[Article ID] 1003 - 6326(2000)05 - 0631 - 04

Numerical simulation of cup hydrodynamic deep drawing①

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[Abstract] The simulation of hydrodynamic deep drawing by means of FEM is an efficient method that can relieve experimental burden and find the optimum process parameters. Some problems such as mathematical description of cavity liquid flow pressure must be solved firstly. A math formula about hydrodynamic flow pressure that can be applied in general FEM software was proposed, and good results were gained. It was proved that the theoretical results keep coincident with experimental results.

[Key words] hydrodynamic deep drawing; overflowing pressure; FEM
[CLC number] TG376 **[Document code]** A

1 INTRODUCTION

Actually, the hydrodynamic deep drawing process (HDD) belongs to traditional deep drawing process. Before drawing, the die cavity is filled fully with liquid such as oil, water or oil water emulsion. When the punch presses the blank and goes down into the die, the liquid is compressed and the counteracting force is formed, the effect of friction-keeping is formed because the blank is pressed tightly onto the surface of the punch. At the same time, the liquid will flow freely between the die and the blank so as to relieve the useless friction force during metal sheet flows, so the effect of flooded lubrication is formed. Due to the reasons described above, the drawing limit of sheets will be increased greatly and the surface quality of formed parts will be improved effectively by means of HDD process[1~3].

Because this technology has many advantages and can be applied widely in the versatile and low volume production with miscellaneous materials, it has been paid much attention in the industrial field of national defence, aerospace and automobile[4~6]. Many researchers have studied the forming of cylindric cup during HDD process and try to get some useful rules that can be used to predict the optimum HDD forming process parameters of other parts with complicated shapes[1,3,7,8]. But, due to the forming complexity and too many influencing factors, it seems impossible to retain a universal rule through experiment. Recently, with the development of FEM technology, this problem can be solved[9,10]. However, it is difficult to describe the flowing behavior of liquid in die cavity during simulation when the general software is applied, so, the whole loading model is usually applied according to practical cavity pressure loading curve. That is to say, any points below sheet would be applied to the equal liquid pressure value same as the cavity pressure at any time. Apparently, this method is not very suitable and the obtained results of simulation are different greatly from practical results.

In this paper, based on general simulation software, the method of mathematical analysis solution is combined with FEM. The distribution rules of liquid pressure before and after overflowing are found and corresponding mathematical models are set, and proper and different loading pressure can be applied onto the different points of sheet.

2 SIMULATION OF CYLINDRIC CUP HDD PROCESS

Cylindric cup is a typical axisymmetric part during deep drawing. Many influencing factors such as material performance and process conditions can affect the forming. Because of the effect of liquid in die cavity on process conditions, besides the traditional influencing factors such as blank holding force, lubrication condition, die corner radius, punch corner radius, blank geometric size and so on, the overflowing pressure and the distribution of liquid pressure after overflowing must be considered. During hydrodynamic deep drawing, the liquid flowing behavior is the key technology and affects greatly the last result and the surface quality of formed parts. In simulation, if the liquid flowing behavior is not taken into consideration carefully, the calculated results will not be accurate. The general software LS-dyna3d is used in this paper. Although the element bases of LS-dyna3d software are very abundant, the liquid element suitable to simulation of HDD is absent. So, for the purpose of getting accurate results, the mathematical analysis so-

① [Foundation item] Project supported by the National Natural Science Foundation of China
[Received date] 1999 - 08 - 03; [Accepted date] 1999 - 11 - 08

lution is applied firstly to describe the liquid flowing behavior such as the overflowing pressure and the distribution of liquid pressure after overflowing. Then, a mathematical model is combined with general software according to the features of cylindric cup deep drawing, thus, the operation of liquid on blank can coincide with the practical condition. In this paper, the mathematical model of overflowing pressure during HDD and the model's application in simulation are discussed firstly.

3 CALCULATION OF OVERFLOWING PRESSURE

3.1 Computational mathematical model

During HDD, there are two kinds of blank holding: varied blank holding force and fixed gap blank holding. The way of varied blank holding force is studied firstly as follows.

In the way of varied blank holding force, when the liquid pressure in die cavity reaches the overflowing pressure, the drawing force in the die corner and the blank holding force will be overcome and the liquid will flow freely through the die corner, and the flooded lubrication can be formed. The course of overflowing generated is shown as Fig.1.

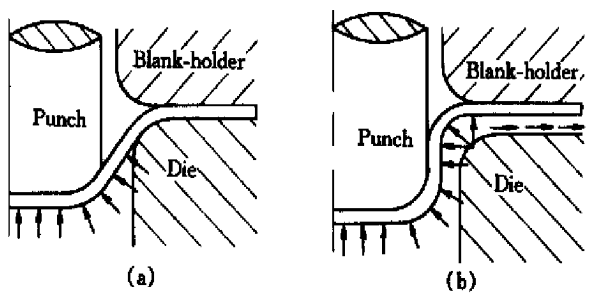

Fig.1 Sheet forming stages
(a) —Before overflowing; (b) —After overflowing

It is known that if the blank in the die corner is raised by liquid in die cavity, the overflowing will be formed. In response to the principle of force equilibrium, the pressure that can raise blank in die corner and is needed to form overflowing equals to the drawing force of blank in die corner:

$$2\pi R_p t \sigma_{re} = \pi r_d (2R_d + r_d) p_s$$

If the above equation is adjusted, the following equation can be retained:

$$\sigma_{re} = \frac{r_d(2R_d + r_d) p_s}{2R_p t} \tag{1}$$

As shown in Fig.2, the cylindric cup deep drawing is a typical axisymmetric deformation. The radial tensile stress and the tangential compressive stress exist in the flange of sheet. According to the stress equation and Mises yielding criterion, the radial tensile stress of any point in flange can be expressed as follows:

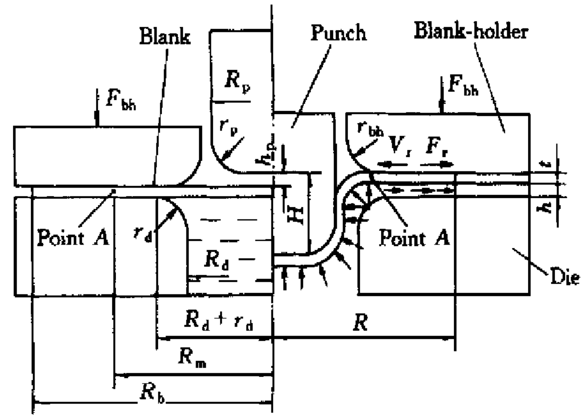

Fig.2 Schematic of overflowing pressure computation applied for varied blank holding force

$$\sigma_r = 2k\cdot\ln\left(\frac{R}{r}\right) + \frac{1}{t}\int_r^R 2m\frac{F_{bh}}{S}\mathrm{d}r = 2k\cdot\ln\left(\frac{R}{r}\right) + \frac{2mF_{bh}(R-r)}{tS} \tag{2}$$

When overflowing, the right items equal to each other in Eqn.(1) and (2), and the following equation can be gotten:

$$2k\cdot\ln\left(\frac{R}{R_d + r_d}\right) + \frac{2mF_{bh}[R-(R_d+r_d)]}{tS} = \frac{r_d(2R_d + r_d)p_s}{2R_p t}$$

And the liquid pressure can be given:

$$p_s = 2R_p t \times \frac{2k\cdot\ln\left(\frac{R}{R_d + r_d}\right) + \frac{2mF_{bh}[R-(R_d+r_d)]}{tS}}{r_d(2R_d + r_d)} \tag{3}$$

Eqn.(3) is the calculation equation of overflowing pressure, in which k concerned with the level of blank deformation is the flow stress of blank in die corner. Provided that the applied material is isotropy and the hardening character of material is considered, the flow stress of sheet can be expressed as

$$k = 0.5c\cdot \varepsilon^n$$

As the deformation condition of blank flange is plane strain state and the radial strain equals to the tangential strain, $\varepsilon_r = \varepsilon_\theta$, the above equation can be given by tangential strain:

$$k = 0.5c\cdot\frac{2^n}{3^n}\varepsilon_\theta^n \tag{4}$$

Using Eqns.(3) and (4), the equation of overflowing pressure concerned with sheet deformation can be obtained.

3.2 Application of computational mathematical model in FEM

In FEM, the liquid pressure in die cavity will be written as the external force in the file of fore treatment, which is concerned with time or punch stroke. In order to apply this computational model in FEM, it is necessary to get the value of punch stroke H when the liquid in die cavity begins to overflow. Thus, during the process of cylindric cup hydrodynamic deep drawing, the liquid pressure loading on blank can be divided into two steps. The first is before overflowing when the punch stroke is less than H and the liquid in die cavity can only affect the blank drawn into die corner. The second is after overflowing when the punch stroke is more than H, the liquid will affect the whole blank and the values of liquid pressure are different from one another according to different position of blank (this part will be discussed in a following paper). For the sake of convenience of analysis, some assumptions are put out as follows according to the deformation character of cylindric cup.

1) The blank of flange will not proceed deforming before the part in punch corner is covered with bulging sheet.

2) Hereafter, the blank of flange will be deformed and the thickness will keep constant.

Meeting the needs of process, the initial pressure method is applied during HDD. When the punch stroke is H and the flooded lubrication has not occurred, the pressure of liquid in die cavity can be expressed as

$$p_s = p_{sp} + 2\pi R_p H E_c / V_c \quad (5)$$

where p_{sp} is the initial pressure, E_c is the elastic module of liquid media and a constant.

When the punch stroke is H and the pressure of liquid in die cavity reaches the pressure of overflow, the following equation can be obtained according to Eqns.(3) and (5):

$$p_{sp} + 2\pi R_p H E_c / V_c = \frac{2 R_p t\left[2k\ln\left(\frac{R}{R_d + r_d}\right) + \frac{2mF_{bh}[R - (R_d + r_d)]}{tS}\right]}{r_d(2R_d + r_d)}$$

$$H = f(p_{sp}, k, \cdots) \quad (6)$$

where

$$R = \sqrt{R_b^2 - F/\pi}$$

$$S = \pi R_b^2 - F$$

$$k = 0.5c \cdot \varepsilon^n = 0.5c\left[\ln\frac{R_m}{(R_d + r_d)}\right]^n$$

$$R_m = \sqrt{F/\pi + (R_d + r_d)^2}$$

$$F = F_1 + F_2 = 2\pi R_p(H - h_p - r_p) + \frac{\pi}{4}[2\pi r_p(2\pi R_p - 2r_p) + 8r_p^2]$$

Eqn.(6) is a nonlinear function. The numerical method can be used and the punch stroke H will be obtained when the overflowing occurs. According to Eqn.(6), the punch stroke H when overflowing occurs is mainly concerned with the sheet material performance and initial pressure after the die has been finished manufacturing.

The described above is about the way of varied blank holding, which is mainly applied in industries. But, in this paper, some simulations and experiments are carried out in the way of fixed gap blank holding, so the following will discuss the overflowing pressure when the way of fixed gap blank holding is applied.

The computational model of overflowing pressure in the way of fixed gap blank holding is similar to that in the way of varied blank holding. Fig.3 shows the schematic diagram of forming in the fixed gap blank holding. For the forming with fixed gap blank holding, it can be provided that the frictional forces between the blank flange and the blank holder, the blank flange and the die, are very small and can be neglected in the initial stage of forming because the thickness of the outer flange increases a little. According to Eqn.(6), the punch stroke when overflowing occurs can be expressed as

$$p_{sp} + 2\pi R_p H E_c / V_c = \frac{2R_p t \cdot 2k\ln\left(\frac{R}{R_d + r_d}\right)}{r_d(2R_d + r_d)},$$

$$H = f(p_{sp}, k, \cdots) \quad (7)$$

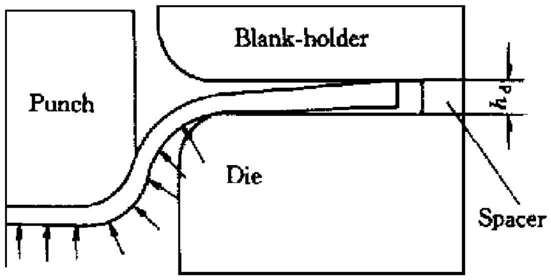

Fig.3 General description of hydrodynamic deep drawing with a fixed gap blank holding

Here, according to Eqn.(3), neglecting the frictional force, the overflowing pressure can be expressed as

$$p_s = \frac{2R_p t \cdot 2k\ln\left(\frac{R}{R_d + r_d}\right)}{r_d(2R_d + r_d)} \quad (8)$$

In FEM, for the way of fixed gap blank holding, the overflowing pressure can be calculated firstly by Eqn.(8). And then, by Eqn.(7), the punch stroke when overflowing occurs can be obtained. The liquid pressure can be applied onto the surface of sheet as pressure force and the varied pressure of every point on blank can be written in the file of fore treatment. The loading of pressure depending on time step on an element is shown in Table 1.

4 ANALYSIS OF EXPERIMENTAL RESULTS

In order to examine and certify the results of theoretical calculation, some experiments have been done. Fig.4 shows the comparison between the experimental results and the simulation results. Some parameters are shown in Table 2. The No.20 machine oil made in China is filled in die cavity. The elastic modulus of this oil is 1 000 MPa. The volume of die cavity is $2.5 \times 10^6\ mm^3$. In experiment, the data of liquid pressure in die cavity can be collected through computer in time. All the collected data can form a liquid pressure variation curve, from which the value of overflowing pressure can be obtained because a severe variation of liquid pressure in die cavity will appear when overflowing begins. Fig.4 shows that the results of theory are close to that of experiment. The results of FEM are 4 to 5 MPa less than that of experiment because the frictional force due to the wrinkling of outer flange of blank is neglected in computational mathematical model during forming in the way of fixed gap blank holding.

Table 1 Loading of liquid pressure in FEM

Time step	Punch stroke	Element pressure
1	0	0
2	0	p_{sp}
3	H	p_s
...	...	...

Table 2 Characteristic parameters of sheet metal and FEM

Title	Value
Material	08Al
Yield strength, σ_s/ MPa	230.0
Poisson ratio	0.30
Elastic modulus, E/ GPa	210
Strength constant, C/ $(kg \cdot mm^{-2})$	68.316
Hardenability value n	0.227
Density/ $(g \cdot cm^{-3})$	7.83
Hardening modulus, E_t/ MPa	1000
Element type	Belytschko-tsay shell
Static friction factor (punch-blank)	0.14
Dynamic friction factor (punch-blank)	0.14
Static friction factor(die-blank) (blank-holder-blank)	0.08
Dynamic friction factor(die-blank) (blank-holder-blank)	0.08

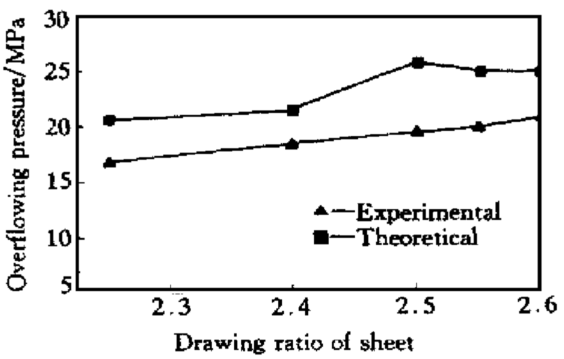

Fig.4 Overflowing pressures with different drawing ratio

NOMENCLATURE

p_s —Liquid pressure in die cavity;
R_p —Punch radius of cylinderic cup;
r_p —Punch corner radius of cylinderic cup;
R_d —Die radius of cylinderic cup;
r_d —Die corner radius of cylinderic cup;
R_b —Initial radius of blank;
R —Outer radius of flange during forming;
σ_{re} —The radial stress in the position of $R_d + r_d$;
k —Yielding stress in shear state;
F_{bh} —Blank holding force;
S —Area of flange;
m —Coulomb friction coefficient;
c —Material coefficient in hardening function;
n —Hardenability value;
ε_r —Radial strain in flange;
ε_θ —Tangential strain in flange;
p_{sp} —Initial pressure;
h_p —Initial height;
E_c —Elastic modulus of liquid;
V_c —Volume of die cavity.

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(Edited by YUAN Sai-qian)