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SIMULATION AND EXPERIMENTAL INVESTIGATION OF WRINKLE DEFECT IN DEEP DRAWING PROCESS OF CARBON STEEL SPCC SHAPED CYLINDER FLANGE CUP

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Abstract -- *A Sheet Metal Forming (SMF) process, especially deep drawing, is one of the manufacturing processes that commonly used in the automotive industry. Compared with casting and forging, the SMF process has several advantages, including lesser weight materials and broader variations in shape that can be made. One of the problems in the SMF process is the wrinkling phenomenon, which can cause the size and appearance defects of sheet products. The wrinkle occurs because of the mechanical properties of the material, product geometry, and blank holder force (BHF). Several variations of BHF were applied in these simulations and experiments to eliminate the wrinkle defects of cylinder flange cup test products. The characteristic of the cylinder flange cup is from the cold-rolled coiled steel plate (SPCC) type of material with a thickness of 0.8 and 1.0 mm, the height of 10 mm, the inner diameter of 58 mm, and flange diameter of 76 mm. Simple simulations of the SMF process were carried out by using Solidworks with version 2017, and the experiment was carried out at a 600 kN press with a punch velocity of 40 strokes per minute and blank holder force variations from 0 to 21 kN. The experimental data performed with a single die on a flanged cup cylindrical test material shows that the higher the blank holder force (BHF) number, the smaller the wrinkle defect, and it can be eliminated starting from the BHF number of 15 kN.*

Keywords: *SMF; Deep Drawing; Wrinkle; BHF; Cylinder Flange Cup; Carbon Steel SPCC*

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INTRODUCTION

Sheet metal forming (SMF) processes are commonly used in the automotive industry by using dies and press machines [1, 2, 3]. Deep drawing is one of the most widely used SMF processes for producing cylindrical cup and flange cup cylinder components in a high level of accuracy and quality. Cylindrical cup shapes and cylindrical flange cups with deep drawing processes are widely used for the production of major components in the automotive, household, and electronic industries [4, 5, 6, 7]. In the deep drawing process, a sheet metal blank is drawn over a die cavity using a shaped punch. When the blank is drawn, radially inwards, the flange undergoes radial tension and circumferential compression [8] [9].

Wrinkles are one of the major defects and often occur in the deep drawing process [1, 2, 10, 11]. The formation of a wrinkle in the deep drawing process of a product shaped flange cup cylinder generally occurs in two locations. The locations are flange and cylinder cup walls due to the strain hardening effect, radial tension on the inner wall drawn, and a large drawing ratio [4, 8, 12, 13]. Wrinkles on the wall occur caused by too much material cumulate over the die drawing, which usually happens when the clearance between the punch and the die is not great enough. This defect can damage the dies and affect the assembly and function of the products [1]. Analytical and experimental approaches with the finite element-based automation simulations (FEM) are applied to predict and prevent wrinkles [2, 6, 9, 11, 13].

One of the ways to prevent wrinkle defects can be done by determining the number of the blank holder force (BHF) appropriately because the BHF is able to avoid the wrinkle at the flange area. If the empty holder is insufficient, the wrinkle on the flange area will be formed, and the wrinkle on the wall area can be approached by determining the right gap between die and punch. The most important parameter is the blank holder pressure [4, 8, 10, 12].

There are two considerations to determine before using the blank holder [1], as follow:

1. Material thickness ratio *(T_r),* and
2. Drawing ratio *(m)*

The ratio of the material thickness *(T_r)* and drawing ratio (m) can be calculated by Equation (1) and (2).

$$T\_r = T/D\ 100\ \geq 2 \quad (1)$$
$$m = Dp/D\ \ \geq 0.8 \quad (2)$$

where T_r is the ratio of material thickness, T is the thickness of the material (mm), D is the diameter of the blank (mm). In contrast, the draw ratio and D_p are the diameter in the cylinder cup flange (mm). If the two parameters are not met, then a blank holder is needed [1].

The pressure and the blank holder force can be calculated by the following equation [1].

$$P_d = (0{,}2{\sim}0{,}3)\left[\left(\frac{D}{D_p} - 1\right)^3 + \frac{Dp}{200T}\right](UTS) \quad (3)$$

$$\mathrm{F_d} = \frac{\pi}{4}\left[\mathrm{D}^2 - \left(2\mathrm{R_p}\right)^2\right]\mathrm{P_d} \quad (4)$$

where P_d is the blank holder pressure (MPa), F_d is the blank holder force (kN), *UTS* is the ultimate tensile strength (*MPa*), and R_p is the radius in the cylindrical flange cup (mm).

Many studies have been carried out to analyze the occurrence of wrinkle defects in the drawing process or deep drawing on sheet metal material. Research is carried out on different types of materials and geometries. Other than that, simulations are carried out with various software, such as ANSYS and ABAQUS.

The effect of BHF on the three-layer wrinkle of Al-PP-SUS sheets during the deep drawing process has been investigated with Abaqus 6.12 automation simulation by [12]. BHF is needed to reduce wrinkles and high-quality test products without tearing using experimental tests and finite element analysis. Polypropylene (PP), which is a thermoplastic polymer, was chosen as the core layer, Al3105 and SS304 were chosen as the skin layer. Al3105 is used because of its low specific weight, and the use of SS304 is to improve structural strength and corrosion resistance. Initially, it is necessary to determine the properties of the material before the deep drawing test and finite element simulation. For this purpose, standard tensile samples from each layer were made according to ASTM E8 standards and tested using the Zwick-Z 250 instrument. The experimental results show that by increasing the BHF number from 6.4 to 12.8 kN, wrinkles decrease, and high-quality test products are obtained.

ANSYS automation simulations have investigated wrinkle defects in the deep drawing process in research conducted by [11]. The finite element method is used as a tool in this study to investigate the effect of wrinkles on a cylindrical cup that occurs in the deep drawing process. Experimental validation was carried out to proved FEM simulation results. The study was conducted on SS 304 material test products with blank diameters of 60 to 120 mm, a thickness of 0.75 and 1.00 mm, and a BHF number from 0 to 7 kN. The experimental results shown in that wrinkles can be eliminated at a BHF number of 5 kN. An additional study also conducted to show the effect of punch speed on product quality and wrinkle. A radial strain is used to indicate the wrinkle effect due to different conditions of the forming process.

The effect of blank holder force on strain distribution and thickness along the walls of the cup cylinder on the part drawn in the deep drawing process has been investigated by [14]. The 2-D cylindrical cup model with an outer diameter of 40 mm and a thickness of 0.5 mm is made from AISI1008 low carbon steel. ANSYS14.0 is used to carry out numerical simulations of the deep drawing process. Experiments were carried out using digital image processing techniques. Five blank holder strength values, namely 5, 7.5, 10, 12, and 15 kN, are applied from the experimental results obtained, the best strain distribution and thickness at 10 kN of BHF.

Study the effects of blank holders, and dies shapes for Al1050 sheet metal has been completed by [8]. The strength distribution of the blank holder force (BHF) is applied to form loads at different drawing depths as well as to reduce the thickness of the cup wall thickness for each matrix set and blank holder geometry. The experimental implementations have shown that the die angle of 12.5° is useful for reducing the tensile strength of Al1050 material.

Research with the experimental design method of Taguchi and Anova to analyze the effect of the punch radius, die radius, and blank holder force on the thickness of the blank sheet being drilled into a cup cylinder has been carried out by [15]. In this study, an experimental method is proposed to understand the effect of various parameters on the variation of the thickness of the cup cylinder formed by the deep drawing process. The deep drawing test was carried out on Aluminum alloy with a thickness of 0.9 mm with a 2000 kN mechanical press machine. The results showed that the parameter with the most substantial influence was blank holder force with the number is 56.98%, the punch radius was 30.12%, and the die radius was 12.90%.

Numerical experiments and analysis of rail shapes with a high tendency to form a wrinkle on surface of flange has been conducted by [7]. The formation process consists of three phases. In the first phase, the die moves downward, clamping the blank between the die and the blank holder with the specified initial 90 kN force. This blank holder force is defined by six nitrogen gas springs connected to ensure the same pressure in each spring. In the second phase, the die and blank holder move down together, starting the process of forming and determining the penetration of the 60 mm punch. At this stage, the gas spring is being compressed, thereby increasing the blank holder force from 90 to 130 kN. The third phase is the product release from dies. The study was conducted on DC06 material with a 210 GPa young modulus and a poison ratio of 0.3, and it shows that the BHF number increases linearly with the rate of punch drawing.

Based on some information from the results of previous research, therefore, in this research, a simulation investigation and experiment will be carried out on the effect of BHF on wrinkle defects in test products with cylindrical flange cup morphology from SPCC carbon steel sheets 0.8 mm and 1.0 mm thickness. Simple simulations were carried out using Solidworks version 2017 with BHF variations from 0 to 21 kN. Experiments using the same material and geometry were carried out using a single die on a 600 kN press.

Cold rolled coiled steel plate is carbon steel formed by cold rollers of commercial quality, referring to JIS-G3141. This material is in sheet form for the cold working process. This material is most widely used in the SMF manufacturing industry especially drawing and deep drawing compared to other types of materials such as ASTM (American Society for Testing and Materials), KS (Korean Steel Standard), or GB (Guojia Biaozhun-China).

The SPCC material has a thickness deviation limit value of 0.06 mm for thicknesses of 0.6 to 1.0 mm [16], so that it has a good ability of draw ability and thickness distribution during the drawing process. Another consideration in the selection of materials is due to the initial characteristics of the material which have a degree of ease of fabrication or are limited based on the desire to achieve the final properties needed to complete the deformation process. The considered specifications of material are the type of material, weight, strength, and stiffness [17], as well as the selected sheet metal from the SPCC carbon steel material. The phenomenon of wrinkle defects at the SMF process of aluminum and stainless steel material has been done in previous research. They have analyzed the effect of the blank holder gap and the slope angle of the blank holder on wrinkle defects with FEM simulation and experiments.

This research aims to carry out the numerical simulation and investigation on the wrinkle defect of the deep drawing process in the shape flange cup cylinder on the SPCC carbon steel sheet by applying a variation of BHF number on the blank holder material. A simple simulation of the SMF process was carried out on the test product with the morphology of the cylindrical flange cup of SPCC material. The characteristic of the cylindrical flange cup of SPCC material is the thickness of 0.8 and 1.0 mm, the geometry of is inside diameter is 58 mm, the flange diameter is 76 mm, the punch radius is 0.3 mm, and the die radius is 3 mm. The simulation of wrinkle defects in SMF with BHF variations is then validated by experiments using a single die on the same material.

METHOD

Material

In this study, a simple simulation and experiment were carried out on the deep drawing process of the cylindrical flange cup cylinder from SPCC carbon steel sheet material as shown in Figure 1. The chemical composition of the cylindrical flange cup test product, as listed in Table 1 and the mechanical properties, as in Table 2.

Table 1. Chemical composition of SPCC materials in % unit [16]

W_t	C	Mn	P	S	Fe
%	0.15 max	0.60 max	0.10 max	0.05 max	Balance

Table 2. Mechanical properties of SPCC materials [16]

Thickness (mm)	Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
0.25 - 0.30	240 max	270 min	28 min
0.30 - 0.40	240 max	270 min	31 min
0.40 - 0.60	220 max	270 min	34 min
0.60 - 1.00	210 max	270 min	36 min
1.00 - 1.60	190 max	270 min	37 min

Dies

To find out the wrinkle defects that occur in SPCC carbon steel sheet material in the form of cylindrical flange cups with a thickness of 0.8 and 1.0 mm, the experiment was carried out by using a single die, namely dies which only did one drawing process as shown in Figure 2 [18].

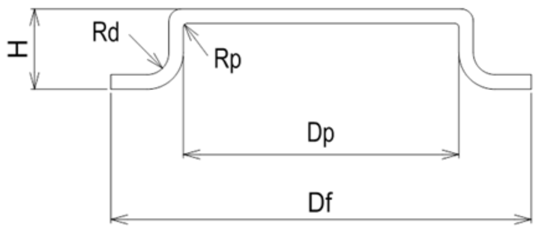

Figure 1. The geometry of cylindrical cup flange test products, H is the height of the test product (10 mm), D_p is the inside diameter of the test product (58 mm), D_f is the flange diameter (76 mm), R_p is the punch radius (0.3 mm), and R_d dies radius (3 mm)

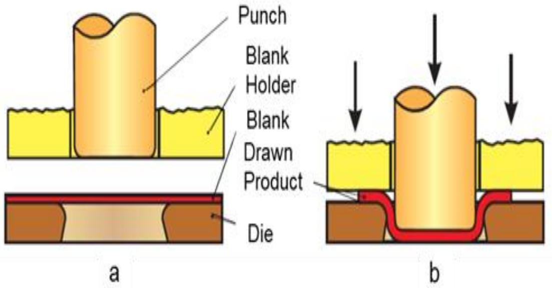

Figure 2. Single die drawing process. a. before and b. during the drawing process

Figure 3 shows the parts of the die used in the experiment that consist of die drawings, punch drawings, blank holders, and knock out collars.

Figure 3. A single die constructed by a. drawing dies, b. drawing punch, c. blank holder, d. knocks out collar

Methods

Simple simulations were carried out using Solidworks version 2017 which was run on a computer with an Intel (R) Core (TM) processor i7-7500U CPU @ 2.70GHz, 8.00 GB memory, VGA AMD Radeon HD 6470M, Windows 10, 64 bits with the material parameters as shown in Table 3.

Table 3. SPCC material parameters in a deep drawing simulation [19]

Properties	Metric
Density (Kg/mm^3)	$7.8x10^{-6}$
Modulus young (GPa)	210
Poisson's ratio	0.3
Yield strength (MPa)	175
Strain hardening exponent	0.06
Anisotropic coefficient (MPa)	1.93
Hardening coefficient (MPa)	5044

The experiments of SPCC carbon steel sheet in deep drawing process with a single die were carried out on a 600 kN mechanical press machine. The punch stroke speed in this study was set at 40 strokes per minute [20]. The press machine specifications were shown in Table 4.

Table 4. The 600 kN mechanic press specification [21]

Specification	Quantity
Capacity (kN)	600
Stroke length (mm)	140
Stroke per minute	45 – 85
Die height, slide to bolster (mm)	300
Slide adjustment (mm)	70
Slide size, length x width (mm)	480 x 400
Bolster size, length x width (mm)	870 x 520
Frame gap (mm)	270
The frame inside measurement (mm)	130
Main motor	5.5 x 4
Required air pressure (MPa)	0.5

Measurement

The measurement of cylindrical flange cup test products was carried out by using Formtracer type SV-C500 included with Formpak v.1.213 software, as shown in Figure 4. The measurement was aimed at obtaining accurate, wrinkle depth values on the flange surface [20] [22].

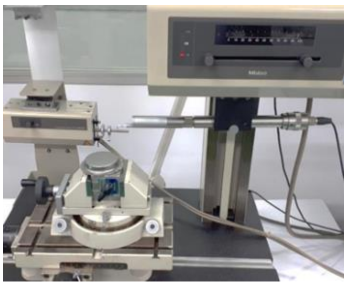

Figure 4. Schematic measurement of the surface contour of the test product flange with the SV-C500 form tracer

RESULTS AND DISCUSSION

The simulation was performed by varying the value of the BHF number. The material used in the simulation is a 0.8 mm and 1.0 mm thickness of SPCC sheet metal with a cylindrical flange cup-shaped morphology in the deep drawing process. Wrinkle phenomenon can be demonstrated by ANSYS and ABAQUS simulation automation as performed by [11, 14, 18, 19]. A simple simulation using Solidworks 2017 version can also demonstrate the phenomenon of wrinkles as in this study are shown in Figure 5.

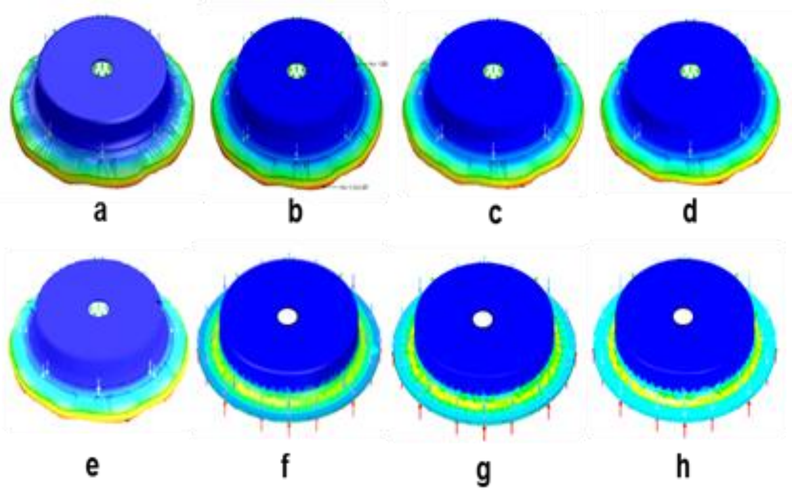

Figure 5. The phenomenon of wrinkle defect in the deep drawing process using a simple simulation of Solidworks 2017 with variations of BHF number, a. 0 kN, b. 3 kN, c. 6 kN, d. 9 kN, e. 12 kN, f. 15 kN, g. 18 kN and h. 21 kN

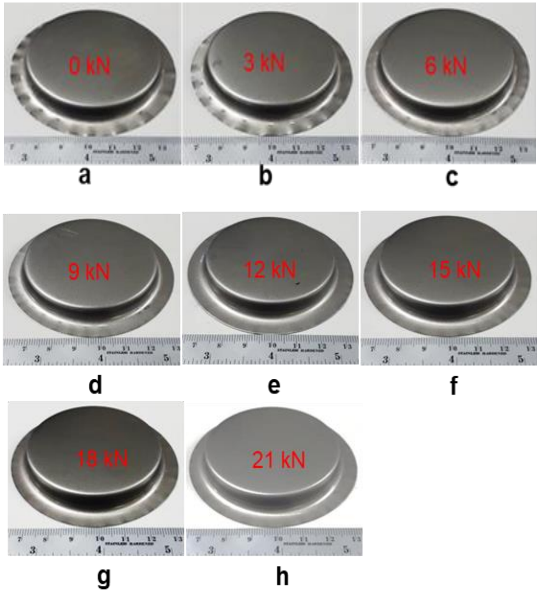

Figure 6. Result of the experimental validation of the SPCC material test products with a thickness of 0.8 mm and variations in the number of BHF, a. 0 kN, b. 3 kN, c. 6 kN, d. 9 kN, e. 12 kN, f. 15 kN, g. 18 kN and h. 21 kN

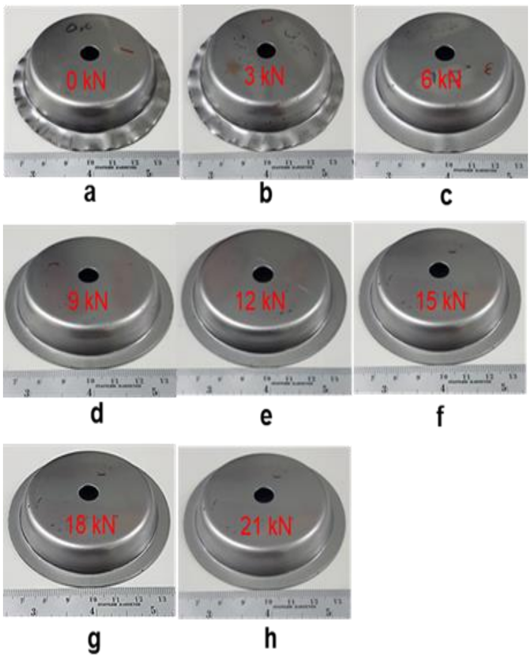

Figure 7. Result of the experimental validation of the SPCC material test products with a thickness of 1.0 mm and variations in the number of BHF, a. 0 kN, b. 3 kN, c. 6 kN, d. 9 kN, e. 12 kN, f. 15 kN, g. 18 kN and h. 21 kN

Based on simulation results, as shown in Figure 5, it has been clear that no wrinkles can be observed when using BHF with large numbers. The BHF influences the distribution of equivalent plastic stresses and strains. For BHF 15, 18, and 21 kN, uniform distributions of stresses and strains can be observed. The condition is led to no wrinkle at the appearance of the flange area. When the BHF number is low, the material flows rapidly in the initial stages of the drawing process. In the absence of prevention in a progressive drawing, extreme compressive stresses are generated and cause a local buckling to the blank sheet. Then metal flow becomes difficult into the die.

The wrinkle is the most crucial reason for the failure of the SMF process, primarily due to the deep drawing. Generally, the lack of area and uneven distribution of pressure on the blank holder causes wrinkles in the deep drawing process. The situation can be clearly seen, as shown in Figure 5(a)-(e). The circular flange on the cylindrical cup of the sheet is mainly affected by the radial tensile stress and axial pressure of the material during the process. For a certain material thickness and die size, the ratio of material thickness to punch and die diameter is an important parameter in this process, as can be clearly depicted in Figure 5(f)-(h). After suffering compressive stress, the blank sheets able to cause an elastic or plastic wrinkle in the flange that leads to undesirable deformation models, which are shown as waves on the flange edges [12].

Increasing the BHF number reduces the wrinkle defect in the flange area of the cylindrical flange cup test product that is drawn to the point where the wrinkle is wholly deformed, as shown in Figure 6 and Figure 7. The results of this experiment confirmed the simulation of the wrinkling phenomenon, as previously presented in Figure 5.

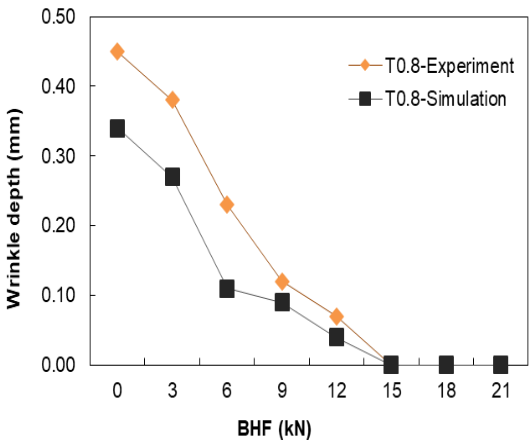

Figure 8. Comparison of experimental and simulation result plot of the effect of BHF variations on wrinkle defects of SPCC material test products with 0.8 mm thickness

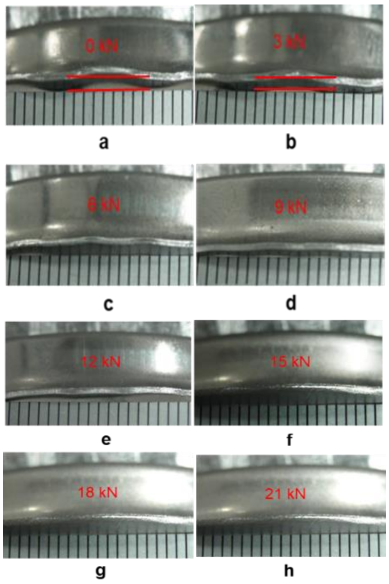

Figure 9. Cross-section view of the wrinkle depth from the experimental results of SPCC material test product with thickness 0.8 mm, with variations in the number of BHF a. 0 kN, b. 3 kN, c. 6 kN, d. 9 kN, e. 12 kN, f. 15 kN, g. 18 kN and h. 21 kN

Figure 8 shows a cross-section of the wrinkle depth of the deep drawing process of SPCC carbon steel material with a thickness of 0.8 mm and eight variations in the number of BHF. While Figure 9 shows the cross-section of the wrinkle depth resulting from the deep drawing process of SPCC carbon steel material with a thickness of 1.0 mm with a variation of the same number of BHF of 0 to 21 kN.

Figure 10 shows the results of the simulation and experimental of the SPCC sheet metal material with a thickness of 1.0 mm. In this simulation and experimental, eight blank holder force variations were applied from 0 to 21 kN. The results of the simulation value of wrinkle depth are decreased linearly with an increase of the BHF number from 0 to 12 kN, namely 0.54, 0.37, 0.27, 0.14, 0.07 mm, respectively. Starting from the BHF number of 15 to 21 kN, the resulting of wrinkle depth is 0 mm. The more profound wrinkle value is 0.34 mm at the BHF number of 0 kN.

Meanwhile, the experimental results are 0.64, 0.59, 0.49, 0.26, 0.12 mm, and starting from the number of BHF 15 to 21 kN is 0 mm. The experimental results show a gap different from a deeper wrinkle value of 0.22 mm compared with the simulation at 3 and 6 kN BHF numbers. The simulation and experimental show similar results when the wrinkle defects can be reduced by increasing its BHF number, and the wrinkle does not occur starting from 15 to 21 kN of BHF number.

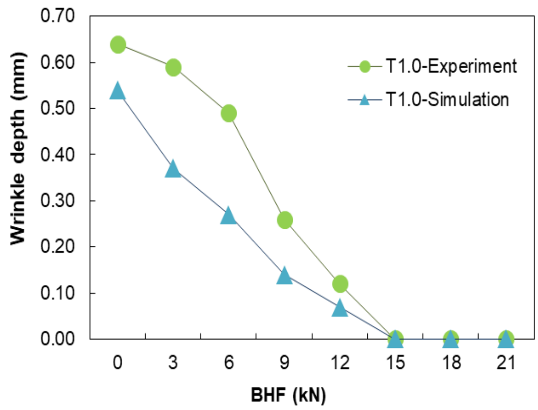

Figure 10. Comparison of experimental and simulation result plot of the effect of BHF variations on wrinkle defects of SPCC material test products with 1.0 mm thickness

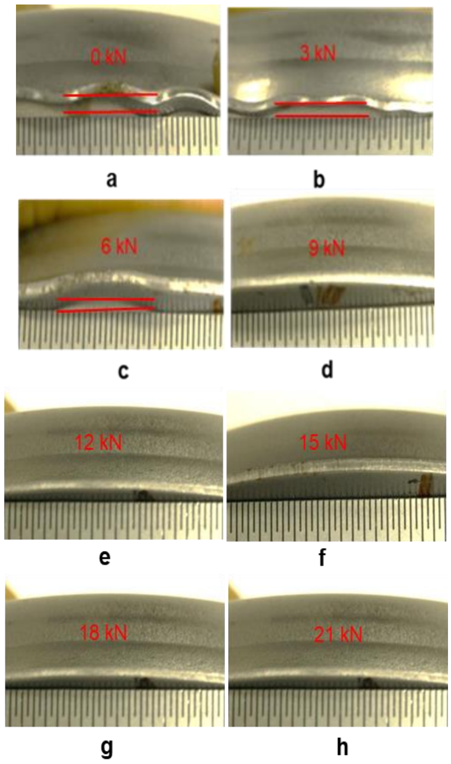

Figure 11. Cross-section view of the wrinkle depth from the experimental results of SPCC material test products with 1.0 mm thickness, with variations in the number of BHF a. 0 kN, b. 3 kN, c. 6 kN, d. 9 kN, e. 12 kN, f. 15 kN, g. 18 kN and h. 21 kN

The SMF process from SPCC sheets with a thickness of 1.0 mm with a BHF number of 0 kN forms a wrinkle with a depth of 0.64 mm in the test product flag area then the wrinkle depth decreases with increasing BHF values and is not indicated at BHF 15 to 21 kN as shown in Figure 11.

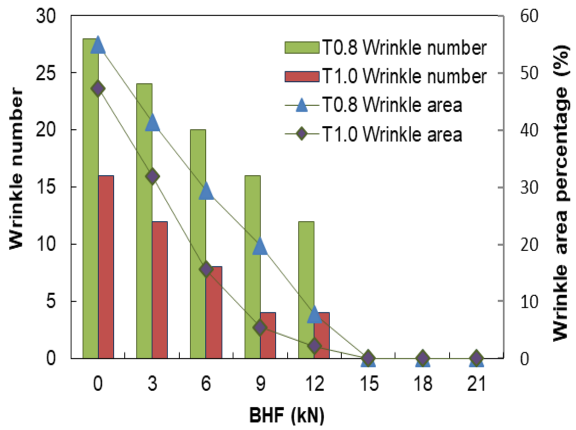

Figure 12. Graph of the effect of BHF on the amount and area of wrinkle on the flange surface of the test product from S
PCC material with a thickness of 0.8 and 1.0 mm

Figure 12 shows the maximum number for the wrinkle of test products from SPCC material with a thickness of 0.8 mm is 28, the minimum number is 12 with an average value of 20, while for thickness 1.0 mm the maximum number of wrinkle is 16, the minimum number is 4, and the average number is 8. The maximum percentage of the wrinkle area is 54.9%, and the minimum is 7.8%, with an average value of 30.7% of the flange surface area for 0.8 mm thickness. As for the thickness of 1.0 mm, the maximum wrinkle area is 47.3%, the minimum space is 2.1%, with an average value of 20.5%. The average wrinkle area value of the test product from SPCC material with a thickness of 0.8 mm is 10.2% greater than that of the test product with a material thickness of 1.0 mm. This difference occurs because the thickness of the material affects the anisotropy of the material [10] [12].

The simulations and experiments of the deep drawing process of SPCC materials with a thickness of 0.8 and 1.0 mm show similar results when the defects are formed in the range of BHF values from 0 to 12 kN and can be reduced by increasing the number of BHF values. Figures 6, 7, 9, and 10 show that no defects can be observed when using a BHF with numbers starting at 15 kN because BHF has an influence on the distribution of stresses and plastic strain that is equal. Thus, defects can be avoided when applying the total BHF value of 15 kN. The simulation and experimental of the deep drawing process of 0.8 and 1.0 mm thickness of the SPCC material showed similar results when the wrinkle defects are formed in the range of BHF number from 0 to 12 kN, and it can be reduced by increasing its BHF number. From Figures 6, 7, 9, and 11, it is clear that no wrinkles can be observed when using BHF number 15 kN because BHF has an influence on the distribution of equivalent plastic stresses and strains. Thus, wrinkle defects can be avoided when applying a BHF number starting from 15 kN.

CONCLUSION

Based on the results of simulations it can be concluded that the most significant wrinkle defect in the cylindrical flange cup test product of SPCC carbon steel material with a thickness of 0.8 is 0.34 mm at 0 kN number of BHF, while the most substantial wrinkle defect in experimental is 0.45 mm at a number of BHF 0 kN. The most significant difference in deep wrinkle value between simulation and experiment is 0.12 at a number of BHF 6 kN, whereas the thickness of 1.0 mm for the most substantial wrinkle value is 0.54 mm at 0 kN BHF value for simulation and 0.64 mm at 0 kN BHF value for the experiments. The most significant difference in wrinkle value between simulations and experiments is 0.22 mm at the number of BHF 3 and 6 kN.

The difference in wrinkle value between simulation and experiment occurs due to differences in material properties parameters. Single deep die drawing processing with SPCC material thickness 0.8 and 1.0 mm able to be reduced by varying the number of BHF values from 3 to 12 kN and can be eliminated at the amount of BHF 15 kN. Simple automated simulations by using Solidworks 2017 version shows that wrinkle defects in the deep drawing process. It helps to determine the proper number of BHF to form the flange cup cylinder products based on the SPCC carbon steel sheets material. Thus, the process of designing and machining of die parts will be more efficient and accurate. This work still requires further research analysis, for instance, by using software that has a higher simulation capability, including ANSYS, Autoform, and others. The experiments with other forming parameters such as punch radius, coefficient of friction also need to be done to determine the forming parameters that will give a big picture of the effect on wrinkle defects.

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