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SPRING-BACK ANALYSIS OF THE VEE BENDING PROCESS FOR HIGH-STRENGTH STAINLESS STEEL

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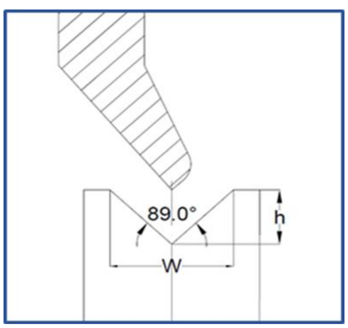
V-Dies abstract



Abstract

This study discussed the evaluation of bending process using high-strength SUS 304 (HS-SUS-304) material of high degree tolerances, and its application in a safe, strongbox, and strongroom protection system. This bending process is one of the several material-forming techniques widely used in the manufacturing industry. Moreover, incorrectly selected parameters such as the V-die punch radius, the angle of V-die bending, and the angle of machine parameters often leads to material failure and wrong final dimensions. The V-bending process was chosen for evaluation because it exhibits significant spring-back effect and has a wide range of industrial applications. The experimental method utilized HS-SUS 304 with a thickness of 3.0 mm that meets the ASTM A-240 requirement, and the input parameters used for V-die angle as well as tip punch radius were chosen in order to achieve the 90° ± 0.5°, and 50° ± 0.5° degrees of the workpieces. The V-die angle of 89° was selected with a tip punch radius of 1.0 mm and 1.2 mm. Furthermore, the spring-back effect was analyzed and evaluated to meet the standard angle requirement, and the results showed that the settings on the bending machine need to be adjusted to achieve angles within tolerances of degrees. It was observed that when the process bend angles on the machine was set at 93.75° and 52.83° with 1.0 mm V-dies tip punch radius, the spring-back factor results produce an average of 0.9609, 0.9618, and 0.9600. Meanwhile, this average increased to 0.9634, 0.9641, and 0.9655, respectively by using 1.2 mm.

Keywords: Metal forming, high-strength SUS 304, Hydraulic press bending machine, V-dies punches radius, Spring-back factor, Bending angle

1.0 INTRODUCTION

The high-strength SUS 304 material (HS-SUS-304) has higher strength than conventional steel grades, as well as high formability, and superior mechanical properties. It has been found that sheet metal processing is one of the earliest manufacturing technologies developed [1], and have improved with the rapid growth of the manufacturing industry. This is the reason the products have been widely used in all industrial sectors, including the application of safe deposit boxes, strongboxes, and strongroom protection systems. Sheet metal bending is a metal forming process developed in response to the demands for diverse shapes, plate specifications, and increased tolerance for metal formation, using a combination of elastic-plastic bending and workpiece stretch deformation [2].

There are two methods of metal forming based on temperature treatment, which include cold metal forming at room temperature and hot working at high temperature. The workpiece is not heated during cold forming, rather it is performed under re-crystallization conditions. The stress used throughout this process include Kinematic shaping and shaping with set tools [3]. It is important to note that the kinematic forming process is more flexible than the other one, and the final shape is not determined by the tool's shape but by its relative motion with the workpiece. Furthermore, metal forming with dies is influenced by the desired workpiece geometry, specifically curvature, and the spring-back caused after pressing. It has been discovered that this formation led to high productivity and shorter processing times in many cases due to the geometry of dying and fixed objects [4].

The bending process used was cold forming and the machine specifications such as the bending machine's pressure capacity, product bending length, and the dies' open height were considered. The method of selecting sheet metal bending machines has become an important practical issue to consider, because it is essential to obtain the exact requirement of the design decision-maker.

It is also important to note that the distance between the punch and die have to permit the workpiece to be mounted or pulled freely during the bending process. Some workpieces, such as some refrigerator components and filing cabinet products, required side mounting called 'side pulls' that need to be avoided. Installation from the front of the bending machine is preferable in view of increasing operational efficiency. This simply showed that sufficient tip-to-die distances help to improve operational efficiency [5].

The Spring-back phenomenon is a complex physical issue, and its value depends on the natural deformation of an element. It was found that the final flexural radius was lower than the reference radius of the compensated party [6]. This is the reason the Spring-back phenomenon in the bending process usually accounts for many dies setups [7]. Several studies conducted on this phenomenon include Cho *et al.,* who investigated the effect of some parameters in specific U-die bending processes such as die corner, radii of punch, clearance between punch, and die on spring-back [8]. Y. Yu also studied the variation of elastic modulus during plastic deformation and further examine its effects on spring-back in U-bending [9]. Phanitwong *et al*. investigated the effect of part's geometry on spring-back in the U bending process [10]. Chikalthankar *et al.* investigated the effects of critical factors in Spring-back addressed in v-shaped bending, and discovered that the punch angle was the most critical and significant parameter in spring-back [11]. Furthermore, Zhiying and Lihui examined the stress distribution of spring-back in the Hydro-forming process and found that as the hydraulic pressure increases, the spring-back becomes smaller. This was consistent with the theoretical analysis, for example, when the liquid chamber pressure was 10 MPa and 20 MPa, the spring-back effect decreased by 8.9% and 26%, respectively [12]. Yang *et al*. studied the spring-back resuming phenomenon in bending 70 mm and 127 mm diameter pipes. The materials used include high strength TA-18, medium-strength TA-18, LF2M, and Cr14Ni9Ti. The method employed was FE (Finite Element) simulation, and it was found that the efficient and precise bending process depended on the material's mechanical properties. This simply means that proper and accurate FE modeling and simulation strongly depended on understanding the modeling of the material's unique response at the time of loading [13]. It is important to note that the phenomenon that occurs in plate bending differs from pipe bending. This is because metal plates are plastically deformed along straight lines, which change their shape during bending, and they are generally used by trial and error. However, bending operations' precision and achievement depend on operating parameters, properties of material, and the investigation of microstructure and texture during continuous bending of rolled AZ31 sheet by experiment and FEM [14], [15].

This current study focuses on the analysis of the bending force, bending work, and spring-back effect in the process of bending 3.0 mm thick HS-SUS 304 materials applied as a safe, strongbox, and strongroom protection system. Furthermore, it aims to determine the effect of angles and spring-back factors at 90-degree and 50-degree bending angles with high precision application. The evaluation problem was the application of V-bending process as cold metal forming using a hydraulic press bending machine. The spring-back effect on the bending angle was observed by varying the tip punch radius and the V-die angle. This tip punch radius and V-die degree input parameters were chosen to meet the target.

2.0 METHODOLOGY

2.1 Material and Dimensions

The HS-SUS 304 has a 3.0 mm thickness and was produced by "Bahru Stainless Sdn Bhd" with batch no. Y181003A05E01442. The degrees of bending angle in the 90o and 50o longitudinal bending directions were selected with 0.5o (30-minute degree) tolerance. Samples A and B were selected for the 1.0 mm and 1.2 V-die punch radii. Furthermore, six samples having twice the bending angle of 90o and 50o, with 320 mm in length and 105 mm in width provided sufficient experimental data. The chemical composition and mechanical properties of HS-SUS 304 are summarised in Table 1 and 2 meanwhile, Table 3 shows the workpiece geometry and specifications in linear and angular geometry.

Figure 1 presents the workpiece dimensional HS-SUS 304 as used in a safe, strongbox, and strongroom protection system.

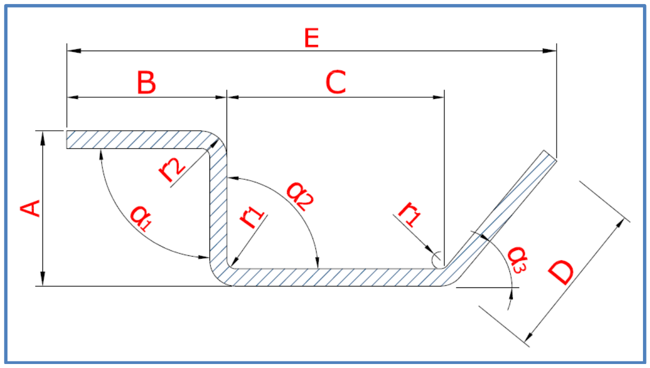


Figure 1 Sample geometry of HS-SUS 304

Table 1 Chemical composition of HS-SUS 304

Elements	Standard [4]	Actual*
C	0.030-0.10	0.049
Mn	2.00	1.090
S	0.030	0.002
P	0.054	0.025
Si	0.75	0.42
Ni	8.0-12.0	8.00
Cr	17.5-19.5	18.2
N	0.10	0.05

*Mild Test certificate Y181003A05E01442

Table 2 Mechanical properties of HS-SUS 304

Mechanical properties	Standard [4]	Actual*
UTS (MPa)	≥ 515	615
YS (MPa)	≥ 250	280
Elongation (%)	≥ 40	52.0
Hardness (HRB)	≤ 92,	85

*Mild Test certificate Y181003A05E01442

Table 3 Sample dimension of HS-SUS 304

Post	Dimensions	Post	Dimensions	Post	Dimensions
A	24.8 ±0.4	E	83.0 ±0.4	α_1	90° ±0.83o
B	28.0 ±0.4	r_1	R 1.5 ±0.4	α_2	90° ±0.83o
C	38.8 ±0,4	r_2	R 4.5 ±0.4	α_3	50° ±0.83o
D	26.5.0 ±0,4				

Six samples were examined, as shown in Figure 2, and the HS-SUS 304 specification was in line with the ASTM A-240 standard [4].

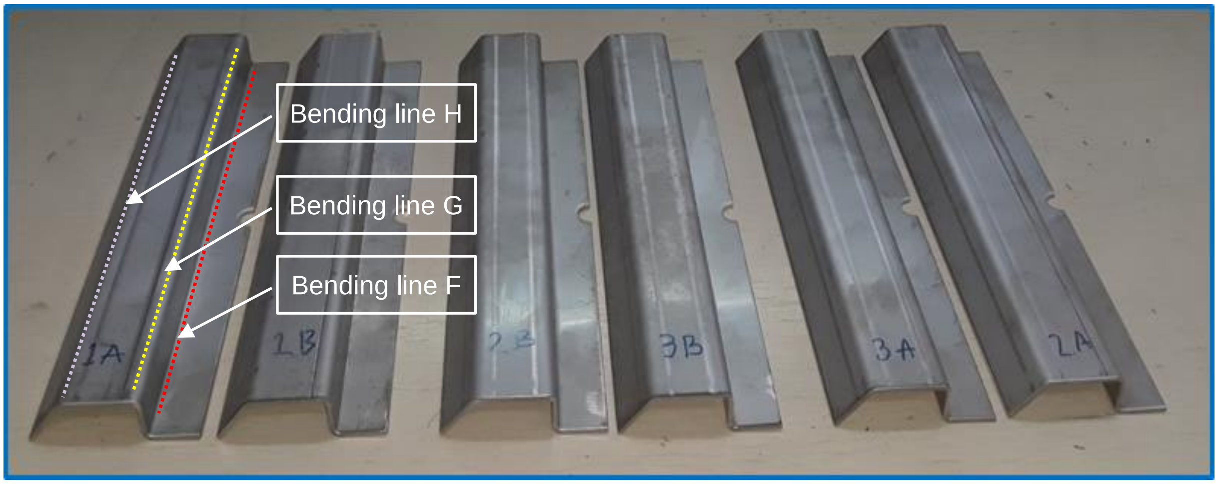


Figure 2 Six units' samples of HS-SUS 304

2.2 Force and Work Bending

The bending radius determines the quality of the bending process because it affects the product's quality. For example, a small bending radius often leads to cracking, and when the radius is too big, it results in wastage of materials. The V-die basically has a width of 49.1 mm, and its punch radius availability include 0.8, 1.0, and 1.2 mm. SKD 11 hardened material with a bending radius of 1.0 mm and 1.2 mm were used for V-die bending in this study as shown in Figure 3. It was observed that the punch does not align with the bending of the V-die, but was designed to achieve the application's greatest or smallest possible bending angle.

The bending radius therefore affected the dimensions and eventually led to the failure of the material (cracks). The bigger radius employed also affected the length of the material needed. This denoted that when a part has many flexure profiles, this condition tends to result in inefficiency of the material used. Therefore, the workpiece length and the blank material have to be controlled in order to determine the radius of the dies. It is important to note that a wrong application of a bending radius is able to affect the last dimension of a part and lead to the failure/crack of the material. To prevent these cases, a V-dies punch bending radius that is not too small need to be used. There is also a need to consider the material's thickness and mechanical properties, specifically tensile strength when determining the bending radius. The resources for calculating the minimum radius for materials with tensile strengths up to 640 N/m^2 are presented in Table 4 [16].

Bending force Fb (N) is generally calculated according to Equation (1) and (2) [17]:

for w/s ≥ 10:

$$F_b = \frac{b_s\, s^2 R_m}{w} \quad (1)$$

for w/s < 10:

$$F_b = \left(1 + \frac{4{,}s}{w}\right) \frac{b_s\, s^2 R_m}{w} \quad (2)$$

Where bs is described as the bending width (mm), w is described as the width of the V-Dies (mm), s is described as the thickness of the material (m), Rm is the tensile strength (N/mm2), and w is the width of the V-die opening. A safety factor of 20% was added from manual calculation to the actual force (F_a). Figure 3 provides the V-dies bending geometry and profile, while Figure 4 shows the force setting matrix in the hydraulic press bending machine.

Calculation of the bending work W_b (in N.m) as shown by the Equation 3 [12].

Table 4 Minimum bending radius (mm) for angles less than 120°

Tensile strength [N/mm2]	Bending Direction	Thickness material (s), mm				
		1.0	> 1 – 1.5	> 1.5 – 2.5	> 2.5 – 3.0	> 3.0 – 4.0
Up to	transverse	1.0	1.6	2.5	3.0	5.0
	longitudinal	1.0	1.6	2.5	3.0	6.0
>390 - 490	transverse	1.2	2.0	3.0	4.0	5.0
	longitudinal	1.2	2.0	3.0	4.0	6.0
400 - 640	transverse	1.6	2.5	4.0	5.0	6.0
	longitudinal	1.6	2.5	4.0	5.0	8.0

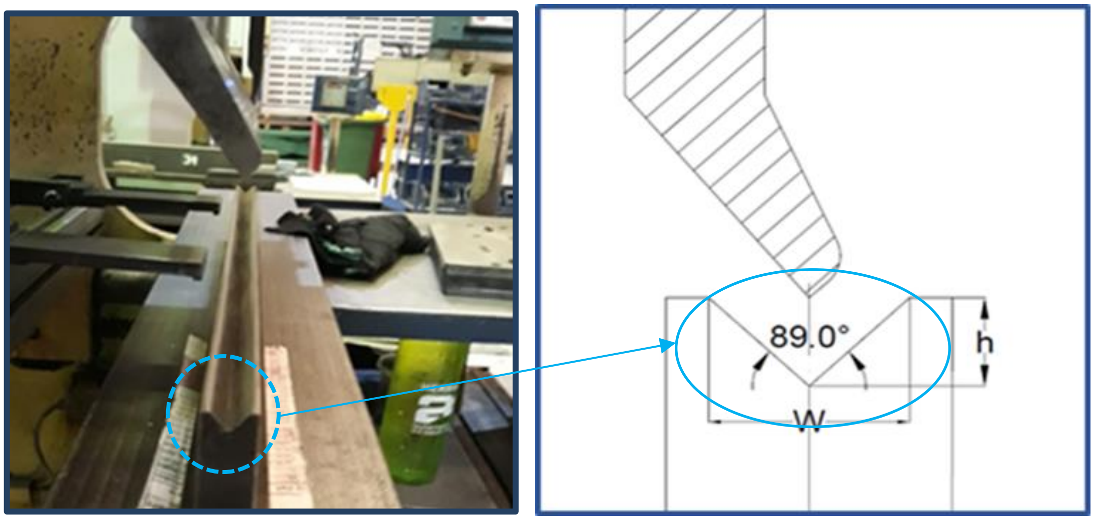


Figure 3 Dies Punch and V-Dies for the bending process

$$W_b = x.F_b.h \quad (3)$$

x is a force uneven constant whose value is between 0.3 and 0.6, The value of the inequality constant x depends on the bending and setting requirements of the bending machine. Meanwhile, w is the depth of the V-die bending in m.

Figure 4 The force setting matrix on a 400 kN of LVD hydraulic press bending machine

2.3 Spring-back Material

The degree of spring-back is a major issue in the metal forming process phenomenon using the cold method [17]. Spring-back occurs due to the influence of the material's elasticity at the time of formation, and its characteristics depends on the type of material used. It was found that Spring-back occurs in all material formation during bending, folding, roll forming, and roll bending processes [18], and affected geometric precision and dimensions. Another study discovered that this phenomenon such as wrinkle instability, are important for maintaining elasticity, increasing die and product costs, and lowering manufacturing efficiency [19]. The spring-back degree (Ø) is expressed as Equation 4 [20], [21].

$$\emptyset = \alpha_1 - \alpha_2 \quad (4)$$

The spring-back factor, kR is the ratio between the bending angle requested for dies (a1), and the bending angle that the workpiece has after spring-back (a2). The spring-back factor is expressed as Equation 5 [16], [17], [22].

$$k_R = \frac{\alpha_2}{\alpha_1} = \frac{r_{i1}+0{,}5s}{r_{i2}+0{,}5s} \quad (5)$$

Where r_{i1} and e r_{i2} are dies radius and workpiece measured in mm, respectively.

The value of the spring-back factor is between 0 and 1 ($0 \leq k_R \leq 1$). When the value of $k_R = 1$, it indicates that there is no spring-back on the material, but when $k_R = 0$, it means the material is perfectly elastic [22]. Table 5 shows the Spring-back factors for some of the materials [17].

Table 5 Spring-back factor for some material

Material	Spring-back facor, k_R	
	$r_{i2}/s = 1$	$R_{i2}/s = 10$
St 13	0.985	0.97
St 14	0.985	0.,96
High temperature ferritic steels	0.99	0.97
Stainless steel	0.96	0.92
High temperature austenitic steels	0.982	0.955
Al99 5F 7	0.99	0.96

The inner radius of the V-dies is calculated according to Equation 6 [17]:

$$r_{i1} = \frac{r_{i2}}{1+\frac{r_{i2}.Rm}{s.E}} \qquad (6)$$

R_m, s, r_{i2}, and E represent tensile strength (N/mm2), material thickness (mm), workpiece radius (mm), and modulus of elasticity (N/mm^2), respectively.

It was observed that the total length of the workpiece as a blank dimension to be bent was affected by the bending angle. This dimension is generally an indication of the expression in Equation 7 and 8 [12].

For the opening bending angle between 0°-165°,

$$l = a + b + v \qquad (7)$$

For the opening bending angle between 165°-180°,

$$l = a + b \qquad (8)$$

Where a and b represent the bending arm length (in mm) and the compensation factor, respectively. The compensation factor is calculated according to Equation 9 and 10) [17].

for β = 0°-90°.

$$v = \pi\left(\frac{180^o-\beta}{180^o}\right).\left(r+\frac{s}{2}.k\right) - z \qquad (9)$$

for β > 90° until 165°,

$$v = \pi\left(\frac{180^o-\beta}{180^o}\right)\left(r+\frac{s}{2}.k\right) - z.tan\emptyset \qquad (10)$$

where $\emptyset = \frac{180^o-\beta}{2}$, and $z = 2.(r+s)$

β represents the inner side bending angle (°)

v, is the compensation factor (mm)

l, is the component length (mm), *k* is the correction factor and its value depends on the r / s ratio as described in equations 11 and 12.

for r/s >5

$$k = 1 \qquad (11)$$

for r/s ≤5

$$k = 0{,}65 + \frac{1}{2}log\frac{r}{s} \qquad (12)$$

To ensure the validity of the data, all measuring equipment that was used has been calibrated as presented in Table 6.

The Spring-back phenomenon is presented in Figure 5. [17], [23]:

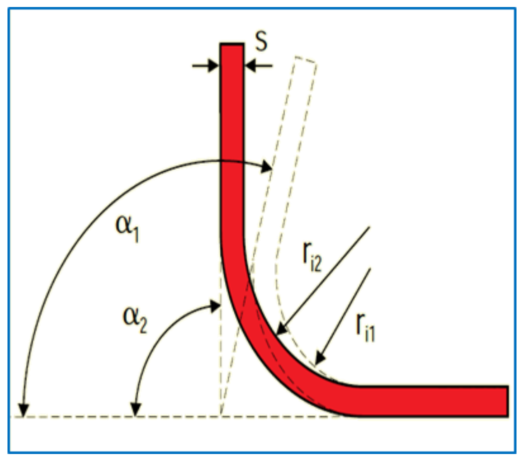


Figure 5 Material elasticity in the bending process

Table 6 Measuring instrument list

Parameters	Full scale	Accuracy
Vernier caliper, mm	200 and 300	0.01
Vernier caliper, mm	1000	0.05
Bevel Protector	-360°-360°	5'' (0.083°)
Bending Machine	400 kN	5 kN

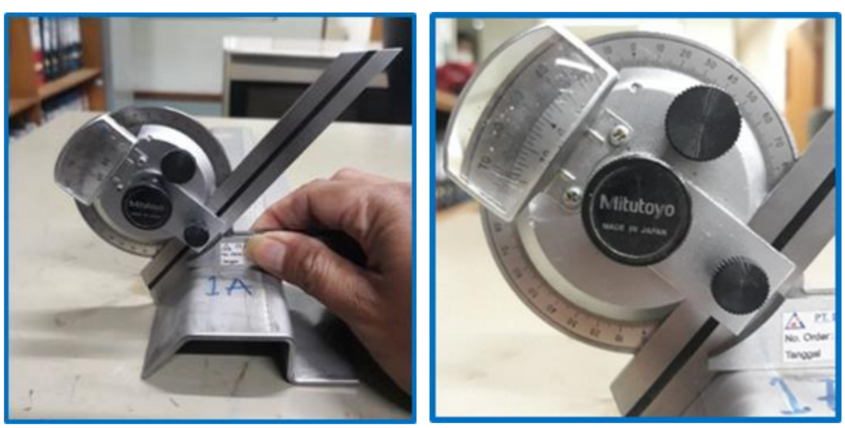


Figure 6 The process of measuring the degree of the samples

3.0 RESULTS AND DISCUSSION

3.1 Bending Force Analysis

Force and work were analyzed according to the bending lengths of F, G, and H, which were 320 mm. The bending process is applied longitudinally using 1.0 mm, and 1.2 mm in tip punches radius. HS-SUS 304 has a 3.0 mm thickness with a tensile strength of 615 MPa. The bending force requirement was calculated using Equation 1 (w/s > 10), and the work was calculated based on Equation 3. The V-Dies model had a bending depth of 23.8 mm, and the unevenness constant denoted as x was set at 1/3. The result of bending force at positions E, F, and G showed that b_s = 230 mm, the thickness of the material, s = 3.0 mm, Rm = 615 MPa (N/mm^2), and the width of the V-dies, w = 49.1 mm.

$$F_b = \frac{b_s\, s^2 R_m}{w}$$

$$= \frac{(320\; mm)(9.0\; mm^2\;)(\;615\frac{N}{mm^2})}{49.1\; mm}$$

$$= 35073.32N = 35.07\; kN$$

The bending machine was set to 40.0 kN based on the bending force calculation, while work bending was calculated at G position using Equation 3 with an uneven constant x = 1/3 and a depth of V-die, h = 0.0238 m.

$$W_b = x.F_b.h$$

$$= (0{,}3)(35.073{,}32\; N)(0{,}0238\; m)$$

$$= 250{,}42\; N.m = 85{,}95\; Joule$$

3.2 Spring-back Analysis

The HS-SUS 304 selected in this study provided spring-back factor at 0.96 as shown in Table 5. Furthermore, the boundary of the experiments was 1.5 mm bending radius, 3.0 mm material thickness, and the radius thickness ratio was $\frac{r_{12}}{s} < 1$, therefore a_1 was calculated based on Equation (4).

$$k_R = \frac{\alpha_2}{\alpha_1}\text{, and}\quad \alpha_1 = \frac{\alpha_2}{k_R}$$

for α_2= 90°

$$\alpha_1 = \frac{90^o}{0.96} = 93.75^o (\approx 93°45")$$

for α_2= 50°

$$\alpha_1 = \frac{50^o}{0.96} = 52.10^o\; (\approx 52°5")$$

Where α_1 represents the degree of the theoretical bending process, and was used to set up the CNC bending machine program.

Table 7 Bending angle result and actual Spring-back factor which $r_{i1} = 1.0\; mm$

Post	Standard	Bending Experimental result (α_2)			
		1A	2A	3A	Average
A	24.8 ±0.4	24.81	24.78	24.62	24.74
B	28.0 ±0.4	28.32	28.21	28.14	28.22
C	38.8 ±0,4	38.72	38.66	38.68	38.69
D	26.5 ±0,4	26.42	26.60	26.65	26.56
E	83.0 ±0,4	83.30	83.16	83.29	83.25
α_1	90.83°	90.08°	90.25°	90.17°	90.17°
α_2	90.83°	90.33°	90.17°	89.92°	90.08°
α_3	50.83°	49.92°	50.25°	49.83°	50.00°

All linear dimension in mm

Table 8 Bending angle result and actual Spring-back factor which $r_{i1} = 1.2\; mm$

Post	Standard	Bending Experimental result (α_2)			
		1B	2B	3B	Average
A	24.8 ±0.4	24.50	24.60	24.55	24.55
B	28.0 ±0.4	27.80	27.60	27.72	27.71
C	38.8 ±0,4	38.50	38.34	38.62	38.49
D	26.5 ±0,4	26.50	26.50	26.73	26.58
E	83.0 ±0,4	82.8	83.1	82.9	82.93
α_1	90.83°	90.50°	90.42°	90.25°	90.38°
α_2	90.83°	90.17°	90.42°	90°25°	90.2.7°
α_3	50.83°	50.08°	50.58°	50°25°	50.30°

All linear dimension in mm

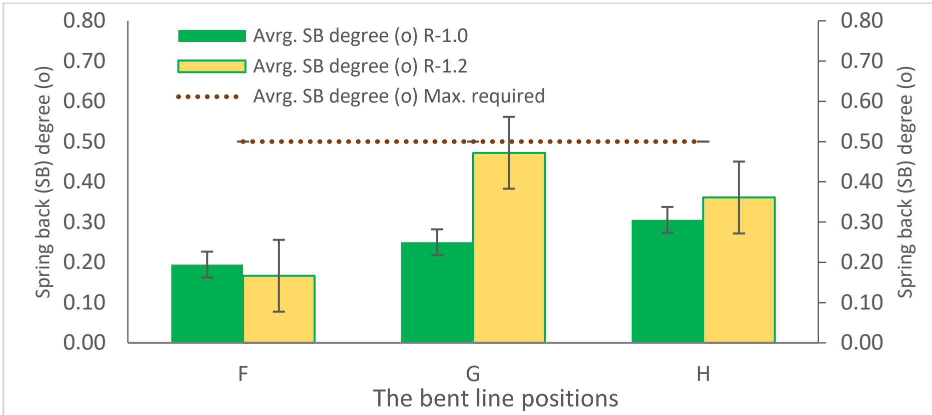


Figure 7 The average spring-back degree result

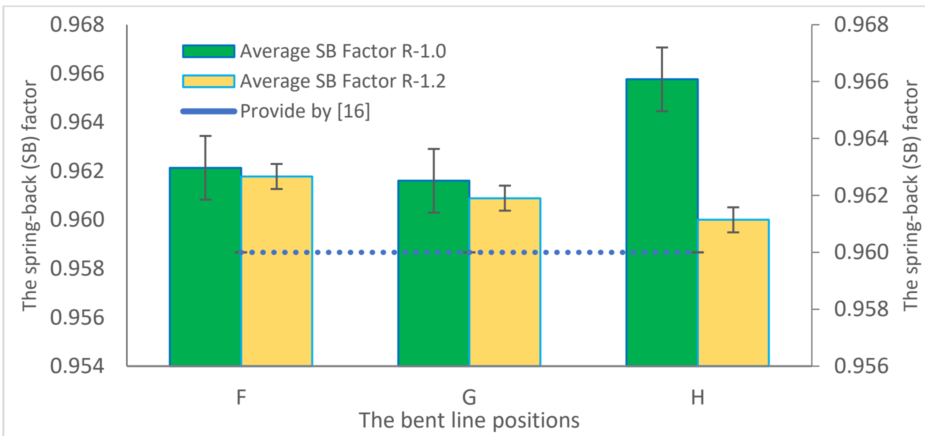


Figure 8 The average spring-back factor result

Tables 7 and 8 listed the results of the linear and angular dimensions. The bending radius of 1.0 mm and 1.2 mm was used during the plastic deformation, and the spring-back degree was calculated using equation 4. Figure 7 shows that the average spring-back degree when using the radius of the tip punch R1.0 was more precise than R1.2. This indicated that the radius of the punch was affected by the spring-back degree. It is therefore concluded that punch tip radius is an essential parameter in the V-bending manufacturing process [20][21].

The spring-back factor was calculated using equation 5 and the result was presented in Figure 8. It was observed that when radius of 1.0 mm was used, the spring-back factor results were 0.9618, 0.9609, and 0.9600 meanwhile, using a bending radius of 1.2 mm the results were 0.9641, 0.9634, and 0.9655. This experiment confirmed that the increase in tip punch radius affected the spring-back factor [19]. It was also observed that there were no cracks or other bending failures in the bending results when the radius was 1.0 and 1.2 mm. This is consistent with previous findings that a minimum bending radius for HS-SUS 304 from 2.66 to 5.0 mm at this thickness is 1.0 mm [18]. The average of the spring-back factors used for both of the tip radius punches has been compared with the theoretical bending [17], and a difference of 0.17 % to 0.60 % was discovered when 1.0 mm was used, while that of R1.2 was around 0.00%–0.19%.

3.3 Blank Dimensions Analysis

The calculation of absolute dimension length is essential for evaluating the accuracy of the bending radius used. The ratio of r/s (radius/thickness ratio) was 0.33 and 0.4. Equation 12 was therefore selected to evaluate the correction factor, k because the ratio of r/s was less than 5. The k factor data were obtained as follows.

$$k_{\alpha 1-320\,mm} = 0.65 + \frac{1}{2}.\log\left(\frac{1.0}{3}\right)$$
$$= 0.41$$

Equation 9 was used to determine the compensation factor (v) because the bending angle was required at 90°. The results of correction (k) and compensation factor (v) using 1.0 mm and 1.2 mm tip punch radius are shown in Table 9 and 10.

$$v_{\alpha 1-320\,mm} = \pi\frac{90}{180}\left(1+\frac{3}{2}.0.41\right) - \left((2)(1+3)\right) = \text{-5.37 mm}$$

Table 9 The value of k and v for $\frac{r}{s} = 0.33$ and $s = 3$

Parameters	Bending line		
	α_1 - 320 mm	α_2-320 mm	α_3-320 mm
β (°)	90	90	50
r/s	0.33	0.33	0.33
k	0.41	0.41	0.41
v (mm)	-5.37	-5.37	-2.27

Table 10 The value of k and v for $\frac{r}{s} = 0.4$ and $s = 3$

Parameters	Bending line position		
	α_1 - 320 mm	α_2-320 mm	α_3-320 mm
β (°)	90	90	50
r/s	1,3	1,3	1,3
k	0.71	0.71	0.71
v (mm)	-5.45	-5.45	-2.28

Equation 10 was used to determine the compensation factor (v) when the bending angle was required at 130° (180o-50o).

$$v_{\alpha 3-320\,mm} = \pi\frac{(180-50)}{180}\left(1+\frac{3}{2}.0.41\right)\text{-}(2(1{+}3)\tan\frac{(180-50)}{180})$$
= -2.27 mm

Equation 7 was selected to determine the required workpiece length (blank dimension) with a radius of 1.0 mm when the bending angle β was lower than 165o.

$$l = A + B + D + E + v$$
$$l = 24.8 + 28.0 + 38.8 + 26.5 - 5.45 - 5.45 - 2.2$$
$$l = 104.00\ mm$$

Furthermore, the same methodology was used to calculate the length of a workpiece with a tip bending radius of 1.2 mm.

$$l = A + B + D + E + v$$
$$l = 24.8 + 28.0 + 38.8 + 26.5 - 5.37 - 5.37 - 2.27$$
$$l = 105.09\ mm$$

It was observed that the bending result was closer to 105 mm than the comprehensive requirement by using a tip punch radius of 1.2 mm. The dimension deviation of the blank material used in this experiment was 0.09 mm. meanwhile, the result was 0.25 mm when a radius of 1.0 mm was used

4.0 CONCLUSION

The findings of this study indicate that the experimental setup used was sufficient, as the spring back value was directly proportional to the die-bending radius. It means that the bending radius significantly affects the blank length of the workpiece. The larger bending radius required more blank lengths for bent workpieces. This experiment was consistent with the existing theory that the compensation factor in the bending process is directly proportional to the V-dies punch radius. Further investigations need to be conducted and evaluated by providing several variations of the bending angle using HS-SUS 304 and a 2.5 mm thick stainless steel with multiple bending parameters included in finite element simulation.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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