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Analytical study and FEM simulation of the maximum varying blank holder force to prevent cracking on cylindrical cup deep drawing

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Abstract

This Research is aimed to predict the maximum varying blank holder force (VBHF) over the punch stroke in order to eliminate cracks on cup deep drawing product. The constant blank holder force during the process, it's frequently not capable to prevent cracking, effectively. Using the slab method with assuming a constant volume of material, the simple analytical approach of maximum VBHF, has been conducted under the failure deformation and cracking criteria on every stage punch stroke. The cracking criteria are based on the maximum strength of materials. Steel sheet of SPCD grade, thickness 0.2 mm was used in this study. And the diameter of the cylindrical cup-shaped product was 40 mm. The analytic calculation of the maximum VBHF has been compared to FEM simulations, and its effects in the prevention of cracking. Analytical Results of maximum VBHF, not much different with FEM simulation. Compared to the application of the constant blank holder force, VBHF can be quite effective for preventing the occurrence of cracking and increasing the formability of deep drawing.

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Keywords: blank holder force: deep drawing process: cracking; FEM; formability

1. Introduction

Cracking is the most critical defects in deep drawing process, which caused by the radial stress and the drawing load too high. Process parameters that greatly affect the magnitude of the radial stress and drawing load is the blank holder force. In order to maintain that proses condition and to prevent cracking, the blank holder force magnitude should be controlled effectively.

Daw-kwei Leu et al. [1] conducted a study of influence of material properties and variable processes against the magnitude of drawing maximum load and the possibility of cracking. In their study, a constant blank holder force (BHF) is applied in every position of the punch stroke, so some product without cracking in special case would be difficult to achieve. T. Cwiekala et al. [2] developed a basic analysis and simulation method using multiple deformation step in order to predict and formability strain to produce a product with applying the constant BHF. Their study could become a reference regard to an analytical approach to calculating the radial stress and thickness strain in cup deep drawing process. Other research conducted by Ravendra et al. [3], estimated the influence of design parameters include the dimension of tools, against the occurrence of the damage of the product, with the application of blank holder force set a constant value. Parametric and FEM modeling method base on forming limit had been considering the occurrence of fracture and wrinkling in cup deep drawing process. Nevertheless, the analysis by applying a constant BHF could not demonstrate for eliminating both defect wrinkling and cracking effectively. B.V.S Rao et al. [4] and Y Marumo [5], studied optimization of the constant blank holder force on cup deep drawing by using Taguchi method. Optimization of the constant blank holder force magnitude has a linear pattern on each stroke punch position. Y. Marumo et al. [5] conducted a research of influence material thickness and limiting drawing ratio (LDR) against constant blank holder force magnitude in cup deep drawing process to produce products without cracking.

Generally, the analysis and experiments on research described above, a constant blank holder force is applied in

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deep drawing process, that it cannot consider to deformation of the material condition over the punch stroke. Therefore, the blank holder force cannot anticipate the dynamics of operating conditions. A good method, Z.Q. Seng et al. [6] implemented an adaptive FEM simulation method attempts to eliminate fracture by applying VBHF. Their study was using a lower and an upper bound criteria approach to eliminate product defects, with maintaining the wrinkle amplitude and maximum thinning of the material by automatically adjusting the BHF. Although specifically about the fracture (cracking) criteria could use the different criterion. S. Candra et al. [8,9] determined a variable BHF base on criteria of wrinkle height dimension and maximum strength of material for predicting the wrinkle and cracking, respectively. In practice, the criteria of maximum strength of the material which is utilized as an index of the cracking, can be easily applied to estimate the maximum drawing force, to control the blank holder equipment optimally. So the application of a defect criteria for determining of a maximum of VBHF could be examined more details.

S. Yoshihara et al. [7] investigated the formability of deep-drawing of magnesium alloy sheet by using variable BHF control. The variable BHF is determined from the LDR test by using the minimum and maximum constant BHF. The variable BHF has a profile: the low constant BHF in the early stage of processes, the increasing BHF in the middle stage of processes, and the high constant BHF at the end of the process. In fact, during the process, tangential stress will occurrence the increasing in early the punch stroke significantly, and the wrinkles will potentially appear. Thus, the BHF should be controlled carefully to anticipate the changing of the tangential and radial stress in every stage of the punch stroke. The forming stress analysis related to determine the VBHF could be further examined.

Refer to the information above, this paper propose the simple analytical approach to predict the maximum varying blank holder force (VBHF) over the punch stroke in order to avoid cracking. The analytical approach of SLAB method with assuming a constant volume of material, a plane strain and using the Tresca yield criterion, utilized for analyzing stress and strain in materials forming of sheet. The maximum VBHF is determined by using a defect criteria of the maximum strength of materials as the upper bound approach of analytical. The effects of friction and an anisotropic of material, are also considered in the analysis. By using a maximum strength of materials as the failure criteria, can be expected simultaneously also prevents wrinkle defects. Finally, the analytical calculation of the maximum VBHF, will be validated by the FEM simulation of cup deep drawing process and compared to some researches related.

1.1. The mathematical equation of the maximum VBHF

Under the equilibrium of force in a small element of the flange and ignoring friction, as shown in Figure 1, the mathematical equation of the radial stress can be written as

$$r\, d\sigma_r\, d\alpha\, s_o + \sigma_r\, dr\, d\alpha\, s_o + 2[\sigma_t] s_o dr \sin(d\alpha/2) = 0 \quad (1)$$

Where σ_r is the radial stress, r is the inside radius at the moment, $d\alpha$ is a small segment angle of the flange, s_o is the initial thickness of material, and σ_t is the tangential stress in the flange.

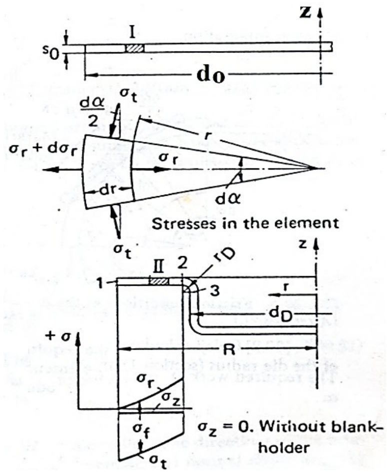

Fig. 1. The equilibrium force diagrams of the flange in a small element [12]

Because of $d\alpha/2$ is very small, then it can be considered to be $\sin(d\alpha/2) \approx d\alpha/2$, so the equation 1 becomes

$$d\sigma_r = (\sigma_r - \sigma_t)\left(\frac{dr}{r}\right) \text{ or } \sigma_r = \int_{r=R_1}^{r} (\sigma r - \sigma t)\left(\frac{dr}{r}\right) \quad (2)$$

Where R_1 is the outer flange radius a moment. Under the condition of plain strains, by using the criterion of Tresca and the definition of equivalent stress [10], the relationship of radial and tangential stress can be obtained relations as.

$$(\sigma_r - \sigma_t) = \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\ \sigma_f \quad (3)$$

Where σ_f is the flow stress a moment on *flange* from the initial position until another position, and $\bar{R}_n$ is the mean anisotropy coefficient of the material. Substituting the equation 3 into equation 2 and then integrating it with the boundary $r = r_m$ until $r = R_1$, so the equation of ideal stress deformation on the flange over the punch stroke obtained as,

$$\sigma_{r,i} = \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\ \sigma_{f,i} \ln\left(\frac{R_{1,i}}{r_m}\right) \text{ or } \sigma_{r,i} = \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\sigma_{f,i} \ln\left(\frac{d_{1,i}}{d_m}\right) \quad (4)$$

Where $R_{1,i}$ is the outer local flange radius under the function of the punch stroke (the height of cup or h), r_m is the average radius of cylindrical cup deep drawing, $d_{1,i}$ is the outer local flange diameter under the function of the punch stroke, i is the punch stroke, d_m is the average diameter of cylindrical cup deep drawing ($d_m = d_D - s_o$), and d_D is the die diameter.

The equivalent strain can be derived from

$$\varepsilon = \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}} \ln\left(\frac{R_0}{R_1}\right) \text{ or } \varepsilon = \sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}} \ln\left(\frac{d_0}{d_1}\right) \quad (5)$$

In order to simplify calculation of the mean flow stress on flange, the strain will be divided into two sections, at point 1 and point 2. Refer to equation 5, the equivalent strain at point 1 ($\varepsilon_{1,i}$) and point 2 ($\varepsilon_{2,i}$) can be calculated respectively by

$$\varepsilon_{1,i}=\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\ln\left(\frac{d_0}{d_{1,i}}\right) \text{ and } \varepsilon_{2,i}=\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\ln\left(\frac{d_{int,i}}{d_D+2r_d}\right) \quad (6)$$

Where d_0 is the blank size diameter (initial blank sheet), $d_{1,i}$ is the outside flange diameter-function of the punch stroke (point 1), d_D is the die diameter, r_d is the die radius and $d_{int,i}$ is unknown inside diameter-function of the punch stroke (point 2).

And then, the mean flow stress between point 1 to point 2 ($\sigma_{fmp1\text{-}2,i}$ – function position of punch stroke) can be calculated by

$$\sigma_{fmp1\text{-}2,i}=\left(\frac{1}{2}\right)K(\varepsilon_{1,i}{}^{n}+\varepsilon_{2,i}{}^{n}) \quad (7)$$

Where K is the strength coefficient of material and n is the strain hardening exponential of material.

Equation 4, can obtain equation as

$$\sigma_{r,i}=\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_{fmp\,1-2,i})\ln\left(\frac{d_{1,i}}{d_m}\right) \quad (8)$$

Furthermore, if the friction on the flange surface is considered, the forming equation of radial stress will be

$$\sigma_{r,i}=\left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_{fmp\,1-2,i})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\}+\left\{\frac{2\mu F_{bh,i}}{\pi d_{1,i}\ s_0}\right\} \quad (9)$$

Considering the friction on all surfaces and the tension of bending at the die radius, the radial stress equation would be

$$\sigma_{r,i}=e^{\mu\pi}\left\{\left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_{fmp\,1-2,i})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\}+\left\{\frac{2\mu F_{bh,i}}{\pi d_{1,i}\ s_0}\right\}\right\}+\left(\sigma_{fmp\,2-3,i}\frac{s_0}{2r_d}\right) \quad (10)$$

Where μ is the friction coefficient, $F_{bh,i}$ is the varying blank holder force and $\sigma_{fmp\,2-3,i}$ is the mean flow stress in cup wall (after passing die radius).

Following the stress equation above, the drawing force ($F_{d,i}$) over the punch stroke can be obtained as,

$$F_{d,i}=\pi\ d_m\ s_o\ \sigma_{r,i} \quad (11)$$

Based on the deformation of material when flows through the die radius and undergoes bending deformation, so mean flow stress can be predicted as:

$$\sigma_{fmp2\text{-}3,i}=\left(\frac{1}{2}\right)K\ (\ \varepsilon_{2,i}{}^{n}+\varepsilon_{3,i}{}^{n}) \quad (12)$$

Where $\varepsilon_{2,i}$ is the radial strain of material on flange until point 2, and $\varepsilon_{3,i}$ is the bending strain, in detail:

$$\varepsilon_{3,i}=\varepsilon_{2,i}+\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}\ln\left(1+\frac{s_0}{2r_d+s_0}\right) \quad (13)$$

To determine the radial stress over the punch stroke, formerly need to calculate the dimensions changing of diameter each punch stroke position. Under the condition of constant volume and refer to Figure 2, so the outer diameter of the flange and unknown in diameter each step can get [11,12],

$$d_{1,i\ (i=h)}=\sqrt{(d_0)^2+4d_D\{h_i-(0{,}43r_p-0{,}43r_d)\}} \quad (14)$$

And,

$$d_{int,i\ (i=h)}=\sqrt{(d_0)^2+(d_D+2r_d)^2-(d_{1,i})^2} \quad (15)$$

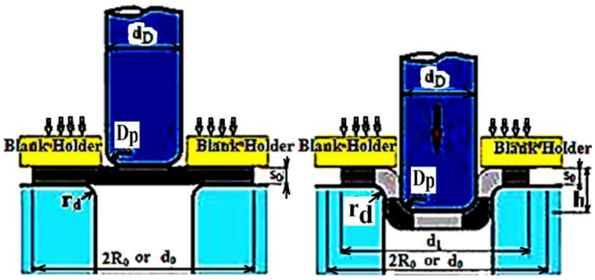

Fig. 2. Changing of the dimensions, over punch stroke in cup deep drawing processes

Criteria of cracking was approached by a maximum stress of material, as an equation of the first approach:

$$\sigma_{1crack\ ,i}\ \geq\ UTS\ .\ c \quad (16)$$

Where $\sigma_{crack\ ,i}$ is the limiting stress failure (cracking), UTS is the ultimate tensile strength of material, and c is the constant multiplier, whose value depends on the behavior of materials. Value c ≈ 1.0 - 1.55

If the failure of products based on the maximum stress (cracking), was suggested by Siebel and Beisswanger [12] and hence, stress cracking (maximum) to every punch stroke can follow equation (second approach):

$$\sigma_{2crack\ ,i}=\frac{1{,}1\ \sigma_{fm\ ,i,max}}{\eta_{def}}\{\ln(LDR)-0{,}25\} \quad (17)$$

Where $\sigma_{fm,i,max}$ is the maximum stress forming, namely the cracking criteria equal to $\sigma_{crack\ ,i}$, LDR is the limiting draw ratio, for the steel material ≈ 1.8 - 2, η_{def} is the efficiency of material deformation ≈ 0,7, and $\sigma_{fm,i,Max}$ is the mean flow stress = $(1/2)$ ($\sigma_{fmpoint\ \ 1-2,i}$+ UTS).

The cracking criteria were used to estimate the maximum varying blank holder force without cracking. By combining the equation 10 to equation 16 and 17, then the maximum radial stress (the cracking stress) becomes,

$$\sigma_{crack\ .i}\geq e^{\mu\pi}\left\{\left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_{fmp\,1-2,i})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\}+\right.$$

2μFbh,iπd1,i s0 + σfmpoint 2−3,is02rd
(18)

Finally, the maximum VBHF equation is obtained

$$F_{bh,i.max}\leq\left\{\frac{(\sigma_{crack\ ,i})}{e^{\mu\alpha}}-\frac{\left((\sigma_{fmp\ 2-3,i})\ \frac{s_0}{2r_d}\right)}{e^{\mu\alpha}}-\left\{\sqrt{\frac{2(\bar{R}_n+1)}{1+2\bar{R}_n}}(\sigma_{fmp\ 1-2,i})\left(\ln\frac{d_{1,i}}{d_m}\right)\right\}\right\} \times \left\{\frac{\pi d_{1,i}\ s_0}{2\mu}\right\} \quad (19)$$

$$F_{bh,i\,max} = f(K, n, UTS, \bar{R}, s_0, d_0, d_D, r_p, d_{1,i}, h, d_m, \mu) \qquad (20)$$

Equation 19 is useful for predicting a maximum of VBHF, which can be applied to produce a product without cracking and can be used for preventing wrinkles. Equation (19) and equation (20) give relationship among and material properties, geometric punch-die, material deformation, flow stress, coefficient of friction and cracking criterion.

1.2. FEM modeling

In this study, FEM provided the essential data, that will be compared to analytical solution. Element formation is carried out using FE of elastic-plastic deformation and ignore the effects of spring back. The curve of flow stress is following the Swift formulation by considering the yield stress and plastic flow stress. Simulation of wrinkling, and tearing (cracking) was done using the implicit AUTOFORM ver3.1 FE solver that is commonly used for FEM solver. FE simulations had been done for cylindrical cups deep drawing with dimensions of product, tools and by using mechanical properties, as shown in the following Figure 3, Table 1 and table 2 below. And then, the analytical result of the maximum VBHF is incorporated into the process generator functions of FEM software for generating an animation and describing the quality of a cylindrical cup drawing over the forming process.

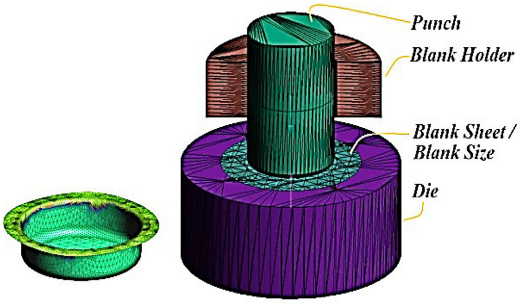

Fig. 3. Finite element model of cylindrical cup, *by using* AUTOFORM

Table 1. Dimension of tools

Dimension of tools	remarks
d_0 (Blank sheets diameter)	64 mm – 84 mm
d_D (Die diameter)	40 mm
d_p (Punch diameter)	39.58 mm
2 x Clearance	0.43 mm
s_0 (Initial thickness of sheet material)	0.2 mm
r_d(Die edge radius)	1 mm
r_p(Edge punch radius)	2 mm
h (height of cylindrical cup)	15-34 mm

Table 2. Mechanical properties and processes variable

JIS G 3141 grade SPCD equivalent to DIN standard D03		Processes Variable	
K	559 N/mm^2	Coefficient of friction	0.4-0.45 (dry) 0.18-0.2 (Palm oil)
n	0.176	Punch velocity	1 mm/Sec.
$\bar{R}_n$	2		
UTS	355 N/mm^2		
Yield Stress	232 N/mm^2	BHF	Constant and Varying

2. Result and discussion

Analytic calculation to obtain the material deformation and the mean flow stress over the punch-stroke under the condition of constant volume, can be shown as table 3 below.

Table 3. Analytic calculation of strain and mean flow stress in flange every punch stroke under conditions of constant volume and base on slab method

i = h (mm)	$d_{1,i}$ (mm)	$d_{int,i}$ (mm)	$\varepsilon_{1,i}$	$\varepsilon_{2,i}$	$\varepsilon_{3,i}$	σ_{fmp1-2} (N/mm^2)	σ_{fmp2-3} (N/mm^2)
0	64.0	42.0	0.000	0.000	0.096	0.0	0.0
2	61.5	45.6	0.045	0.091	0.196	345.3	393.5
4	60.5	46.9	0.061	0.120	0.228	363.8	408.3
6	57.9	50.1	0.111	0.195	0.310	399.8	437.3
8	55.0	53.2	0.166	0.260	0.382	424.7	456.9
10	52.1	56.1	0.227	0.319	0.447	444.3	471.5
12	48.9	58.9	0.296	0.372	0.505	460.8	483.0
14	45.5	61.5	0.375	0.420	0.558	475.4	492.5
15	43.7	62.8	0.419	0.443	0.583	482.3	496.7
16	41.9	64.1	0.466	0.465	0.607	488.9	500.6
Etc							

Remarks: i=h is the punch stroke

And also, analytic calculation have been obtained the maximum of VBHF distribution, based on both of criteria cracking approach, by using equation 16 and 17, respectively. The magnitude of the maximum of VBHF base on equation 18 and 19, gives the effect of radial stress and drawing force, can be displayed as Table 4.

Table 4. Analytic calculation of the maximum VBHF, radial stress and maximum drawing force – no cracking; $F_{crackh,i}$ = 10196.2 N, $\sigma_{crackh,i}$ = 451.4 N/m2, μ =0.45, d_0 = 64 mm

i = h Punch Stroke (mm)	Analytic calculation with first cracking criterion (Eq. 16)			Analytic calculation with second cracking criterion (Eq. 17)		
	$F_{bh,i}$ Max (N)	$\sigma_{r,i}$ Max. (N/mm^2)	$F_{d,i}$ Max (N)	$F_{bh,i}$ Max. (N)	$\sigma_{r,i}$ Max. (N/mm^2)	$F_{d,i}$ (N)
0	0.0	0.0	0.0	0.0	0.0	0.0
2	3954.4	401.2	9665.5	1359.3	308.2	7003.2
4	1467.4	401.2	9665.5	1363.1	388.1	8819.3
6	1480.7	401.2	9665.5	1702.6	402.2	9138.3
8	1874.7	401.2	9665.5	2291.7	411.6	9353.0
10	2479.9	401.2	9665.5	3019.9	418.7	9513.5
12	3224.7	401.2	9665.5	3840.2	424.3	9640.6
14	4069.1	401.2	9665.5	4725.1	428.9	9745.1
15	4519.6	401.2	9665.5	5184.8	430.9	9791.0
16	4984.4	401.2	9665.5	5652.4	432.8	9833.5
Etc.						

With the application of the maximum VBHF can maintain the radial stress and drawing force magnitude below a critical value. The maximum VBHF magnitude in early of the punch stroke (the stroke punch of 0- 2 mm) allowed quite large (around 1300N-3900N). Then VBHF should be decreased up to 1359N-1467N at punch stroke position of 4 mm. Furthermore, from punch stroke position of 4 mm until the end of the punch stroke, gradually allowed raised with a gradient by around 0.28. The maximum VBHF having a pattern of the distribution as shown in the table 4, is expected to anticipate concerning the transformation dynamics of the tangential and radial stress that appears over punch stroke on a flange.

According to the results of the analytic calculation and simulation of FEM, the maximum VBHF profile could be described by Figure 4. The VBHF profile can be used as reference to estimate a safe zone without cracking, which it recommended slightly below of the maximum VBHF line.

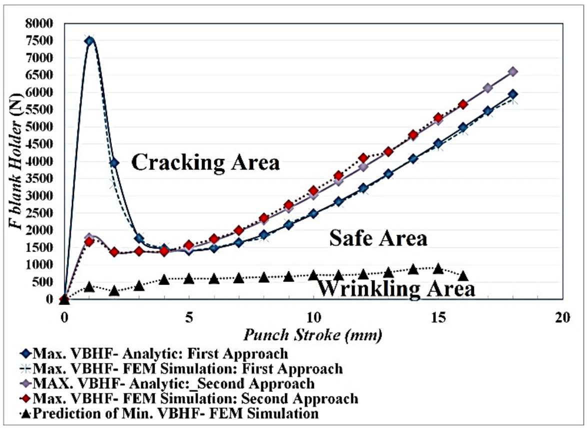

Fig. 4. The maximum and minimum VBHF to avoid cracking and wrinkling, by using the slab method (analytic calculation) and FEM; d_0=64 mm; μ=0.45

Drawing force over the punch stroke related to the application of maximum VBHF could be maintained in a safe area without cracking, as shown in Figure 5.

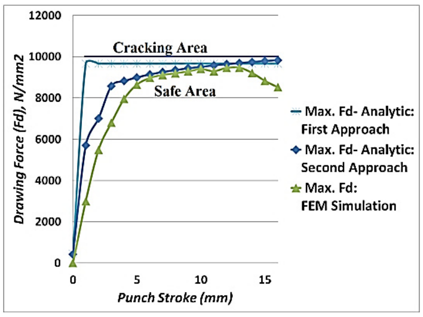

Fig. 5. Drawing Force with the application of the maximum VBHF to avoid cracking.

The maximum VBHF without lubrication on blank-sheet with initial diameter between 64 mm up to 76 mm, can be applied effectively to produce a cup-product without cracking (as shown in Figure 6). And for forming of blank size greater than 76 mm, the Application of VBHF is necessary to use lubrication to further optimize the process of deep drawing. As verification, the analytical calculation is incorporated into the process generator functions for running the FEM simulation. The results with both methods had given an information that the maximum VBHF provide a fairly good result and not much different result, in order to avoid cracking, as shown in Figure 6 and 7.

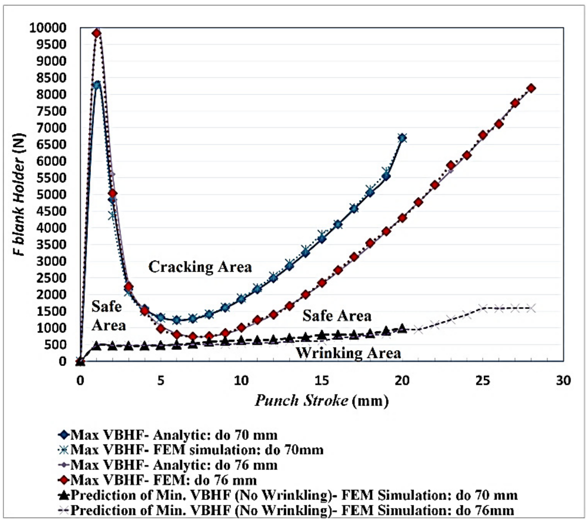

Fig. 6. The maximum VBHF to avoid cracking, by using the slab method (analytic calculation) and FEM Sim.; d_0=70 mm and d_0=76 mm; μ=0.45

A Figure 7 shown, the applications of maximum VBHF by using μ= 0.2 can still optimally form the blank sheet up to a diameter of 82 mm. In practically, The Maximum VBHF profile could give a guidance to determine the process parameter in safe zone without cracking and wrinkling. In this set up condition of VBHF can maintain stress forming and eliminate not only cracking, but also wrinkles phenomenon on flange in early and end of the punch stroke. The application of maximum VBHF is quite effective to prevent cracking over the punch (punch stroke). However, it is still to be tested further by experimentation. Compared to the researches related [6,7], there are small different regard to a recommendation of the VBHF magnitude in early of the punch stroke. The FEM simulation by using the results of analytical approach proving, that the maximum VBHF gives a good effect for preventing an excessive tangential stress in early of the punch stroke. So this application is more effective to eliminate wrinkles in early of the punch stroke.

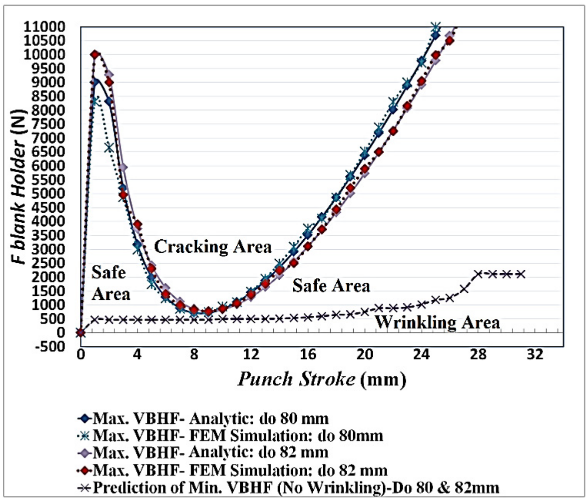

Fig. 7. The maximum VBHF to avoid cracking, by using the slab method (analytic calculation) and FEM Sim., d_0=80 mm and d_0=82 mm μ=0.2

The application of maximum VBHF without the lubrication of mineral oil (μ= 0.4 - 0.45) could increase the formability up to 5.7% and could increase the cup depth up to 7%. The cup is formed up to 28 mm depth by using an initial blank sheet (do) 76 mm. Meanwhile, the application of maximum VBHF with the lubrication of palm oil (μ= 0.18 - 0.2) could increase the formability up to 8 % and could increase the cup depth the cup depth up to 17 %. The cup is formed up to 33 mm depth with an initial blank sheet (do) 82 mm by the application of the maximum VBHF. Compared to the application of constant BHF, the cup could be drawn up to 28 mm by using initial blank sheet (do) 76 mm, as shown in Figure 8.

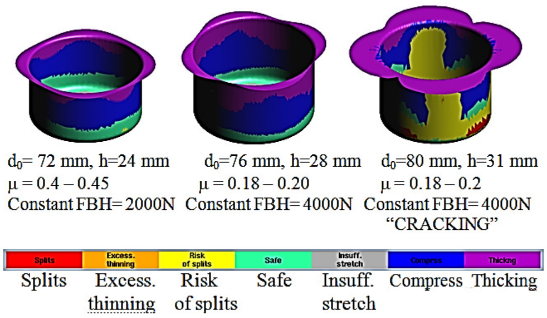

Fig. 8. FEM simulation on the variation of an initial blank sheet and result of cup height by using the constant force of blank holder from analytically

The analytical approach results of the maximum VBHF have been running well in the software of FEM simulations, as shown in figure 9.

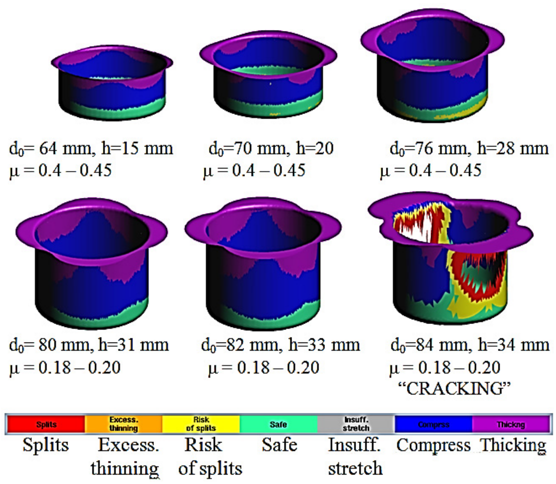

Fig. 9. FEM simulation on the variation of an initial blank sheet and result of cup height by using the maximum VBHF from analytically approach

3. Conclusion

Results of the calculation of VBHF maximum, not much different with FEM simulation. Compared to the application of the constant blank holder force, VBHF can be quite effective in preventing the occurrence of cracking and improve the formability. Mathematical modeling of VBHF can be used as a simple approach for estimating the magnitude of blank holder force in every punch stroke. From VBHF modeling indicated a tendency and its similar trend compared to FEM simulation results. Compared constant BHF, the application of maximum VBHF with the lubrication of palm oil (μ= 0.18 - 0.2) would increase the formability up to 8 % and increase the cup depth the cup depth up to 17 %.

The results of this study are indeed a simple approach of a mathematical modeling and have been verified by FEM simulation, but it has provided evidence of a BHF improvement in deep drawing processes. The VBHF profile have not much different, if compared with previous related research [6,7], especially in the middle and the end of the punch stroke. The results of this study will be explored through further experiments.

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