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Key technologies of numerical simulation of cup hydrodynamic deep drawing①

LANG Li-hui(郎利辉), KANG Da-chang(康达昌), ZHANG Shi-hong(张士宏), DAI Kun(戴 昆), WANG Zhong-ren(王仲仁), YUAN Shi-jian(苑世剑)
(School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, P.R.China)

[Abstract] A math formula about the relation between fluid pressure after overflowing and punch stroke that can be applied in general FEM software was proposed. It is proved that theoretical results keep coincident to experimental results and the method to simulate hydrodynamic deep drawing process that integrates general FEM software with mathematical description is feasible.

[Key words] hydrodynamic deep drawing; fluid pressure; FEM
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1 INTRODUCTION

The forming theory of hydrodynamic deep drawing (HDD) process is shown in Fig.1[1]. It has been paid much attention in the world because it has many advantages[2~4]. However, many influencing factors exist in the process of HDD, and the most important influencing factor is the effect of liquid in the die cavity[5]. Many ways to solve this problem were proposed and studied, and the main way is to do a great deal of experiments to find a general rule that can be applied in the forming of any parts[6]. But, it proved that the experimental way is not satisfied. In recent years, the development of numerical simulation provides a good method to solve the problem of liquid pressure in HDD process[7]. Yet, it is still because of the complexity of liquid flowing that delays the research work[8].

This paper is based on the contents in Ref.[1], the distribution rule of the liquid pressure between sheet metal and the upper surface of the die after overflowing is mainly studied. A mathematical computation model about liquid flowing is put up and this model can be combined with FEM. The method how to integrate mathematical computation model with the general FEM software is studied and proposed.

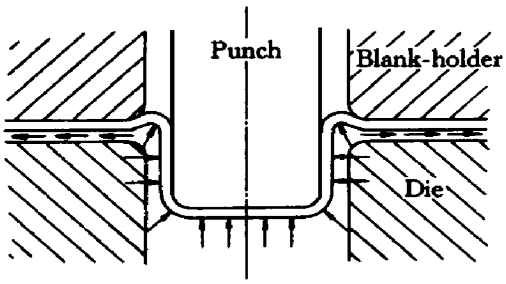

Fig.1 Schetch of cup hydrodynamic deep drawing

2 MATHEMATICAL COMPUTATION MODEL AFTER OVERFLOWING

During HDD, there are two ways of blank holding: varied blank holding force and fixed gap blank holding. The two ways of blank holding have both been applied in experiments in this paper. The way of varied blank holding force is studied firstly as follows.

As shown in Fig.2, the character of liquid flowing between sheet metal and the upper surface of the die can be expressed by the equation of Navier-Stokes. It is provided that the inertia and turbulent flow can affect the liquid flowing little and can be neglected in the model, and the liquid stage between die and sheet metal is a thin film and laminar flow. A one-dimension equation of Navier-Stokes can be expressed as:

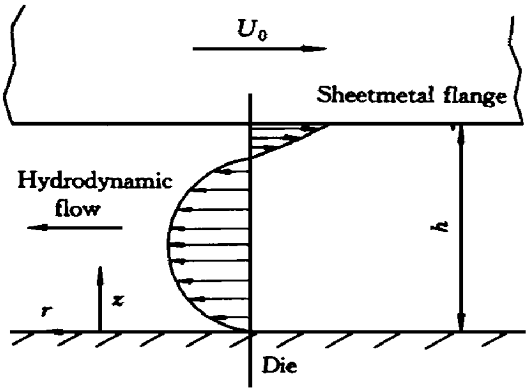

Fig.2 Velocity distribution in gap between blank flange and die

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$$\frac{\partial p(r)}{\partial r} = \eta \frac{\partial^2 u_r}{\partial z^2} \tag{1}$$

where $0 \leqslant z \leqslant h$, $R_b \leqslant r \leqslant a$, $a = R_d + r_d$.

The boundary conditions Eqn.(1) can be given as:

$u_r(z) = 0$ when $z = 0$

$u_r(z) = u_0 \frac{a}{r}$ when $z = h$

To solve Eqn.(1), some assumptions can be devised as follows. 1) the liquid cannot be compressed, 2) the flooding layer is a thin film and the liquid flows as the state of laminar flow, 3) the liquid pressure at the border of sheet flange is zero, that is to say $p(R) = 0$. Then, the velocity distribution of liquid flowing along radial direction of blank flange can be retained

$$u_r = \frac{h^2}{2\eta}\frac{\partial p(r)}{\partial r}\left(\frac{z}{h}\right)\left(\frac{z}{h} - 1\right) + u_0\left(\frac{a}{r}\right)\frac{z}{h}$$

Integrating $p(r)$ with respect to r, the following expression can be gotten as:

$$p(r) = p_s - \frac{6\eta}{h^3}\left(u_0 ah + \frac{Q}{\pi}\right)\ln\left(\frac{r}{a}\right) \tag{2}$$

where Q is the rate-of-flow of liquid flooding from the gap between sheet metal and the die. After it is provided that the flooding rate-of-flow meeting the need of control by the proportional pressure-relief valve is so little as to be ignored and punch corner radius is thought as zero, the value of Q equals to the volume that the punch goes into the die cavity per unit of time and Q is a constant. Here, the velocity of punch pressing is set as a constant.

Eqn.(2) shows that the variables of h and r will affect the function $p(r)$ more greatly than the other variables. For the forming with varied blank holding force, for the purpose of preventing wrinkling, the needed blank holding force can be retained according to the integral transformation of Eqn.(2):

$$\begin{aligned} F_{bh} &= 2\pi\int_a^R p(r)\,\mathrm{d}r \\ &= \pi(R^2 - a^2)\left(p_s - A\ln a - \frac{A}{2}\right) + \\ &\quad \pi A(R^2\ln R - a^2\ln a) \end{aligned} \tag{3}$$

where

$$A = \frac{-6\eta}{h^3}\left(u_0 R_p h + \frac{Q}{\pi}\right)$$

It is known by Eqn.(3) that the blank holding force is closely related the variables of flooding rate-of-flow of liquid, the liquid pressure in die cavity and the thickness of overflowing layer.

According to the numerical simulation of HDD process with the condition of varied blank holding force, at the beginning of calculating, the value of F_{bh} is given firstly and the thickness of flooding layer h must be gotten by calculation. The variable of h is a very important parameter for modeling in FEM. According to the boundary condition of $p(R) = 0$, the following equation can be given from the transformation of Eqn.(2):

$$p(R) = p_s - \frac{6\eta}{h^3}\left(u_0 ah + \frac{Q}{\pi}\right)\ln\left(\frac{R}{a}\right)$$

and

$$\frac{p_s}{\ln\left(\frac{R}{a}\right)}h^3 - 6\eta u_0 R_p h - 6\eta\frac{Q}{\pi} = 0 \tag{4}$$

Eqn.(4) is that with one unknown and cubic form. Because it will be applied in FEM, it is convenient to solve this equation by the numerical method, through which the data can be transferred freely among modules in computer.

In Eqn.(3), when the blank holding force F_{bh} keeps invariable, the variable of h is only related to the liquid pressure in die cavity of p_s and the flooding rate-of-flow of Q. If the values of Q and p_s increase and the flooding layer h will become thicker. Generally, the value of h is very small correspondingly. If the value of flooding layer thickness h increases a little, the liquid pressure in die cavity will drop down sharply.

For the forming with fixed gap blank holding, because the blank holding force is preset large enough so that the blank holder cannot be lifted by the liquid pressure below flange of blank. Then, through Eqn.(2), the liquid pressure distribution below the flange of blank that can be applied in FEM can be gotten directly.

3 APPLICATION OF MATHEMATICAL COMPUTATION MODEL OF PRESSURE DISTRIBUTION AFTER OVERFLOWING IN FEM

In the simulation during HDD, the flowing of liquid which acts on the sheet belongs to the boundary condition. Meet the necessity of numerical simulation, after the continuous forces are dispersed, the pressure calculated by computation mathematical model can be brought to the shells or the membranes in response to the punch stroke at different time steps. For handling the loaded pressure effectively through the liquid in the die cavity, the three segments A, B and C as shown in Fig.3 can be divided in theory.

Just as above mentioned, during HDD of cylin-

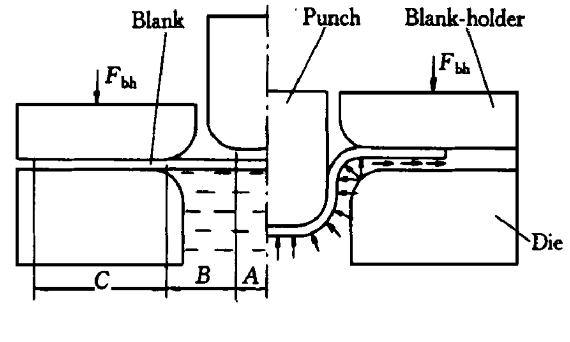

Fig.3 Three segments of sheet during HDD

dric cup, there are three steps according to characters of liquid operation. The first step is initial pre-bulging pressure when the segments of A and B will be bulged by the liquid pressure. The second step is that the punch begins to go down until the phenomenon of liquid overflowing occurs. At this step, because the liquid has the feature of compressibility, the liquid pressure can reach the overflowing pressure after some punch displacements against the elastic reaction of the liquid in the die cavity. At this time, the pressure of liquid in the die cavity increases linearly with the going down of the punch. The pressure of liquid in the die cavity can be expressed as follows:

$$p_s = p_{sp} + 2\pi R_p H_p \cdot E_c / V_c \qquad (5)$$

The third step is that from the beginning of overflowing to the finishing of drawing. To the fixed gap blank holding, as shown in Fig.4, the element quantities of blank flange (segment C) are $N_\theta \times N_r$, where N_r is the element number divided in the radial direction and N_θ is the element number divided in the tangential direction. Due to the symmetry, only one quarter of the geometry is considered. Using the rule that the area of deformed blank around punch equals to that of the reduction of flange at any time, at time t, the loaded pressure of blank flange can expressed as:

$$p(r_i) = p_{s,t} \qquad \text{where} \quad r_i \leqslant R_d + r_d$$

$$p(r_i) = p_{s,t} - \frac{6\eta}{h^3}\left(u_0 ah + \frac{Q}{\pi}\right)\ln\left(\frac{r_i}{a}\right) \qquad (6)$$

$$\text{where} \quad r_i > R_d + r_d$$

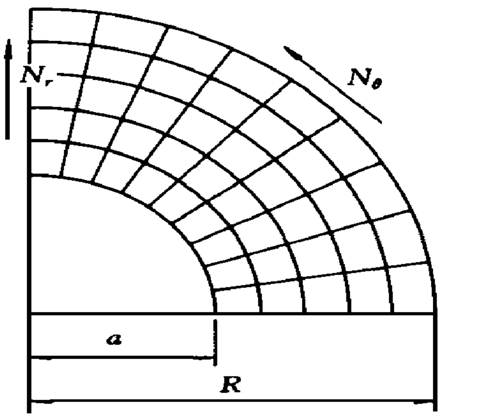

Fig.4 Blank flange in FEM

It is provided that the sheet covered on the punch corner comes completely from the bulging of sheet in segment B. At time t, the punch stroke is H_t, the sheet blank in flange begins to be drawn after the whole punch corner is covered with bulged sheet in segment B. According to the above assumption, the effects of the sheet around the punch corner will not be taken into account when the deformation of flange is calculated.

For ith row element in the radial direction in blank flange, the loaded liquid pressure can be expressed as:

$$p(r_{t,i}) = \frac{p(r_{t,i}) + p(r_{t,i+1})}{2} \qquad (7)$$

And by Eqns.(6) and (7), the following equation can be obtained:

$$p(r_{t,i}) = p_{s,t} \qquad \text{where} \quad r_{t,i} \leqslant R_d + r_d$$

$$p(r_{t,i}) = p_{s,t} - \frac{6\eta}{h^3}\left(u_0 ah + \frac{Q}{\pi}\right)\ln\frac{r_{t,i}}{a} \qquad (8)$$

$$\text{where} \quad r_{t,i} > R_d + r_d$$

where

$$r_{t,i} = \sqrt{r_{t_0,i}^2 - \frac{F^2}{\pi}} \qquad \text{when} \quad r_{t_0,i}^2 - \frac{F^2}{\pi} \geqslant 0$$

$$r_{t,i} = 0 \qquad \text{when} \quad r_{t_0,i}^2 - \frac{F^2}{\pi} < 0$$

$$F^2 = 2\pi R_p(H_t - h_p - r_p)$$

$$\text{when} \quad H_t \geqslant h_p + r_p$$

where $p_{s,t}$ is the liquid pressure in die cavity at time t; $p(r_{t,i})$, $p(r_{t,i+1})$ are the loaded pressures on the former nodes and the latter nodes of the ith row of elements in the radial direction at time t, respectively. $r_{t,i}$, $r_{t,i+1}$ are the radii of the former nodes and the latter nodes of the ith row of elements in the radial direction at time t, respectively. $r_{t_0,i}$, $r_{t_0,i+1}$ are the radii of the former nodes and the latter nodes of the ith row of elements in the radial direction at time t_0, respectively.

According to mathematical model (5) and (8), the loaded pressure on any elements at any time after overflowing can be calculated. The data of loaded pressure can be written in the card file with specific format which can be read by LS-DYNA3D code.

The discussion above mentioned about the pressure loading methods on the flange sheet can be applicable during drawing with varied blank holding force and fixed gap blank holding. But, for the condition of varied blank holding force, because the gap between blank and die varies in different time as the blank holder is not fixed, the displacements of blank holder at different times must be input in this card file read by LS-DYAN3D, which will keep coincidence with the practical condition. Eqn.(4) can be used to calculate the displacement of blank holder at different times, then, the data can be added into the card file with specific format.

4 NUMERICAL SIMULATION AND PROCESS EXPERIMENTS DURING HDD OF CYLINDRIC CUP

The applied material of blank is 08Al, and the hardening model of bilinear law is used. The law of Coulomb is used to deal with the friction. The radii in both punch corner and die corner are 8.0 mm. The clearance between punch and die is 1.25 times of blank thickness. The diameter of punch is d99.86 mm. The fixed gap between blank and die is 1.11

times of blank thickness. The geometry of blank applied in simulation and experiment is a circular shape. The original diameter of blank is 250 mm. The other parameters are listed in Table 1 in Ref.[1]. The applied finite element code is LS-DYNA3D, which is efficient in the simulation of sheet metal forming[9,10]. The finite element model is shown in Fig.5.

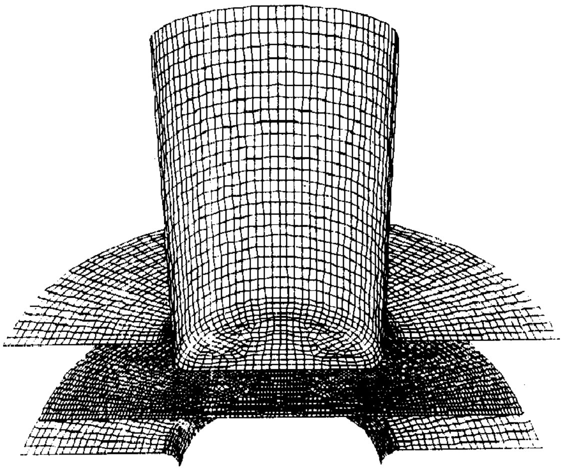

Fig.5 Finite element model

The initial pressure is used to pre-bulge the sheet, and the applied initial pressure is 7.5 MPa. The overflowing pressure at a punch stroke can be known firstly according to Ref.[1]. The finished part in simulation is shown in Fig.6. In order to examine and verify the simulated results and the applied mathematical model, some experiments have been done and an experimental part is shown in Fig.7. The comparison of thickness thinning ratios of curvilinear distance to the cup bottom center is shown in Fig.8. The two curves keep concordance approximately, which proves that the applied mathematical models in Refs.[1] and [2] are feasible and agree with the practice.

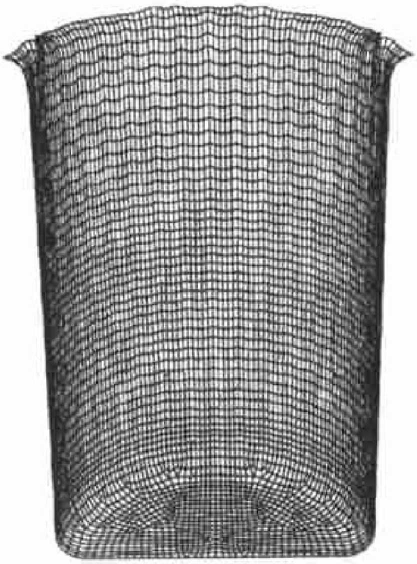

Fig.6 Meshed finished part after simulation
(Drawing ratio is 2.5)

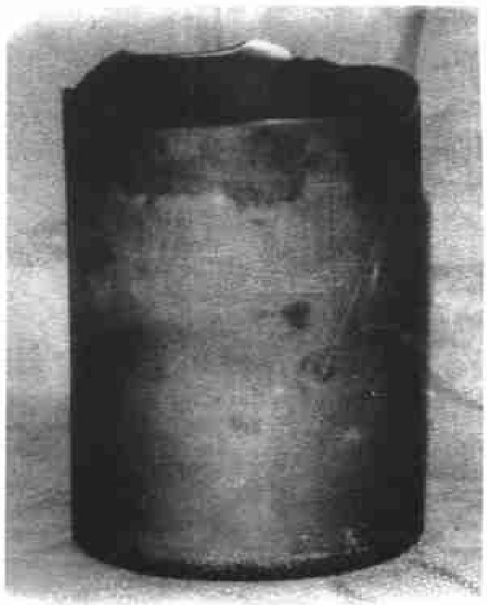

Fig.7 Photograph of finished part after experiment
(Drawing ratio is 2.5)

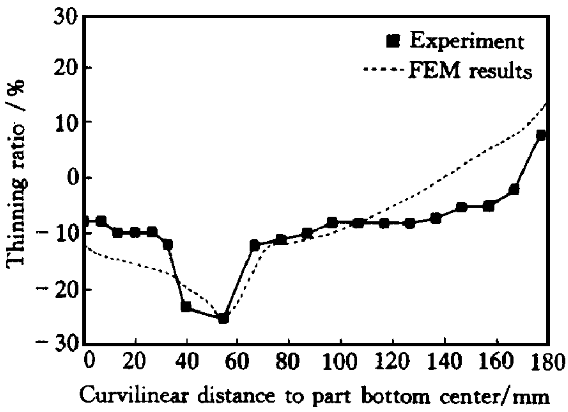

Fig.8 Comparison of thickness thinning ratios of curvilinear distance to parts bottom center
(Between FEM and experimental results)

During HDD, because of the function of the liquid in the die cavity, the condition of stress and strain is totally different from that in traditional deep drawing, which stops the thickness thinning of the sheet in punch corner and die entrance corner. In fact, a different phenomenon from the traditional deep drawing has been found in experiment of HDD, the fractured position always locates in the die entrance corner but not the punch corner. Fig.9 shows that the tensile stress distribution of sheet during HDD. At initial punch displacement, the position with the most radial tensile stress is in the punch corner. And when the punch goes on, the position with the most radial tensile stress will transfer from punch corner to die entrance. Thus, the possibility of sheet fracture in punch corner is reduced and high drawing ratio can be retained. The ratio of wall thickness thinning can get

24 % in HDD, but 8 % in traditional deep drawing. In primary processing of HDD, the sheet in punch corner will become thinner severely, and after a small punch displacement, the sheet in punch corner will stop thinning and keep constant. This is the effect of friction-keeping between punch and deformed sheet, and at the last step of drawing, the sheet in the upper will become even more thick, which is shown in Fig. 9.

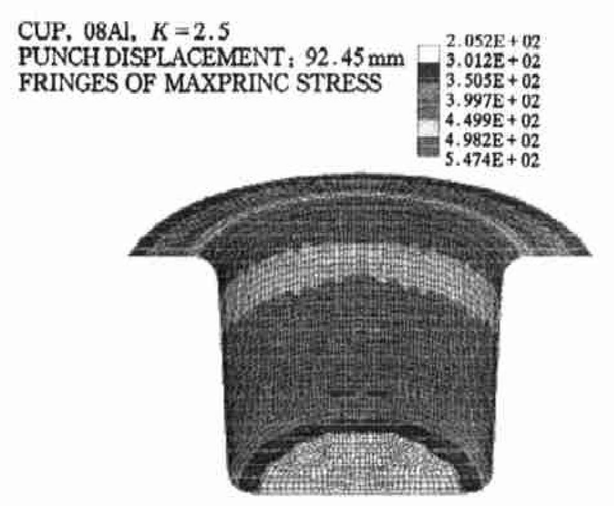

Fig.9 Radial stress distribution during drawing

5 CONCLUSIONS

1) It is feasible to analyze the HDD of sheet with general software LS-DYNA3D.

2) The mathematical computation models of the overflowing pressure and the pressure distribution of liquid after overflowing are applied in the simulation of sheet in cylindric cup hydrodynamic deep drawing.

3) The applied method that analyze the cylindric cup hydrodynamic deep drawing can be used to analyze the HDD forming of other parts with special shape such as square case and tapered rectangular case etc.

NOTATION

p_{sp} Initial pressure
$p_{s,t}$ Liquid pressure in die cavity at time t
$p(r)$ Liquid pressure at r
σ_r Radial stress in sheet flange
σ_θ Tangential stress in sheet flange
σ_{rz} Shear stress in the plane r_z of sheet
u_0 Punch velocity
u_r Velocity of liquid at r in flooding layer
R_d Die radius of cylindric cup
r_d Die corner radius of cylindric cup
p_s Liquid pressure in die cavity
F_{bh} Blank holding force
η Viscosity of liquid
Q Flow-rate of liquid
N_r Element number divided in radial direction of flange
N_θ Element number divided in tangential direction of flange
H_t Punch stroke at time t
a Radius at die entrance, equals to $R_d + r_d$

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