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Modeling of the minimum variable blank holder force based on forming limit diagram (FLD) in deep drawing process

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Abstract. This paper presents the mathematical approach of minimum blank holder force to prevent wrinkling in deep drawing process of the cylindrical cup. Based on the maximum of minor-major strain ratio, the slab method was applied to determine the modeling of minimum variable blank holder force (VBHF) and it compared to FE simulation. The Tin steel sheet of T4-CA grade, with the thickness of 0.2 mm was used in this study. The modeling of minimum VBHF can be used as a simple reference to prevent wrinkling in deep drawing.

1. Introduction

The wrinkle is a type of product defect that often occurs in deep drawing. One thing that can be pursued to prevent product defects is determining the magnitude of the blank holder force (BHF) accurately. To solve this problem, the magnitude of BHF should be set by safe value. Some research related to the determination of blank holder force for prevention product defect is still widely performed. Reddy et al. [1], Agrawal et al. [2], Wang et al. [3], and Qin et al. [4] conducted the research to obtain the linear BHF distribution magnitude for reducing wrinkling. Based on restraining energy calculating and buckling criterion, Agrawal et al. [2], Wang et al. [3] and Qin et al. [4] developed the mathematical modeling of minimum constant BHF to avoid wrinkling. The wrinkling would occur when the buckling strain as the tangential strain is excessive. Furthermore, they have developed the buckling analysis to predict the onset of wrinkling and determined the BHF magnitude by using the theory of strain energy.

Kadkhodaya et al. [5], Chu et al. [6], Correia et al. [7], and Shafaat et al. [8, 9] have proposed the mathematical model of wrinkling by using the approach of bifurcation function and Tresca criterion. Furthermore, these models are used to predict the minimum constant BHF without wrinkling, during the punch stroke. Candra et al. [10] continued these researches to estimate the variable blank holder force by using the maximum gap criterion.

Based on the researches above, this paper develops a different approach to determine the minimum VBHF by using the forming limit diagram (FLD) criterion to prevent wrinkling. Modeling of the minimum VBHF would also be verified by FE simulation.

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2. Mathematical modeling of minimum variable blank holder force

Based on the equilibrium force diagrams in a small element and considering the friction on the flange surface, as shown in Figure 1, the tangential stress equation is obtained as follows [10, 11].

$$\sigma_{t,i} = \sigma_{r,i} - \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_f) \tag{1}$$

And

$$\sigma_{t,i} = \left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\,(\sigma_{fmp1-2,i})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\}+\left\{\frac{2\mu F_{bh,i}}{\pi d_{1,i} s_0}\right\}-\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_f) \tag{2}$$

Where $\sigma_{r,i}$ is the stress in radial direction, $\bar{R}_n$ is average of material anisotropic value, $\sigma_{fmp1-2,i}$ is the mean flow stress on flange over punch stroke, $d_{1,i}$ is the outer local diameter of flange - function of punch stroke, d_m is the average radius of cylindrical cup deep drawing, μ is the coefficient of friction, $F_{bh,i}$ is the variable blank holder force (VBHF), s_O is the initial thickness of material and σ_f is the flow stress a moment on *flange*.

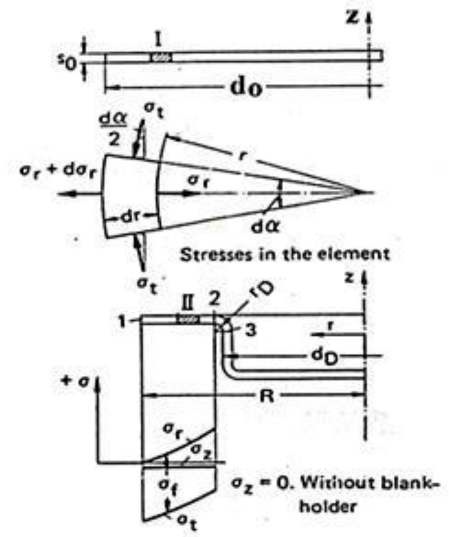

Figure 1. The equilibrium force diagram in a small element on flange [10, 11].

The mean flow stress on flange over punch stroke ($\sigma_{fm,p1-2,i}$) can be calculated by Eq. (3) [10].

$$\sigma_{fm,p1-2,i}=\left(\frac{1}{2}\right)\left(\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\right)^n K\left[\left(\ln\frac{d_0}{d_{1,i}}\right)^n + \left(\ln\frac{d_{int,i}}{d_D+2r_d}\right)^n\right] \tag{3}$$

Where d_D is the die diameter and r_d is the die edge radius and $d_{int,i}$ is the inside diameter.
To determine the changing of diameter should be calculated under the condition a constant volume. The outer local diameter of flange and inside diameter each step could be determined by equation as follows [10, 11].

$$d_{1,i} = f(d_0, d_D, r_p, r_d, i=h) = \sqrt{(d_0)^2 + 4d_D\{h - (0{,}43r_p - 0{,}43r_d)\}} \tag{4}$$

Where r_p is the punch edge radius, i=h is the punch stroke and $d_{int,i}$ can be calculated by Eq. (5),

$$d_{int,i} = f(d_0, d_D, r_p, h, d_{1,i}) = \sqrt{(d_0)^2 + (d_D + 2r_d)^2 - (d_{1,i})^2} \tag{5}$$

The deformation of deep drawing process can be represented by a minor strain (strain tangential) and major (tensile strain). The safe value of the radial and tangential strain ratio in the flange area could be determined by the forming limit diagram (FLD) as shown in Fig. 2. The force and stress tangential equation each punch stoke with considering the friction and no differences of the cross section area (see Figure 3) can be determined by Eqs. $F_{t,i} = F_{\mathrm{t\,minor,i}} - F_{\mathrm{friction,i}}$ and $\sigma_{\mathrm{t,i}} = \sigma_{\mathrm{t\,minor,i}} - \sigma_{\mathrm{friction,i}}$, respectively. Where, $F_{t,i}$ is the tangential force, $F_{\mathrm{t\,minor,i}}$ is the ideal tangential force, $F_{\mathrm{friction,i}}$ is the tangential friction force, $\sigma_{\mathrm{t\,minor,i}}$ is the ideal tangential stress and $\sigma_{\mathrm{friction,i}}$ is the tangential friction stress.

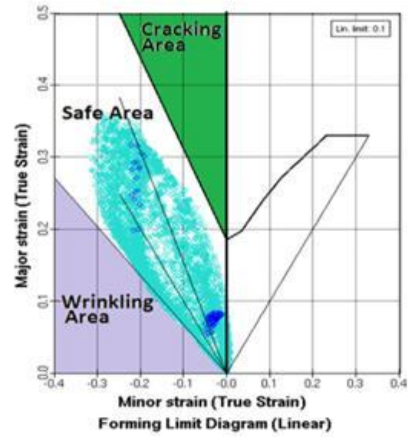

Figure 2. Forming limit diagram [19].

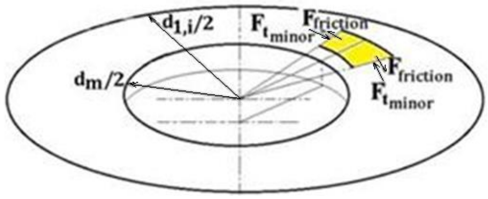

Figure 3. Equilibrium of the force diagram in tangential direction.

Based on defect criterion and the forming limit diagram (FLD), the wrinkling will be predicted when the ratio of minor and major strain around 1.3. In order to achieve these conditions, the equation of tangential stress of each punch stroke also becomes,

$$\sigma_{\mathrm{t,i}} = \left(\frac{1}{2}\right)\left(\left(1.3\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\right)^{n} K\left(\left(\ln\frac{d_0}{d_{1,i}}\right)^{n} + \left(\ln\frac{d_{\mathrm{int,i}}}{d_m}\right)^{n}\right)\right) - \left(\frac{2\mu\, F_{\mathrm{bh,i}}}{s_0\left(\frac{d_{1,i}-(d_D+r_d)}{2}\right)}\right) \tag{6}$$

Combining Eqs. (2) and (8), the minimum VBHF ($F_{\mathrm{bh,i}}$) could be determined with the equation,

$$F_{\mathrm{bh,i}} = \mathrm{VBHF} = \frac{\left(\frac{1}{2}\right)\left(\left(1.3\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\right)^{n} K\left(\left(\ln\frac{d_0}{d_{1,i}}\right)^{n} + \left(\ln\frac{d_{\mathrm{int,i}}}{d_m}\right)^{n}\right)\right) - \left(\left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\,(\sigma_{\mathrm{fmp1-2,i}})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\} - \left(\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\sigma_f\right)\right)}{\left((2\mu/\pi d_{1,i} s_0) + \left(2\mu/s_0\left(\frac{\left(\frac{d_{1,i}+d_{\mathrm{int,i}}}{2}\right) - \left(\frac{d_D+r_d}{2}\right)}{2}\right)\right)\right)} \tag{7}$$

3. FE modeling

In this study, the analytical solution provided was compared to FE Modeling. Forming simulation used the implicit Auto form FE solver as shown a virtual image in Fig. 4. The FE simulation was utilized element formation using elastic-plastic deformation approach and ignore the effects of spring back. The number and shape of meshing were done automatically by FE software. The number of meshing was determined based on deformation conditions. Meanwhile, the shape of meshing is defined as a triangle, which is often used for sheet metal forming simulations.

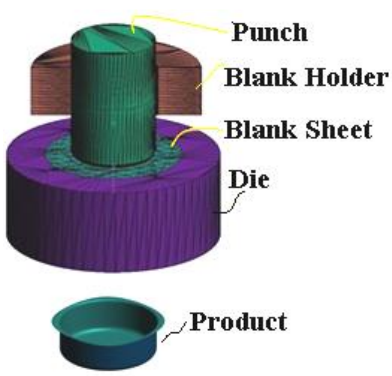

Figure 4. Finite Element modeling.

The analytical approach and FE simulation used the detail value of the punch-die dimension, the steel sheet and process parameters, as shown in Table1.

Table 1. Dimension of tools, mechanical properties and variables of processes.

Dimension of tools		Mech. properties Tin plate T4 CA		Processes parameters	
d_0	64 mm	K	559 N/mm^2	μ	0,45 (dry)
d_D	40 mm	n	0.176		
d_p	39.576 mm	$\bar{R}$	2	BHF	Not constant
Clearance	0.288 mm	UTS	355 N/mm^2		
s_0	0.2 mm	c	1.125		
r_d	1 mm				
r_p	2 mm				
H	15 mm				

4. Results and discussion: analytical and FE simulation of minimum VBHF

Table 2 shows the magnitude of tangential-radial stress and minimum VBHF by using the equations 1 to 7, based on the minor and major limiting strain ratio, during the punch stroke. A minimum VBHF application under maintaining the strain ratio was effective for controlling the equilibrium of stress deformation. The profile of minimum VBHF increases with an average of gradient slopes around 39.6 to prevent wrinkling.

Table 2. Minimum $F_{bh,i}$(VBHF) from analytical based on the limiting strain ratio.

i=h Punch stroke (mm)	The absolute of minor strain and major strain ratio	$\sigma_{t,i}$	$\sigma_{r,i}$	Min. $F_{bh,i}$ (MinimumVBHF)
6	1.3	418.35	399.47	682.40
8	1.3	444.43	424.37	739.38
10	1.3	464.92	443.94	788.80
12	1.3	482.21	460.45	831.00
14	1.3	497.55	475.10	865.13
Etc.				

Table 3 shows the details of the FE simulation result, related to tangential stress, radial stress and minimum blank holder force, based on the minor and major strain ratio and the forming limit diagram (FLD). The simulation was conducted to present an application of the minimum VBHF, should be applied slightly increase. The virtual image of minimum VBHF application leads to the major strain and minor strain at punch stroke 6, 10 and 14 mm, as shown in Fig. 5. In addition, the minor and major strain ratio can be maintained around 1.3 without excessive wrinkling product. FE simulations prove that the modeling of minimum VBHF could be applied as a reference in deep drawing process without excessive wrinkling. Results of FE simulation have no different significantly compared to the analytical results before.

Table 3. Minimum $F_{bh,i}$ (VBHF) from FE simulation.

i=h Punch stroke (mm)	The absolute of minor strain and major strain ratio	$\sigma_{t,i}$	$\sigma_{l,i}$	Minimum $F_{bh,i}$ (MinimumVBHF)
6	1.23	381.3	402.2	546.4
8	1.25	406.9	423.2	577.9
10	1.35	425.5	438.7	631.6
12	1.35	439.8	450.7	719.3
14	1.40	455.3	464.5	852.8
Etc.				

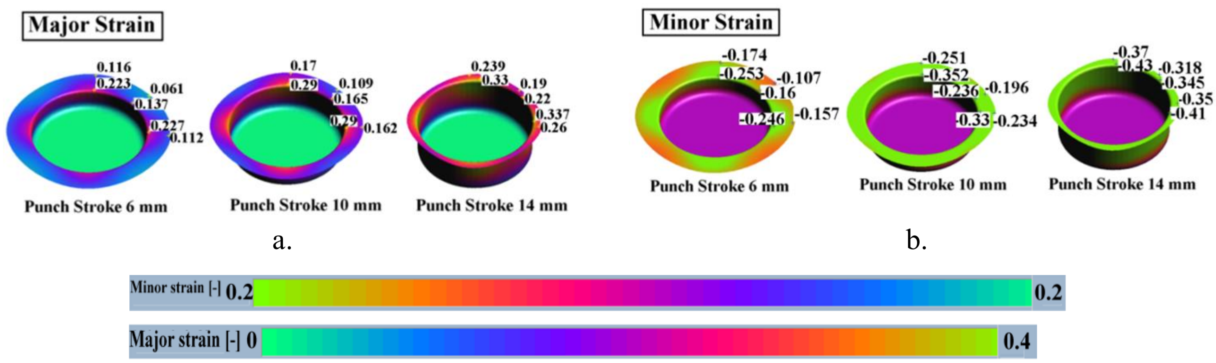

Figure 5. a. Major Strain, b. Minor Strain.

The final results of calculation and FE simulation have been displaying the minimum VBHF each punch stroke, as shown Fig. 6. To prevent wrinkling at each punch increment, the BHF should be maintained slightly above the minimum VBHF line. These conditions will keep the value of minor and major strain ratio around 1.3 and control the magnitude of the tangential stress. Finally, the process can be operated properly without excessive wrinkling product.

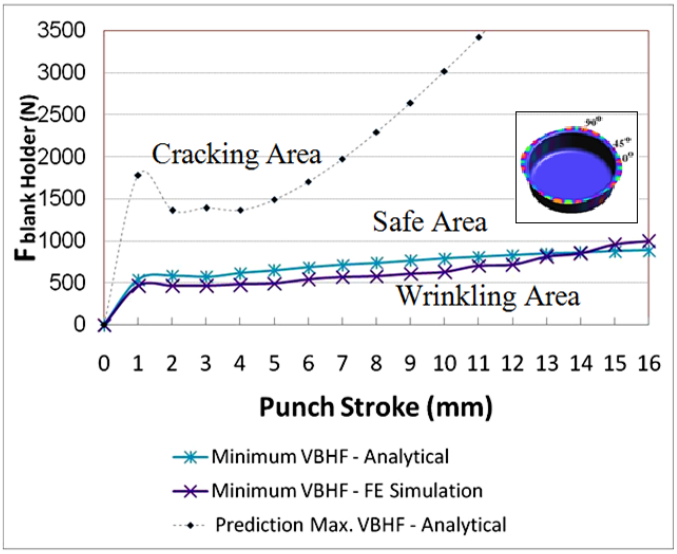

Figure 6. Minimum VBHF vs Punch Stroke.

5. Conclusion

The results of the minimum VBHF calculation are not much different from FE simulation. VBHF could be effective for preventing the occurrence of wrinkling, and also for improving the permeability of the process. VBHF modeling indicated a similar trend compared to FE simulation results. Mathematical modeling of VBHF can be used as a simple approach for estimating the magnitude of minimum blank holder force in every punch stroke. The minimum VBHF has provided the information about a safe area on cylindrical cup deep drawing. Therefore, the safe area must be maintained above the minimum VBHF. Modeling minimum VBHF based on the ratio of minor and major strain and FLD can be used as a reference in the process of deep drawing.

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