	62mm × 62 mm
Blank holder force	5000 N
Diameter of blank	125 mm
Thickness of blank	0.95 mm

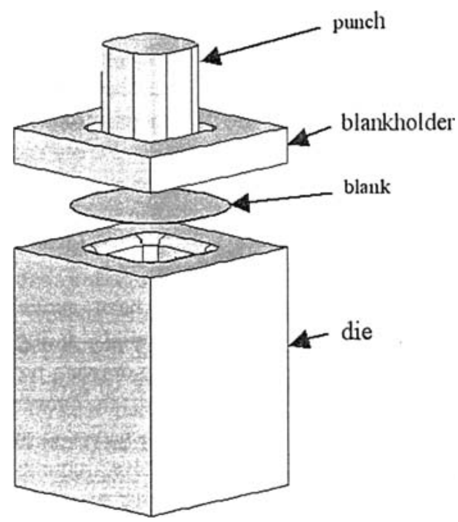

Fig. 2. Schematic diagram of the cylindrical cup drawing process.

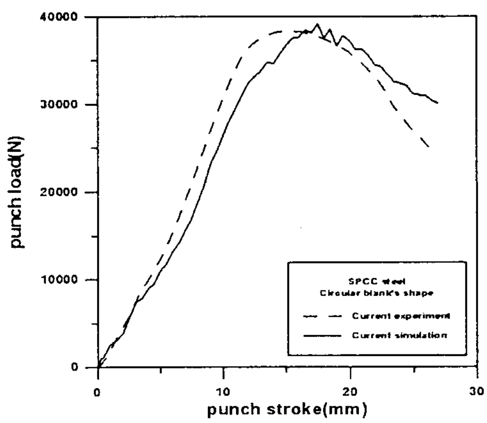

Fig. 3. Comparison between the current simulation and the experimental results for punch load.

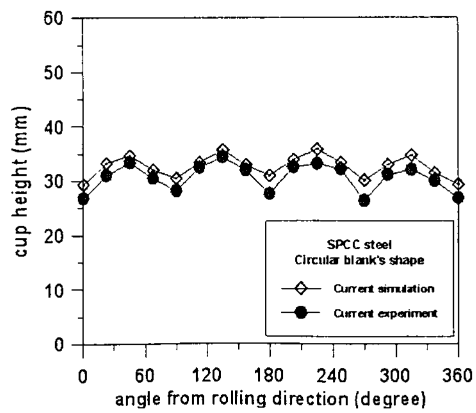

Fig. 4. Comparison between the current simulation and the experimental results for cup height.

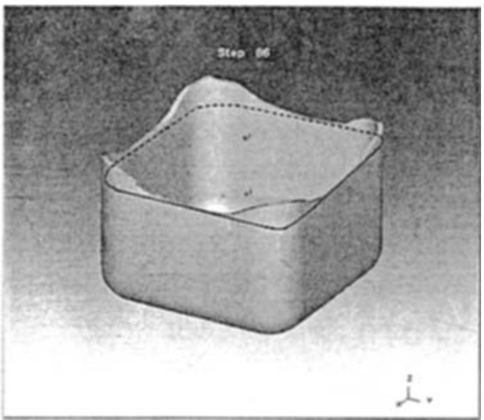

Fig. 5. Final shape of square cup drawing with circular blank (current simulation).

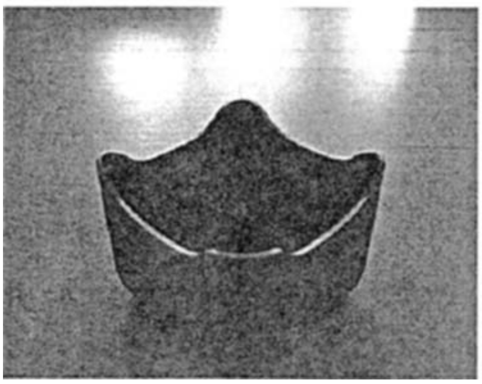

Fig. 6. Final shape of square cup drawing with circular blank (current experiment).

Finite element analysis is also utilized to obtain the designed profile of the drawn products. In order to form a uniform cup height, a reverse forming method for obtaining the initial blank's shape according to the forward square cup drawing simulation is proposed. The method is that the cup height above the black line in Fig. 5 is trimmed after the square cup is drawn completely, and the finite element analysis is then returned back to the first step to obtain the desired initial shape of blank. The obtained modified initial shape of blank is used to form the square cup by current simulation and experiment. The cup height of the products is then investigated for uniformity. Fig. 8 shows the circular blank's shape and the modified blank's shape. The trimmed part at the four corners with crests of square cup corresponds to the concavity of the modified blank. The maximum radius of the modified blank's shape is almost equal to the radius of circular blank. Fig. 9 shows the final shape of

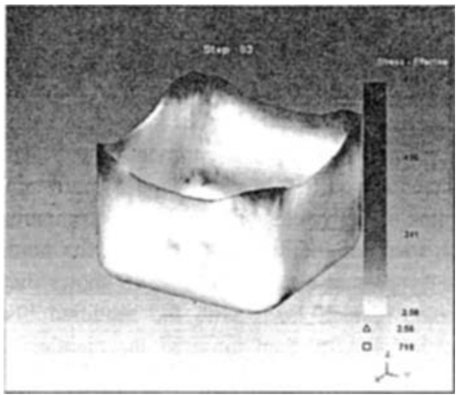

Fig. 7(a). Effective stress distribution of the workpiece.

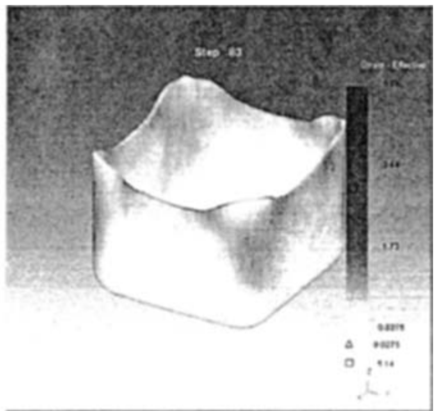

Fig. 7(b). Effective strain distribution of the workpiece.

square cup with modified blank's shape by current simulation. The final shape of square cup with modified blank's shape by present experiment is shown in Fig. 10. The shape of square cup by the simulation is similar to that of the experimental results. The drawn cup height with the modified blank's shape is more uniform than that with the circular blank. Fig. 11 and Fig. 12 compare the current simulation and the experimental results for the cup height and punch load with modified blank's shape. The results show that the calculated punch load and cup height agrees well with the measured values. The cup height of simulation result is slightly larger than the experimental data. Figs. 13 (a) and (b) show the effective stress and effective strain distributions in the final cup. When the workpiece is formed into the die completely, the maximum effective stress and effective strain occurred at the top edge of the product. The values of maximum effective stress and maximum effective strain are about 687 MPa and

3.57, respectively. Fig. 14 compares the drawn cup height for the circular blank and the modified blank by current simulation. Fig. 15 compares the drawn cup height for the circular blank and the modified blank's shape by present experiment. The drawn cup height with modified blank's shape is more uniform than that of the circular blank. Fig. 16 compares the punch load for the circular blank and the modified blank by present experiment. Fig. 16 shows that the maximum punch loads with the modified blank's shape are smaller than those of the circular blank shape. Furthermore, the maximum effective stress and effective strain of the drawn square cup with the modified blank's shape is smaller than that of circular blank shape. The main superiority of the drawn cup using the modified blank's shape over the circular blank shape is that the drawn cup height is more uniform; and in addition the maximum punch load, effective stress and effective strain of drawn square cup are smaller.

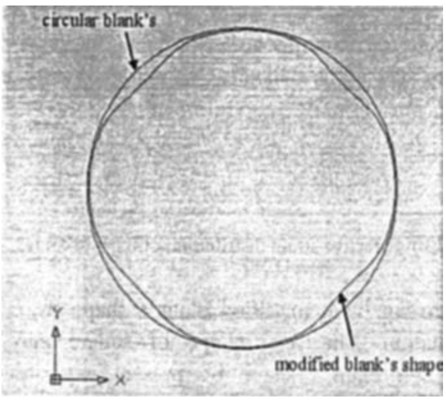

Fig. 8. Circular blank's shape and modified blank's shapes.

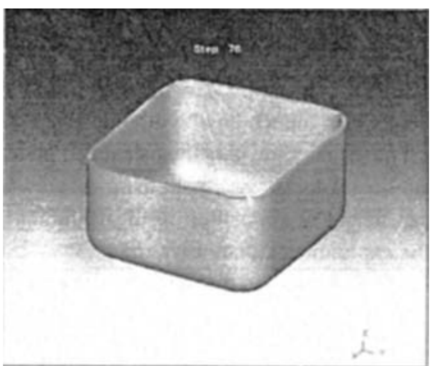

Fig. 9. Final shape of square cup drawing with modified blank shape (current simulation).

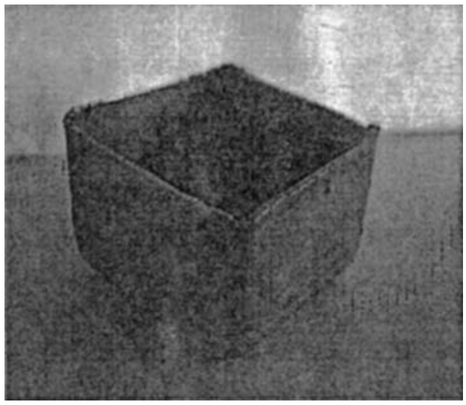

Fig. 10. Final shape of square cup drawing with modified blank shape(current experiment).

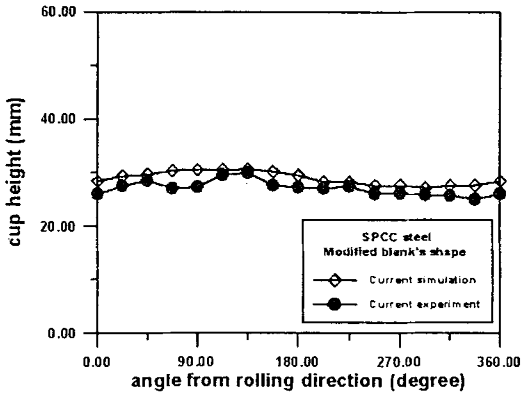

Fig. 11. Comparison between the current simulation and the experimental results for cup height.

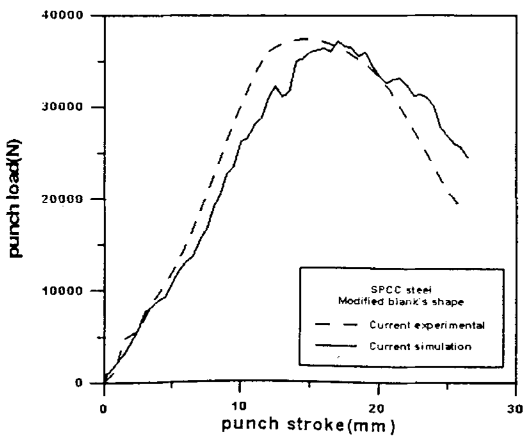

Fig. 12. Comparison between the current simulation and experimental results for punch load.

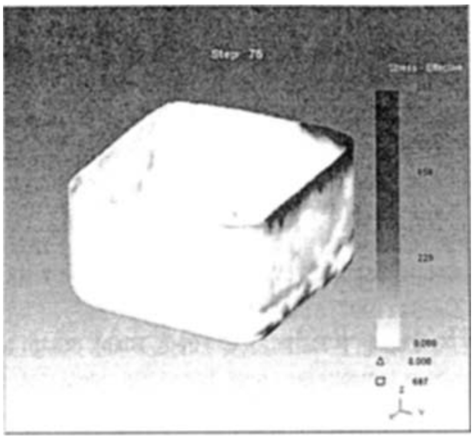

Fig.13(a). Effective stress distribution of product with modified workpiece.

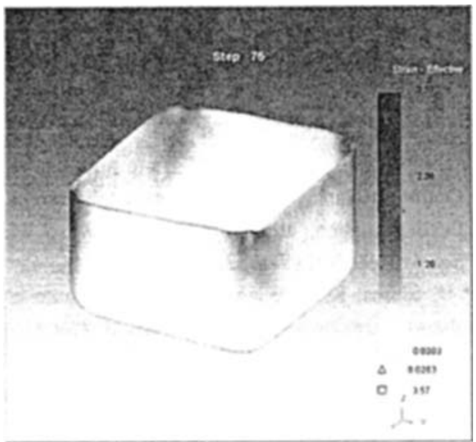

Fig. 13(b). Effective strain distribution of product with modified workpiece.

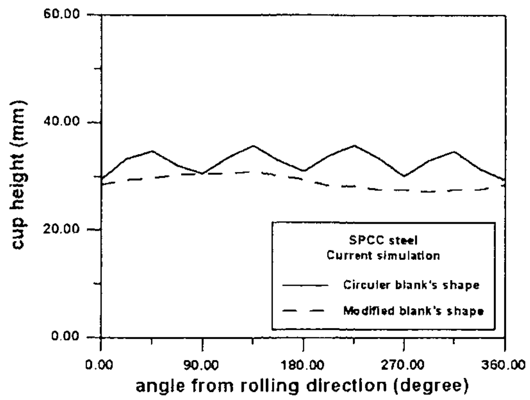

Fig. 14. Comparison between the modified and initial blank's shape for the cup height by current simulation.

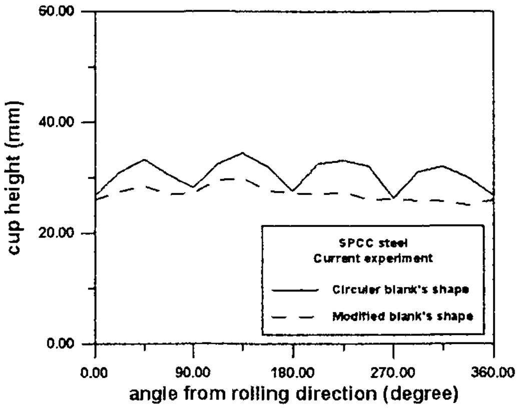

Fig. 15. Comparison between the modified and initial blank's shape for the cup height by current experiment.

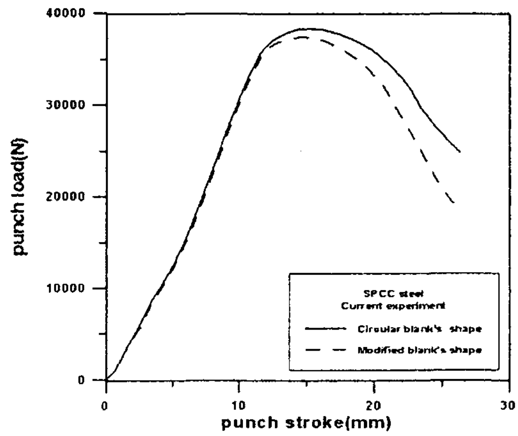

Fig. 16. Comparison between the modified and initial blank's shape for punch load by current experiment.

4. Conclusions

In this paper, a finite element method is used to investigate the cup height of the square cup drawing process. In order to verify the predicted FEM simulation of the product's cup height and forming load in the square cup drawing process, the experimental data are compared with the results of the current simulation. Finite element analysis is also utilized to obtain the designed profile of the drawn products, and a reverse forming method for obtaining the initial blank's shape according to the forward square cup drawing simulation is proposed. The design of initial blank's shape is also certified to obtain the designed profile of drawn cups by experiment. The main superiority of the drawn cup using the modified blank's shape over the circular blank shape is that the drawn cup height is more uniform; and in addition the maximum punch load, effective stress and effective strain of drawn square cup are smaller.

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