Analysis and Experiment of Blank Holder Gap in the Cylindrical Cup Deep Drawing of Low Carbon Steel to Prevent Cracking-Wrinkling

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ABSTRACT

This paper aims to investigate Blank Holder Gap (BHG) in order to prevent wrinkles and crack defects in the deep drawing process of cylindrical cups with a diameter of 30 mm, using low carbon steel grade SPCC that is 0.7 mm thick. Mathematical and experimental approaches were applied to study the effect of BHG on wrinkle wave height and product quality. The analytical approaches used were the slab method and the Forming Limit Diagram (FLD) to determine the final thickness of the product specimen and the height of the wrinkling wave, respectively. Each method in this study had been compared to each other. Punch-die dimensions were determined based on the standard tool designed. According to the research, BHG is set 100% to 114% of the thickness of the initial material or equivalent about 0.70 to 0.80 mm. By using the value of this gap, the height of wrinkles can be avoided, the magnitude of the drawing force is still below the critical limit, and the product specimen does not experience wrinkles and cracks. The results of this study are applicable to the deep drawing of cup products on SPCC material with a thickness of no more than 1 mm.

Keywords: *Blank Holder Gap; Wrinkles and Cracks; Cup Deep Drawing; Forming Limit Diagram; Drawing Force*

Introduction

Wrinkles and cracks are the most common product defects in the deep drawing process. Usually, the cause of the problem is due to the incorrect

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determination of the blank holder load. Nevertheless, the magnitude of blank holder load is influenced by several factors such as product dimensions, material mechanical properties, material thickness, and stress of the state [1]-[3]. If it is based on the state of the radial forming stress at each punch stroke position, the value of the blank holder load should not be constant [4]-[5]. Determining the inconstant blank holder load at each punch stroke position is quite difficult because it requires a load control device.

The determination of the blank holder load aims to control the flow of material and prevent the blank sheet from being lifted excessively in the flange area. Several studies related to the prevention of wrinkles and cracks are still interesting topics for researchers to discuss. The mechanism of the initiation and growth of wrinkles can be controlled with constant Blank Holder Force (BHF) [6]. Based on restraining energy, the researcher carried out mathematical modeling of the constant minimum blank holder force to avoid defects in the cylindrical cup. Generally, the wrinkling and cracking criteria can be based on the thinning and buckling criteria, respectively, and the blank holder implements a constant load [7]. Analytical and numerical investigations of the kink boundary diagrams in drawings in two-layer sheets with experimental verification were carried out to avoid product defects [8]. Development of a forming tool concept validator with variable rigidity empty holders and with logoless to avoid product defects. The implementation of this blank holder is based on the stiffness variable [9]-[10].

The semi-active control refers to the ability to dynamically adjust the blank holder force in real-time during the forming process [11], and this adjustment can be based on factors such as material properties, die geometry, or sensor feedback. By continuously monitoring and adapting the blank holder force, it can ensure that the material flows smoothly into the die cavity without any issues. The analytical study and FEM simulation of the maximum Varying Blank Holder Force (VBHF) provide valuable insights into the deep-drawing process, enabling the optimization of their processes and production of high-quality products with reduced defects [12]-[13]. Additionally, the data-driven accurate design of variable blank holder force is a modern approach that leverages data analytics and machine learning to enhance the deep-drawing process further and achieve better-formed products with reduced defects [14].

The proper combination of blank holding forces and draw beads plays a critical role in achieving high-quality deep-drawn products [15]-[16], as it allows the blank holder to control material flow, minimize defects, and produce parts with the desired geometry and dimensional accuracy. Additionally, the implementation of an antilock brake mechanic system for blank holder control is an innovative approach that leverages real-time data and feedback to optimize the deep-drawing process [17]-[18]. This system effectively controls the flow of material drawn into the die, resulting in higher-quality products, reduced defects, and increased process efficiency.

Moreover, draw-in control in the deep-drawing process by adjusting the force on the blank holder has been carried out to obtain products without wrinkling and cracking.

Analytical approaches and fast process optimization on cup-deep drawings have been done to avoid wrinkles and crack product defects in [19]. Wrinkling and fracture limits have been determined and BHF control methods have been developed to eliminate defects, improve part quality, and increase the draw depth. The results are still approximations using the Taguchi approach and simulations that still need to be proven [20]. Several research studies have analyzed and experimented with determining Limiting Drawing Ratio (LDR) in deep drawing [21], single-action stroke deep drawing without the blank holder [22], and deep drawing process using radial segmental blank holder based on electro-permanent magnet technology [23]-[24]. The three researchers aim to optimize the formation and use of other equipment blank holders that can improve process quality. The use of LDR in cup deep drawing, a single-action stroke of cup deep drawing, can be used as an initial reference for analysis and experiments.

The effect of the blank holder gap with the finite element method [25] and its several applications on micro deep drawing [26] are very important to maintain the magnitude of the clamping value so that wrinkles and cracks do not occur. The blank holder gap (BHG) is one of the effective parameters to control the material flow in the deep drawing process on the Hydro-mechanical Deep Drawing (HDD) of a cylindrical cup [27]. The application of BHG is to set the gap of the blank holder constantly, which is similar to the determination of varying blank holder force. The wrinkling and cracking criteria approach using the gap limits can be tested further by comparing it to other wrinkling and cracking criteria. Likewise, the cup shape also gives different results in determining the recommended gap. Based on some information from previous research, this paper aims to create simple analytical modeling and experiments on the value of the blank holder gap range in the cylindrical cup bolting process, where the product does not have cracks and wrinkles. Based on the research above, further studies were directed to determine the BHG, where the product is free from wrinkles and cracks.

Determining of Blank Holder GAP

In the deep drawing process, wrinkles and cracks are phenomena caused by buckling at the flange area and breaking at the die radii, respectively. Wrinkles typically indicate the occurrence of excessive tangential deformation values of the material, while cracking is caused by excessive thinning due to tensile radial stress, which can lead to fracture. One important factor in preventing product defects is the determination of the blank holder force as a process parameter. Nevertheless, the determination of the varying blank holder force during the punch stroke can be transformed into a constant value of the blank holder gap between the blank holder and the die. The gap distance can be approximated by the magnitude of the tangential strain and the final thickness of the flange and cup walls through mathematical modeling.

Based on the forming limiting diagram, the strain in the flange region can be represented by the deformation ratio or the ratio of major strain (radial-tensile strain) and minor strain (tangential strain). By using the strain approach, safe conditions can be achieved in this forming process by following the rules in the Forming Limit Diagram (FLD), as in Figure 1.

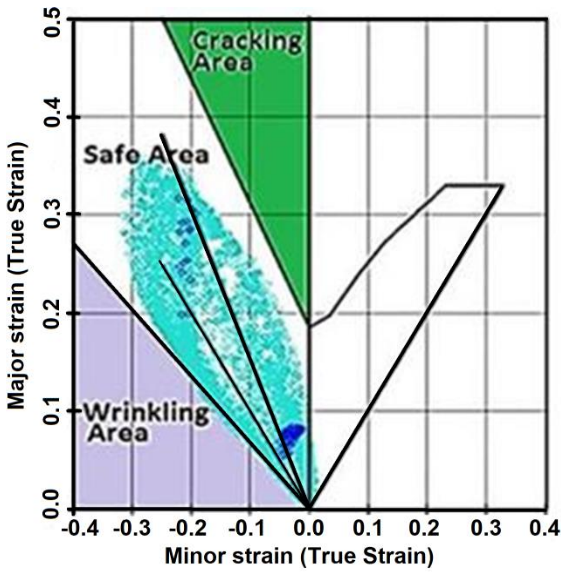


Figure 1: Forming limit diagram [11], [28]

The forming strain limit (major and minor strain ratio) in the flange area is used as a boundary condition for the minimum and maximum blank holder gap, which prevents wrinkling and cracking. The major forming strain which is expressed as radial strain ($\varepsilon_1 = \varepsilon_r$) in the product flange region can be calculated using the following equation [28]:

$$\varepsilon_1 = ln\left(d_0/d_p\right) \tag{1}$$

where d_0 is the initial diameter of the blank sheet and d_p is the diameter of the punch. Assuming that the condition does not change in the direction of the vertical axis (z-axis), the tangential stress can be considered the same as the stress in the direction of a thickness ($\varepsilon_2 = \varepsilon_3$). The strain in the direction of thickness can be approximated using the equation [28]:

$$\varepsilon_2 = ln(s_1/s_0) = \ln[Gap/s_0] \tag{2}$$

where ε_2 is the strain in the direction of thickness, the gap is the distance between the blank holder and the die, s_0 is the initial thickness of the blank sheet.

Based on the above assumption, the gap is considered equal to s_1. Likewise, referring to the formation boundary diagram, the maximum major and minor strain ratio is proportional to the LDR value of the material. By combining Equations (1) and (2), the following equation is obtained:

$$\varepsilon_2 = s_1 = s_0\left(d_0/d_p\right)^{1/LDR} \tag{3}$$

Another analytical approach can be described based on the theory of Levy-Mises, where the differential equation for formation in all directions of deformation is obtained as follows [28]:

$$d\varepsilon_1/\sigma_1' = d\varepsilon_2/\sigma_2' = d\varepsilon_3/\sigma_3' \tag{4}$$

The decomposition of the stress tensor and the assumption of local stress conditions with plane stress, then Equation (4) becomes as follows [28]:

$$\sigma_1' = \frac{(2\sigma_1 - \sigma_3)}{3}; \sigma_2' = \frac{(-\sigma_1 - \sigma_3)}{3}; \ \sigma_3' = \frac{(-\sigma_1 + \ 2\sigma_3)}{3} \tag{5}$$

where σ_1', σ_2' and σ_3' are stress tensors 1, 2, and 3, respectively. σ_1, σ_2, and σ_3 are principal stress 1, 2, and 3, respectively. By combining Equations (4) and (5) then the equation becomes:

$$d\varepsilon_2 = (\sigma_2'/\sigma_3')d\varepsilon_3 \tag{6}$$

Equation (6) is integrated to obtain:

$$\varepsilon_2 = ((-\sigma_1 - \sigma_3)/(-\sigma_1 + 2\sigma_3))\varepsilon_3 \tag{7}$$

If ε_2 is a change in thickness or gap, then Equation (7) will be obtained:

$$\varepsilon_2 = ln(s_1/s_0) = ((-\sigma_r - \sigma_t)/(-\sigma_r + 2\sigma_t))\varepsilon_t \tag{8}$$

Equation (8) is used to estimate the final thickness of sheet metal (s_1) as a representation of the gap with the following equation [28]:

$$Gap = s_1 = s_0 \, ln(s_1/s_0) = Exp \, ((-\sigma_r - \sigma_t)/(-\sigma_r + 2\sigma_t))\varepsilon_t \qquad (9)$$

Referring to the forming limit diagram, the major and minor strain ratios are assumed to be 2, so that $\varepsilon_t = (\varepsilon_r/2) = (LDR/2) = 1$ [28]-[29]. Where the LDR of low-carbon steel is 2. The material is used the general value for steel is 2. Then Equation (9) can be obtained as [11], [28]:

$$Gap = s_0 Exp\left(\frac{(-2\sigma_r - 1{,}15\sigma_{max.})}{(-\sigma_r + 2{,}3\sigma_{max.})}\right) \qquad (10)$$

where $\sigma_{\max}$ is the maximum forming stress which is equal to the value of the ultimate tensile strength material (UTS). While σ_{r} is the radial stress and can be approximated by the equation [29]:

$$\sigma_r = UTS\left(\left(d_0/d_p\right) - 0{,}7\right) \qquad (11)$$

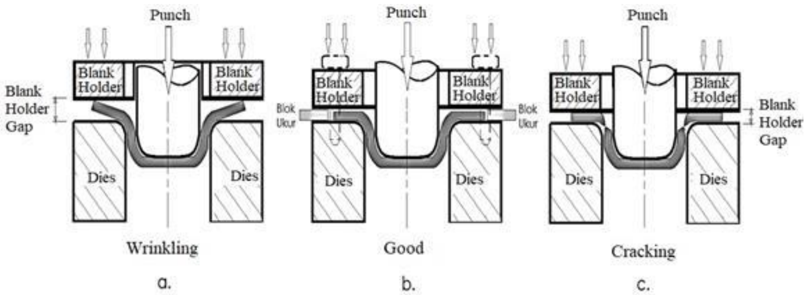
and drawing force (*Fd*) can be used as Equation (12) [29]:

$$F_d = \sigma_r, \pi, d_p, s_0 \qquad (12)$$

Equations (3), (9), (10), and (12) are used as references for analytical and experimental approaches to determine the minimum gap in the deep drawing process of cylindrical cup products.

Equations (9) and (10) are used to estimate the minimum gap, while the magnitude of the maximum gap has not been definitively determined in several studies. Therefore, this experiment aims to not only establish the minimum gap but also to determine the maximum gap. The maximum gap criterion is a condition where the product does not excessively wrinkle, and the product's body wall has no scratches due to wrinkling. Excessively high wrinkling waves can also be detected from the magnitude of the deep drawing force. Increasing the height of the wrinkling wave will have an impact on increasing the deep drawing force. Increasing the wrinkling wave will result in an increase in the deep drawing force. If the value of the deep drawing force is higher than the allowable deep drawing force limit, this condition will cause cracking.

This scientific study aims to determine the ideal conditions for the material to avoid breaking and while shrinking only to adjust the gaps permanently as illustrated in Figure 2.



A loose BHG may result in product wrinkling	An optimal BHG produces good-quality products	A narrow BHG may lead to product cracking

Figure 2: Possible fixed blank holder gap options [11]

There is no single equation to calculate the blank holder gap, understanding several factors and conducting empirical testing will help in determining the appropriate gap for a successful deep drawing process. Therefore, a combination of theoretical considerations, empirical testing, and experience is necessary to determine the appropriate blank holder gap for a successful deep drawing process.

Materials and Methods

Quantitative research methods were employed to compare analytical and experimental results. This study aimed to determine the effect of the blank holder gap on the material flow and product quality results. The cylindrical cup used as the specimen product is shown in Figure 3.

Punch-die dimensions based on standard tool designs that fall within acceptable tolerances and are capable of producing parts with the desired characteristics, as well as process conditions such as lubrication and punch speed, are presented in Table 1 [27]. Meanwhile, the mechanical properties of the specimen material for cup-deep drawing in this study are presented in Table 2 [28].

According to the theories, the experiment was set in several gap settings; 78.5%, 86%, 93%, 100%, 107%, 114%, 120%, 143% of the thickness of the blank sheet (s_0) or equivalent to 0.55 mm, 0.60 mm, 0.65 mm, 0.70 mm, 0.75 mm, 0.80 mm, 0.85 mm, 0.90 mm, and 1 mm. Lubrication was not implemented and the punch speed was 1 mm per second.

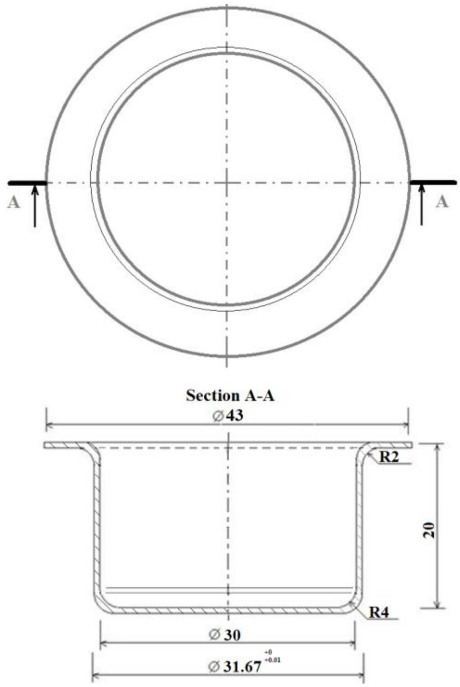


Figure 3: Drawing product scheme (unit: mm)

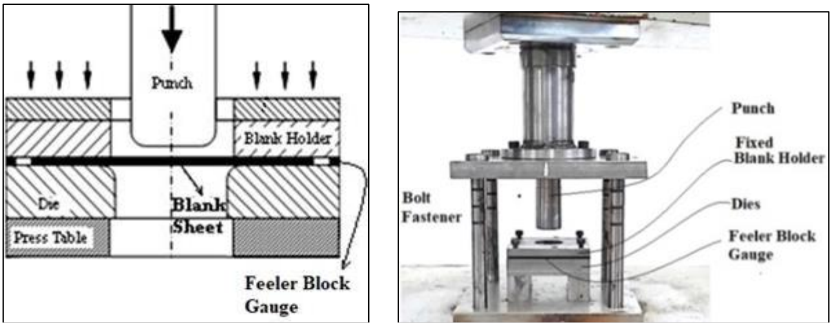
Table 1: Dimensions of punch-die set, blank sheet, and process variable

Description	Value
d_0 (blank sheet diameter)	59 mm
d_D (die diameter)	31.67 mm
d_p (punch diameter)	30 mm
Clearance	0.84 mm
s_0 (thickness of material)	0.7 mm
r_d (die radius)	2 mm
r_p (punch radius)	6 mm
h (height of cup)	20 mm
μ (coefficient of friction); no lubrication with smooth die surface	0.4 ÷ 0.5
Punch speed	0.5 mm/sec

A schematic of the punch-die set and the placement of the filler block gauge as a gap spacer can be seen in Figure 4(a). The gap spacers can be replaced as required to test the gap. It is important to note that the minimum size increase of the feeler is 0.05 mm. A complete series of punch-die sets on the press machine can be seen in Figure 4(b).

Table 2: Mechanical properties of SPCC

Mechanical properties material of JIS G3141 SPCC	Value
Strength constant (*K*)	559 N/mm^2
Strain hardening (*n*)	0.25
UTS	270 N/mm^2
Yield stress	180 N/mm^2
$LDR_{raw\ material}$	2.0



(a) (b)

Figure 4: (a) The schematic of the punch-die set [17], and (b) setting of the punch-die set on press machine

Results and Discussion

Using Equations (3) and (10), the minimum and maximum blank holder gap heights for the cylinder cup deep drawing process of 0.7 mm thickness SPCC material were found to be between 0.73 mm and 0.96 mm. In other words, the total gap height is equivalent to 104% to 137% of the blank sheet thickness. By using Equation (12), the drawing force with the minimum gap is 21858 N or 2230 kgf. The maximum gap which is revealed from Equation (3), which is equal to 137% of the initial thickness, was then compared with the experimental results.

Table 3 and Figure 5 present the experimental results involving the average flange thickness and product specimen quality, based on several variations of the blank holder gap. When comparing the mathematical approach of Equation (12) with the experimental results, both do not show a significant difference in the magnitude of the deep drawing force. The mathematical results of the deep drawing force are confirmed to be in accordance with the experimental results. Therefore, it is certain that the product will crack when the deep draining force is above 2230 kgf, which is confirmed by the experimental results. When the gap is set from 0.55 mm to 0.65 mm, the magnitude of the deep drawing force will appear in the range of 2233 to 2440 kgf. The magnitude of the tensile force has exceeded the critical value of 2230 kgf. Based on this experiment, the more impact it will have the smaller the BHG, the more impact it will have on increasing the internal tensile force and radial stress, resulting in thinning of the material at the edge of the cup. In addition, material thinning will continue to necking and cracking. In the implementation of BHG less than 0.65 mm, the drawing force that occurs is definitely more than 2233 kgf, and the product cracks. The critical drawing force in this study is 2233 kgf. When compared with several related studies, it shows similar indications. Insufficient BHG leads to products tending to crack, which is a consequence of employing very high BHF [6]-[7].

Similar results indicate that the cracking of the product occurred as a result of excessively high blank holding pressure and tight BHG [13]. When the BHF value is higher, there is a greater risk of splits and tearing. Conversely, excessive BHG can lead to the formation of wrinkles in the product. The research conducted by Palmieri et al. [18] confirmed the findings of this study, demonstrating that the force applied to the blank holder, represented by the BHG value in this case, significantly affects the achievement of an optimal draw-in profile and the production of a defect-free product. Generally, the blank holder gap should be set to provide sufficient restraint on the blank without causing excessive friction or wrinkling.

Table 3: Experimental results based on several variations of the BHG

Blank holder gap (BHG) (mm)	Final thickness of material (mm)				Drawing force (kgf)	Remark; result of cup deep draw
	Replication			Average of flange thickness (mm)		
	1	2	3			
0.55	0.7	0.7	0.7	0.7	2283	Cracking
0.60	0.7	0.7	0.7	0.7	2440	Cracking
0.65	0.7	0.7	0.7	0.7	2233	Cracking
0.70	0.7	0.7	0.7	0.7	2217	Good
0.75	0.7	0.7	0.7	0.7	2177	Good
0.80	0.8	0.82	0.82	0.81	2217	Good
0.85	0.88	0.9	0.88	0.89	2040	Wrinkling
0.90	0.94	0.98	0.98	0.97	2121	Wrinkling
1.00	1.1	1.1	1.3	1.17	2177	Wrinkling

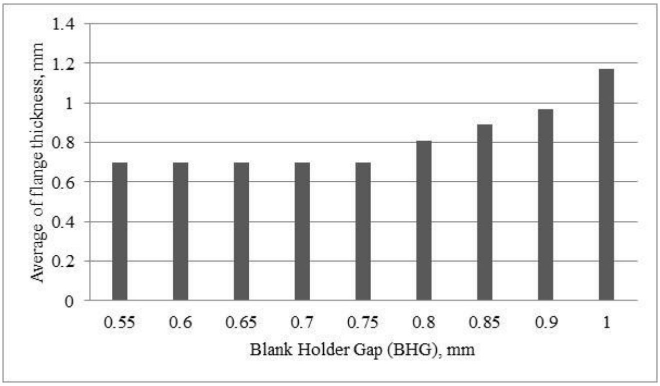


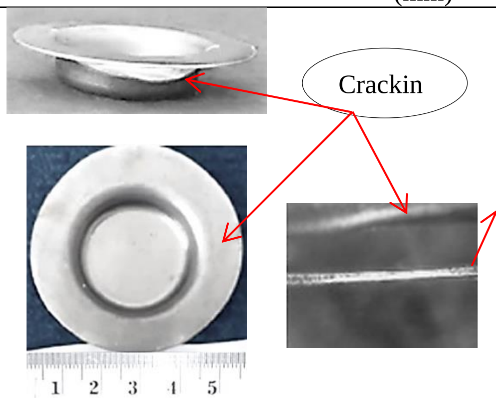
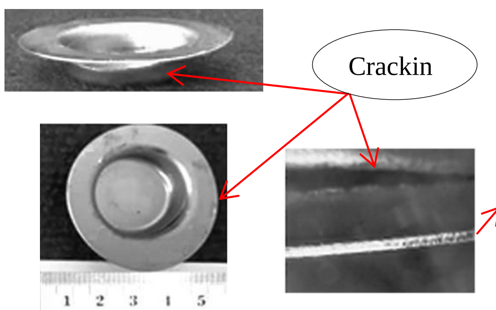
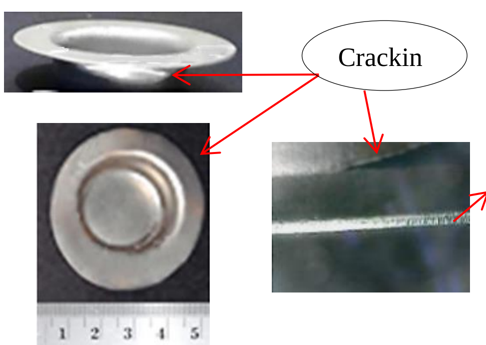
Figure 5: Blank holder gap vs. average of flank thickness

The experimental results, on the effect of the blank holder gap on the final dimensions of sheet thickness, wrinkling waves, and product quality conditions, are shown in Tables 4(a), 4(b), and 4(c).

Table 4(a) shows that if the BHG is employed below 100% of the initial blank sheet thickness or 0.55 mm, 0.60 mm, and 0.65 mm, the experimental results indicate that the product tends to crack. Moreover, if the blank holder gap is set smaller than 0.55 mm, the incidence of cracking becomes even more severe. The distribution of BHF applied by the radial blank holder is more reasonable and can effectively suppress corrugation. The use of BHF with electro-permanent magnet technology allows for maintaining a constant BHG distance, and importantly, prevents wrinkling [23]. This study aligns with BHG regulations, emphasizing the importance of maintaining a consistent BHG level that is neither too tight nor too loose to prevent product cracking and wrinkling.

The height value of the BHG has a direct impact on BHF value, which, when reaching a critical limit, can cause the product to crack. This phenomenon was confirmed by research on the effect of BHG on formation conditions, especially those related to wrinkling and cracking [24]-[25]. A small BHG value affects the flow resistance of material flowing into the die and deep drawing forces. If the BHG value is too small it will result in resistance to material flow and an increase in the value of the deep drawing force. If the value of the deep drawing force reaches a critical limit, cracking will occur [24]-[25].

Table 4(a): The final thickness dimension with fixed BHG is between 0.55 to 0.65 of the material thickness

No.	Fixed BHG (mm)	Product specimen (mm)	Flange thickness or height of flange (mm)	Remark
a.	0.55		0.70 mm	Cracking
b.	0.60		0.70 mm	Cracking
c.	0.65		0.70 mm	Cracking

In other conditions, if the BHG is not tightened, it will have a positive effect on reducing the deep drawing force and the material will not thin out excessively, as shown in Table 4(b). Meanwhile, if the BHG is raised above 0.80 mm or 114% of the thickness of the material, excessive buckling and wrinkling on the flange area cannot be prevented. In addition, if the BHG is too narrow, the clamping becomes too tight and consequently, the material could not flow properly, leading to material locking and cracking. In other words, cracking is caused by obstructed material flow and consequently, the magnitude of radial stress exceeds the critical stress limit. Based on the results of calculations with the mathematical formula and the experiment, as a first conclusion, cracks occur when BHG is set below the thickness of the material.

In this experimental work, the interpretation of the safe blank holder gap refers to Table 4(b). For BHG above 0.70 mm to 0.8 mm or equivalent to 100% to 114% of the thickness, the blank sheet does not indicate thinning and increasing the thickness of the material in the flange area. This BHG range will safely provide good processing conditions. The blank sheet of material will still be able to flow safely without any obstacles, in every position of the punch stroke. When compared with stress analysis, the safe condition occurs if the radial stress does not exceed the maximum material stress and the tangential stress is not excessive. If this is compared to the material strain conditions and FLD, thus the major and minor strain ratios are still in the safe area. From the experimental results, the drawing force when cracking occurs is above 2230 kgf, at BHG values below the thickness of the material.

The magnitude of the drawing force from the results of analytical calculations compared to the experiment shows no significant difference. The experimental results, as shown in Table 4(b), are consistent with the research conducted by Hamaza Blala et al. [26], even when considering different types of material applications. This consistency is observed in the determination of the gap distance, which is based on the thickness of the deep-drawing material. The optimal gap should not be smaller than the material thickness and should also not be excessively loose.

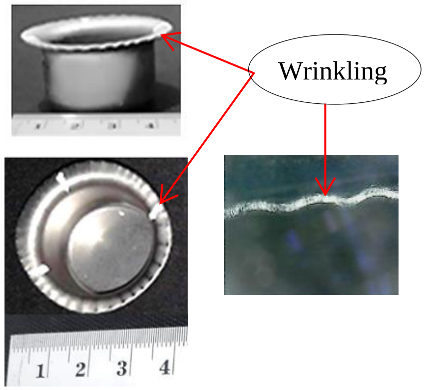
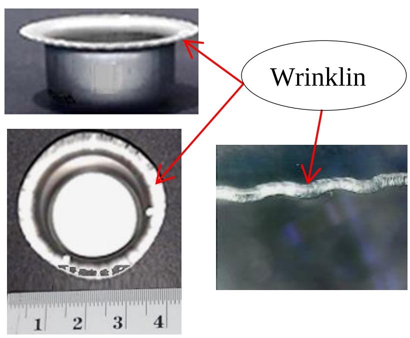
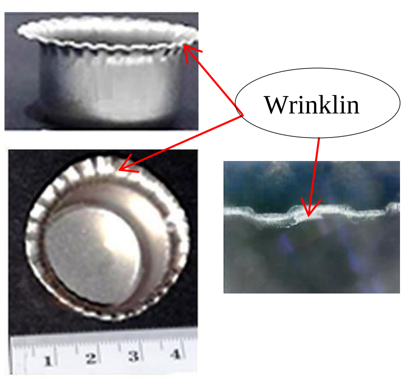
Table 4(b): The final thickness dimension with fixed BHG is between 1.00 to 1.14 of the material thickness.

No.	Fixed BHG (mm)	Product specimen (mm)	Flange thickness or height of flange (mm)		Remark
d.	0.70 (1.00 of thickness)	 		0.70 mm	Good
e.	0.75 (1.07 of thickness)	 		0.70 mm	Good
f.	0.80 (1.14 of thickness)	 		0.81 mm	Good

Furthermore, Figure 4(c). presents the experimental results with a blank holder gap of 121% to 143% of the thickness of the blank sheet or equivalent to 0.85 mm and 1.04 mm, respectively. Consequently, with these blank holder gaps, the wrinkling product starts to appear. The appearance of wrinkling begins at the height of the wrinkling wave in the flange above 138% of the material thickness or 0.97 mm. Within this gap range, wrinkling wave conditions did not result in a cracking product, although a scratch may appear on the body of the cup.

By following Equations (9) and (10), the BHG setting is confirmed to be similar to the experiment as shown in Tables 4(a), 4(b), and 4(c). The BHG value will affect the magnitude of the deep drawing force value. The deep drawing value is within the safe limit range, which is according to Equations (9) and (10), and the critical deep drawing force limit is according to Equations (11) and (12) so that the product can avoid cracks and wrinkles. The experimental results indicate that implementing both the BHF [18] and the BHG yields similar outcomes. However, the BHG system is significantly easier to use while effectively controlling material flow and preventing issues such as cracking and wrinkling defects. The blank holder gap system provides a simpler and more straightforward approach to controlling material flow during the deep drawing process. Adjusting the gap enables easy modification of the restraining force applied to the blank, resulting in improved control over material distribution and a reduced risk of defects. By optimizing the BHG, cracking and wrinkling can be minimized. Research conducted by Harith Yarub Maan et al. [25], Liang Luo et al. [26], and Hamza Blala et al. [27] confirmed the benefits of using BHG for controlling material formed in the deep drawing process and preventing cracking and wrinkling. However, these studies do not provide a precise description of the BHG height range, and its value is not associated with the thickness of the blank sheet material. By setting the correct BHG, obstructed material flow can be avoided, and forming stress conditions can be controlled properly and easily in a balanced manner. The recommended BHG value limit for which deep drawing processes can be implemented safely should be between 100% and 114% of the material thickness. In conditions of thickness above 1 mm and for different types of materials, further research is needed to ensure a safe BHG value.

Table 4(c): The final thickness dimension with fixed BHG is between 1.20 to 1.43 of the material thickness

No.	Fixed BHG (mm)	Product specimen (mm)	Flange thickness or height of flange (mm)	Remark
g.	0.85		0.89 Mm	Wrinkling
h.	0.90		0.97 mm	Wrinkling
i.	1.00		1.17 mm	Wrinkling

Conclusion

BHG adjustment is a simple and feasible way to prevent the cracking and wrinkling of cylindrical deep drawing cups. Nevertheless, it is necessary to ensure the use of punch-to-die set dimensions by the rules of punch-and-die design, such as punch-die radius, clearance, diameter, and a blank sheet. Determination of blank sheet dimensions and diameters can follow Table 1. Simple mathematical models such as Equations (3) and (10) can be used as a simple approach to determine the minimum and maximum BHG. The mathematical approach has been confirmed by experimental results. Based on experimental results, the recommended BHG for forming deep drawing cup products with SPCC material and 0.7 mm thick ranges between 100% to 114% of the thickness of the blank sheet. BHF above 114% of the thickness of the material indicates wrinkling and reveals a scratch on the cup body. This BHG range can be used as a simple reference for the industries involved in deep drawing cup manufacturing.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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