Optimizing the Punch Parameters for V-Bending Stainless Steel Using Application Response Surface Methodology

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Optimizing the Punch Parameters for V-Bending Stainless Steel Using Application Response Surface Methodology

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Abstract - *Bending is a commonly applied metal processing technique in manufacturing. It involves technical issues during the bending process, including estimating springback and bending load. The experiment examines the springback and bending load responses on two steel plates of different thicknesses. It intends to evaluate the effects of different punch variables on springback and bending load and optimize its calculation to generate punch values with the lowest spring back and bending loads. The applied sheet plate thicknesses are 1 and 2 millimeters. The testing parameters were determined on each variable, such as punch angle (80, 85, and 90 degrees), punch radius (2, 4, and 6 millimeters), and punch travel (18.5, 19, and 19.5). The experiment employed Response Surface Methodology (RSM) to examine punch radius, angle, and travel, including the responses (springback and bending load). Hence, RSM aimed to optimize all the data to achieve the lowest possible springback and bending load. As a result, the springback and bending load can be determined based on punch variables. The test result values indicate that punch angle and travel have more impact on springback than punch radius. On the other hand, the punch angle and radius significantly impacted the bending load.*

Keywords: *Punch Parameters, V-Bending, Stainless Steel, Response Surface Methodology*

1. Introduction

Today, the manufacturing method of creating and producing metal plates is expanding significantly, particularly the bending technique. It is the curvature process of sheet plates with minimal, no alteration, damage in the surface area through the punch pressure and forming die. A straight bending line is produced in the bending operation by extending the neutral place axis along the bending area [1]. Manufacturing industries that use metal plates to make their goods or product components are triggered by the widespread use of metal technologies in society.

Bending is a manufacturing technique of altering the sheet plates on a press tool with a punch mechanism to form a shape based on the die. Hence, a stable stress-strain distribution is pivotal to producing perfect bending shapes as desired by the manufacturers. However, the bent material stretches back to its initial shape when the load is released, called springback phenomenon [2]. Several aspects can affect the springback results during the bending operation, such as punch and die angle, radius, clearance, material thickness, friction conditions (both static and dynamic), material size, and modulus elasticity. Finite element analysis and tests are employed to characterize springback behavior and determine the optimal process parameters [3].

Springback occurs when the punch is lifted and the bending load is reduced [4]. When the material is bent, the resulting shape is not always the same as the punch and die shape. Several studies have been conducted on the topic, including one on producing a basic press tool for V-bottom bending in mild carbon steel. This tool features V-shaped dies and a punch. This instrument has a springback of more than 90 degrees in most cases. It is designed for a small-scale V-bending experiment in the lab [5, 6].

The plastic deformation of the blank that occurs during the bending of sheet metal results in enduring modifications and the formation of bends in the originally straight sheet. Sheet metal bending processes can be categorized into four main types: air bending, edge bending, rotary bending, and V-bending [7]. In V-bending, the bending uses a convex punch a v-shaped concave die. Although several researchers have studied springback on stainless steel plates, little evidence addresses how effect of current density and current duration on springback in bending [8], how predict the springback in V-bending using analytical and numerical [9], how effects of grain size and strain gradient to analyze microscale bending behavior and calculate springback angles [10], and how the punch and die radius impact springback in air V-die bending [11]. In addition, research related to process parameters in springback is still lacking. There are several researchers who have investigated springback using the design of experiment (DOE) method [12-15]. In this paper, the full factorial method and analysis of variance (ANOVA) in DOE is used to examine the importance of process parameters, including punch and die radii, and bending loads, in relation to springback.

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In light of the issues mentioned previously, the experiment aims to improve the model to create a more precise sheet plate bending tool (the press tool). It aims to design and build a well-performed press tooling structure and produce more precise bending shapes. Additionally, the influence of punch specifications on springback and bending loads is examined in this experiment. After that, a technique for optimization is performed to achieve punch parameters that create the least amount of springback and the smallest amount of bending force. Hence, sheet plates are frequently made of stainless steel, a common material utilized in the transportation and household products industries.

II. Springback

During the experiment, springback is one of the phenomena that can occur during the process. It occurs due to the influence of several parameters with several angle variations, such as punch and die radius, die gap and punch travel [16]. General bending of sheet metal is performed by creating a V-shape [13] and channel shape (U shape)[17] utilizing a single-forming axis model. The accurate assessment of springback is fundamental for equipment design and product durability [18]. It is possible to get significant reductions in springback by performing the bending technique by compressing the plate between the punch and die. Although it happens in all bending operations, the bending effect is the most easily measurable. The measurement is given through equations 1 and 2 below [7].

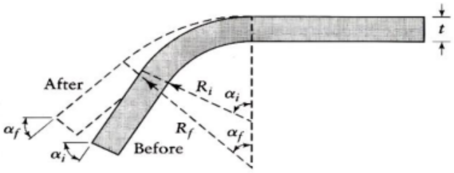


Fig. 1. The measurement of the springback effect during the bending operation

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1 \quad (1)$$

$$\frac{\alpha_f}{\alpha_i} = \frac{\left(\frac{2R_i}{T}\right)+1}{\left(\frac{2R_f}{T}\right)+1} \quad (2)$$

Where α_f represents the plate angle (°), α_i represents the die angle (°), and R_f represents the plate radius, R_i represents the punch radius, yield strength is given by Y(N/mm^2), E represents modulus elasticity (MPa), and T represents the material thickness (mm).

III. Experimental setup

The experiments were conducted at a vocational higher education institution in Indonesia, specifically in the mechanic's laboratory, the school of mechanical engineering. The experiment's equipment is as follows:

- A press equipment set (see Figure 2)
- A die set with varying angles and diameters. (see Figure 3).
- A Galdabini PM 100 Universal Testing Machine (UTM) (see Figure 4)

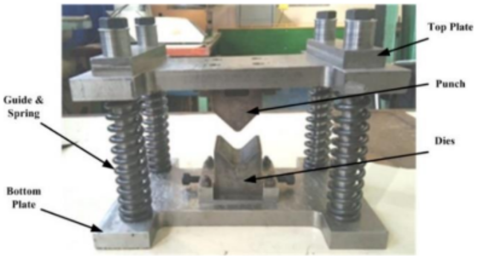


Fig. 2. A Press Equipment Set

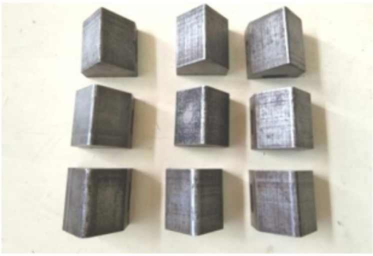


Fig. 3. A die set with varying angles and diameters

Fig. 4. Universal Testing Machine (UTM)

The research specimens are 1-millimeter and 2-millimeter stainless steel plates. In this study, the thickness of the plate has been adjusted to the size of the punch and dies used. Therefore, the measurement method involves varied punch angles, radius, travel, and test specimen. Hence, the punch angle variations are set for 80°, 85°, and 90°. The punch radius variations are set for 2, 4, and 6 millimeters, while the punch travel varies between 18.5, 19 and 19.5 inches. The test sample dimensions are 100 x 50 millimeters, with equivalent thicknesses of 1 and 2 millimeters. The composition of the parameter is determined to optimize the operation, as presented in Table 1 below.

TABLE I
PROCESS PARAMETERS WERE USED

Parameters	Levels		
	Low (-1)	Center (0)	High (+1)
Punch Radius (mm)	2	4	6
Punch Angle (°)	80	85	90
Punch Travel (mm)	18.5	19.0	19.5

The experimental plan was developed using the Design-Expert software version 6.0.5 [19]. The observation data for each response was repeated three times for each parameter.

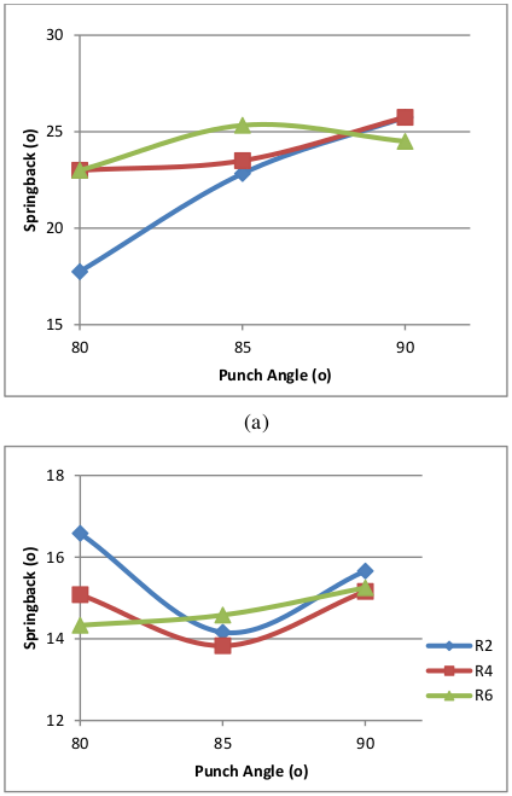
IV. Result and Discussions

IV.1. Punch Parameters' Effects on Springback

Table 2 displays the springback records derived from the bending experiments results on two different thicknesses of sheet plates. The springback data shown in Table 2 is the average data from three repetitions of springback measurements.

As depicted in Figure 5, springback records from the V-bending test of sheet plates are illustrated to analyze the relationship between springback and punch angle. Figure 5 demonstrates that the springback angle recorded at a 1-millimeters plate is proportional to the punch angle given, with the springback angle increasing as the punch angle increases. For a 1-millimeter sheet plate with punch angle values of 80°, 85°, and 90°, the springback values indicate 19.19°, 22.22°, and 21.83 ° for a 2° radius, and 20.5°, 22.97°, 23.75 ° for 4° radius, and 21.61°, 23°, 22.97° for 6° radius.

Moreover, a punch test on the angle of 85° produces the minimum springback at a 2-millimeter plate. The test angle of 80°, 85°, and 90°, the springback values consecutively indicate 15.05°, 13.44° and 13.94° for a 2° radius, 13.75°, 12.28°, and 14.91° for a 4° radius, and of 13.66°, 11.86°, 12.3° for a 6° radius. The experiment results are generally aligned with previous research examining the impact of punch and die radius on stainless steel springback [11]. It was discovered that punch radius emerged as a major variable impacting the springback responses in V-die sheet plate bending. A case of testing a metallic sheet in V-shaped air bending discovered that the plate's characteristics significantly impact the bending process and the precise estimation of spring using FE analysis [20]. For example, the punch travel effect researched by [21] discovered that changes in the variable with a quasistatic value are affected by punch travel and will impact its operations. This metamodel allows the researchers to construct the correction factors.



(a)

(b)

Fig. 5. Reverse graphic for distinct punch radius and angle for 1-mm (a) and 2-mm (b)

TABLE II.
SPRINGBACK RESPONSES AS PER PUNCH PARAMETERS

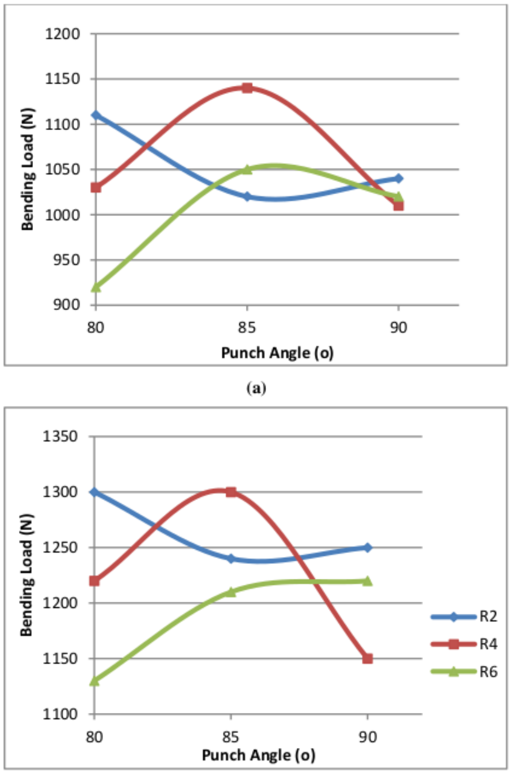
Punch Angle (°)	**Punch Radius (mm)**	**Springback (°)**							
		The thickness of 1 millimeter				**The thickness of 2 millimeters**			
		Punch Travel 18.50	**Punch Travel 19.00**	**Punch Travel 19.50**	**Average**	**Punch Travel 18.50**	**Punch Travel 19.00**	**Punch Travel 19.50**	**Average**
	2	17.75	19.00	20.83	19.19	16.58	14.25	14.33	15.05
80	4	23.00	19.16	19.33	20.50	15.08	13.16	13.00	13.75
	6	23.00	21.33	20.5	21.61	14.33	14.25	12.41	13.66
	2	22.83	22.66	21.16	22.22	14.16	13.25	12.91	13.44
85	4	23.5	23.25	22.16	22.97	13.83	11.25	11.75	12.28
	6	25.33	22.58	21.08	23.00	14.58	10.66	10.33	11.86
	2	25.75	18.33	21.41	21.83	15.66	14.16	12.00	13.94
90	4	25.25	22.41	23.58	23.75	15.16	16.25	13.33	14.91
	6	24.5	23.08	21.33	22.97	15.25	12.5	9.16	12.30

TABLE III.
RESULTS FOR BENDING LOAD BASED ON PUNCH PARAMETERS

Punch Angle (°)	Punch Radius (mm)	Bending Load (N)							
		The thickness of 1 millimeter				The thickness of 2 millimeters			
		Punch Travel 18.5	Punch Travel 19	Punch Travel 19.5	Average	Punch Travel 18.5	Punch Travel 19	Punch Travel 19.5	Average
80	2	1110	1150	1250	1170.00	1300	1310	1300	1303.33
	4	1030	1060	1050	1046.67	1220	1240	1310	1256.67
	6	920	940	950	936.67	1130	1130	1200	1153.33
85	2	1020	1030	1060	1036.67	1240	1290	1290	1273.33
	4	1140	1140	1160	1146.67	1300	1400	1450	1383.33
	6	1050	1070	1070	1063.33	1210	1240	1260	1236.67
90	2	1040	1040	1060	1046.67	1250	1290	1370	1303.33
	4	1010	1020	1020	1016.67	1150	1200	1260	1203.33
	6	1020	1040	1050	1036.67	1220	1350	1630	1400.00

IV.2. Impact of Punch Variables on Bending Load

Table 3 displays the bending force information derived from stainless steel bending test results. The bending load data shown in Table 3 is the average data from three repetitions of bending load. As depicted in Figure 6, the data from the V-bending test results on sheet plates are presented through an infographic diagram to see how bending force relates to the punch angle.



(a)

(b)

Fig. 6. The springback illustration of punch radius and angle for 1-mm (a) and 2-mm (b)

Figure 6 illustrates the bending load effects of varied punch radius and angles. The load value indicates 1170 N, 1036.67 N, and 1036.67° for a 2° radius, while 1046.67 N, 1146.67, 1016.67 for a 4° radius, and the load value indicates 936.67 N, 1063.33 N, 1036.67 N for a 6° radius on a 1-millimeter plate with the angle values are 80°, 85°, 90°. While the 2-millimeter plate with the angle values of 80°, 85°, and 90°, the load value shows 1303.33 N, 1273.33 N, and 1236.67° for 2° radius, then 1256.67 N, 1383.33, 1203.33 for 4° radius, and 1153.33 N, 1236.67 N, 1400 N for a 6° radius.

In [22] asserted that punch variations influence the different values of the bending load. The variables (die angles, die widths, and punch radius) are reported to affect the springback and bending load differently.

IV.3. Effect of Material Thickness on Springback and Bending Load

Figure 7 presents the effect of material or sheet plate thickness on both springback and bending load based on previously presented data. Figure 7 demonstrates that the influence of material size variations in springback responses and bending loads values is insignificant on 1- and 2-millimeter thickness plates.

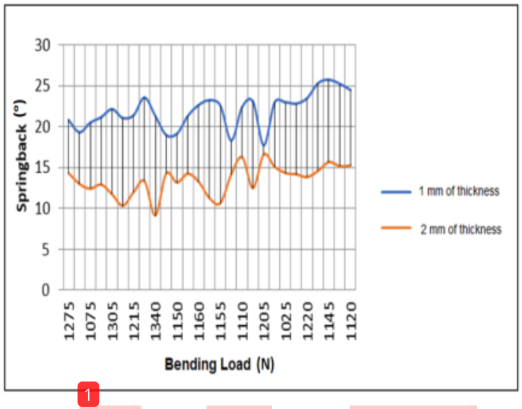


Fig. 7. Effect of material thickness variations on springback and bending load

IV.4. The Process of Optimization

The RSM was performed to optimize the test results data using Design-Expert Software. DoE data analysis will aid in assessing the input and response data collected, producing a formula for determining the magnitude of the response and enabling the determination of the optimal results. Scholars also use this application to calculate the energy usage of the metal bending operation [23] and 316L sheet plate [24]. Furthermore, the optimization results via DoE analysis are as follows.

Using the software mentioned earlier and the RSM, the punch angle and radius variance were analyzed. The analysis of variance (ANOVA) on the two variables is presented in Table 4 (springback) and Table 5 (bending load):

TABLE IV.
ANOVA FOR RESPONSE SURFACE REDUCED LINEAR MODEL FOR SPRINGBACK

Source	Sum of Square	DoF	Mean Squares	F Value	Prob > F	
Model	49.77	2	24.88	8.66	0.0015	significant
A	22.29	1	22.29	7.76	0.0103	
B	27.48	1	27.48	9.56	0.0050	
Residual	68.96	24	2.87			
Cor Total	118.72	26				
Std. Dev.	1.70		R^2	0.4192		
Mean	22.02		Adj R^2	0.3708		

TABLE V.
ANOVA FOR RESPONSE SURFACE REDUCED 2FI MODEL FOR BENDING LOAD

Source	Sum of Square	DoF	Mean Squares	F Value	Prob > F	
Model	79772.22	3	26590.74	12.82	< 0.0001	significant
B	1422.22	1	1422.22	0.69	0.4161	
C	42050.00	1	42050.00	20.28	0.0002	
BC	36300.00	1	36300.00	17.51	0.0004	
Residual	47694.44	23	2073.67			
Cor Total	1.275E+05	26				
Std. Dev.	45.54		R^2	0.6258		
Mean	1055.56		Adj R^2	0.5770		

The DoE analysis yields an equation for springback (Equation 3) and bending load (Equation 4).

$$\text{Springback} = +43.30 - 2.23 * \text{Punch Travel} + 0.25 * \text{Punch Angle} \tag{3}$$

$$\text{Bending Load} = +3173.33 - 23.78 * \text{Punch Angle} - 491.67 * \text{Punch Radius} + 5.50 * \text{Punch Angle} * \text{Punch Radius} \tag{4}$$

Equation 3 indicates that punch angle has a more substantial effect on springback than punch travel. In Equation 3, the punch variables (travel and angle) are essential to determine the expected springback. While Equation 4 showed that punch variables (angle and radius) affected the bending load, which can be determined by combining equation 4 and punch variables (angle and radius). As illustrated in Figures 8 and 9, the DoE analysis shows the 3D contours of springback and bending load data models.

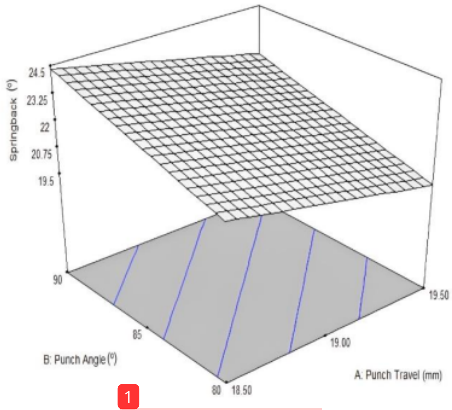


Fig. 8. 3D contour for springback

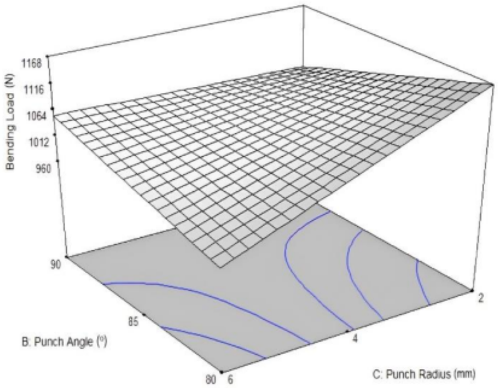


Fig. 9. 3D contour for bending load

In addition, a process of optimization will be processed from the raw data (i.e., punch radius, angle, and travel) to the springback and bending load data. As seen in Figure 10, the greatest prediction of RSM is 0.82, which provides a broad overview of the value of input and response data.

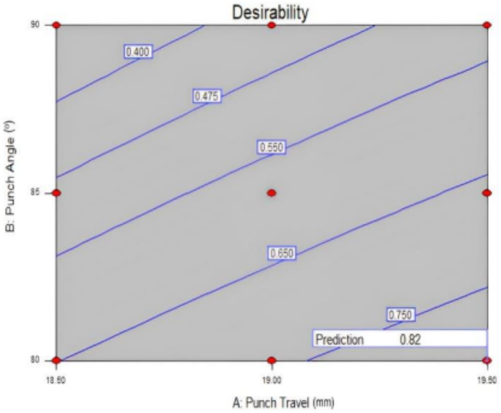


Fig. 10. Desirability after optimizing the data

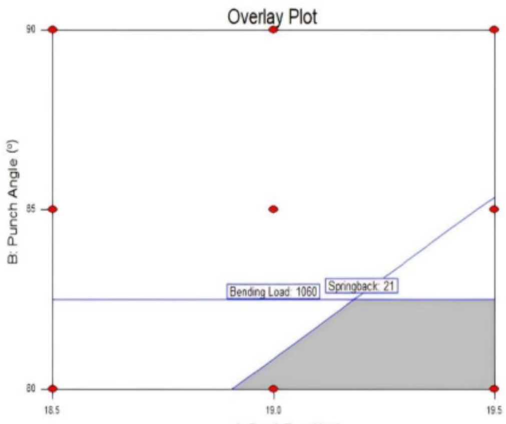


Fig. 11. Punch variables optimization to minimize the springback (maximum of 21°) and the bending load (maximum of 1060 N)

The process of graphic optimization involves constructing an overlay plot by combining the contours of various response surfaces, as shown in Figure 11. The shaded area within the overlay plot indicates the range of acceptable values for the dependent variables, serving as a constraint for all desired outcomes. Specifically, in this instance, the objective was to determine the feasible range for the process settings, ensuring that the springback remains at or above 21 degrees and the bending load stays below 1060 N.

IV.5. The Confirmation Analysis

As before, numerous information runs have been conducted to assess the adequacy of the generated models (Equations 3 and 4). The results of the point prediction function are presented in Table 6.

TABLE VI.
POINT PREDICTION FUNCTION

Factor	Name	Level	Low Level	High Level	Std. Dev.		
A	*Punch Radius*	4	2	6	0.000		
B	*Punch Angle*	85	80	90	0.000		
C	*Punch Travel*	19.00	18.50	19.50	0.000		
	Prediction	SE Mean	95% CI low	95% CI high	SE Pred	95% PI low	95% PI high
Springback	6.496	0.66	5.15	7.84	2.54	1.29	11.70
Bending Load	129.91	1.57	126.68	133.14	9.04	111.35	148.46

The predicted value, the actual experiment, the residual and percentage error are presented in Tables 7 and 8. The percentage error range between the actual and predicted values for the springback, and bending load are as follow:

Springback	~ -1.99 to -3.18 %
Bending Load	~ 2.291 to 3.81 %

The accuracy of the empirical models developed can be substantiated. This was confirmed by the fact that all actual results from the confirmation run fell within the 95 percent prediction interval (PI), which represents the range within which any given value is predicted to fall 95% of the time.

TABLE VII.
CONFIRMATION ANALYSIS OF EXPERIMENTS FOR SPRINGBACK

Responses		Springback (°)			
Punch Travel (mm)	*Punch Angle (°)*	Actual	Predicted	Difference	% Error
19	82	21.01	21.43	-0.42	-1.99
19	87	21.98	22.68	-0.70	-3.18

TABLE VIII.
CONFIRMATION ANALYSIS OF EXPERIMENTS FOR BENDING LOAD

Responses		Bending Load (N)			
Punch Radius (mm)	*Punch Angle (°)*	Actual	Predicted	Difference	% Error
3	82	1145	1101.36	43.64	3.81
3	87	1090	1064.96	25.04	2.29

In order to minimize springback in the V-bending plate process, several things can be analyzed, such as: design of punch and die using Finite Element Analysis (FEA) [25, 26], thickness, width, bend angle parameters [27], and temperature factor when heating during bending [28].

V. Conclusions

Results from a V-bending test performed on stainless steel and analyzed with the RSM technique lead to several implications as follows, Punch angle and travel parameters significantly contribute to springback, while angle and radius are both associated with the bending load. The RSM and DoE analysis are the two approaches performing precise analysis for best bending outcomes. Mathematical models developed to predict the various punch parameters are statistically valid for all of thickness plate. The study suggests a further work to investigate a wider range of plate dimensions, both size and thickness. Die sets, which may be used to mass-produce several kinds of plates, are ready for patent protection and commercialization at the medium-industrial level.

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