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

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Abstract – *Bending is a widely employed metal processing technique in manufacturing, presenting various technical challenges during the process, including the estimation of springback and bending load. In this experiment, the authors investigate the springback and bending load responses on two steel plates with different thicknesses to understand how variations in plate thickness impact these mechanical behaviors. The primary objective is to assess the effects of various punch variables on springback and bending load, aiming to optimize their calculation and yield punch values with the least springback and bending loads. This investigation involves sheet plate thicknesses of 1 and 2 millimeters. The testing parameters were defined for each variable, including punch angle (80, 85, and 90 degrees), punch radius (2, 4, and 6 millimeters), and punch travel (18.5, 19, and 19.5 millimeters). In the experiment, Response Surface Methodology (RSM) was employed to analyze punch radius, angle, and travel, in conjunction with the corresponding responses (springback and bending load). The application of RSM aimed to systematically optimize all collected data with the ultimate goal of achieving the lowest possible springback and bending load. Consequently, the determination of springback and bending load relies on the analysis of various punch variables. The test results indicate that punch angle and travel have a more pronounced impact on springback than punch radius, while conversely, punch angle and radius significantly influence the bending load.*

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

Nomenclature

ANOVA	Analysis of Variance
DoE	Design of Experiment
E	Modulus elasticity
FE	Finite Element analysis
PI	Prediction Interval
R_f	Plate radius
R_i	Punch radius
RSM	Response Surface Methodology
T	Material thickness
UTM	Universal Testing Machine
Y	Yield strength
α_f	Plate angle
α_i	Die angle

I. Introduction

Today, the manufacturing method for creating and producing metal plates is expanding significantly, with a particular emphasis on the bending technique. This technique involves curving sheet plates with minimal to no alteration or damage to the surface area through punch pressure and a forming die. In the bending operation, a straight bending line is produced by extending the neutral plane axis along the bending area [1], [2]. The manufacturing industries that utilize metal plates for crafting their goods or product components are propelled by the widespread adoption of metal technologies in society. The manufacturing industries that utilize metal plates for crafting their goods or product components are driven by the widespread adoption of metal technologies in society.

Consequently, achieving a stable stress-strain distribution becomes crucial for producing perfect bending shapes as desired by manufacturers. However, when the load is released, the bent material tends to stretch back to its initial shape, and this behavior is referred to as the springback phenomenon [3]. Several aspects can affect the springback results during the bending operation, including punch and die angle, radius, clearance, material thickness, friction conditions (both static and dynamic), material size, and modulus of elasticity. Finite Element (FE) analysis and physical tests are employed to characterize springback behavior and determine the optimal process parameters [4]-[6]. Springback occurs when the punch is lifted, and the bending load is reduced [7].

This phenomenon is characterized by the material returning to its original shape or undergoing elastic recovery upon the release of the applied load. While bending, the resulting shape may not always precisely match the punch and die shape. This discrepancy, known as springback, refers to the material's tendency to partially revert to its original form after the bending process.

Numerous studies have delved into this phenomenon, with one specifically focusing on producing a basic press tool for V-bottom bending in mild carbon steel. This tool, featuring V-shaped dies and a punch, is designed for a small-scale V-bending experiment in the lab and exhibits a springback of more than 90 degrees in most cases [8], [9].

The plastic deformation of the blank during sheet metal bending results in enduring modifications and the formation of bends in the originally straight sheet. This process is integral to shaping the material into the desired form for various applications. Sheet metal bending processes can be categorized into four main types: air bending, where the material is bent using a punch and die without touching the tool; edge bending, where the material is bent along the edge of a die; rotary bending, involving the rotation of the material around a central axis; and V-bending, which uses a V-shaped die and punch [10].

In V-bending, the process involves using a convex punch and a V-shaped concave die for bending. While several researchers have studied springback on stainless steel plates, there is limited evidence addressing the effects of current density and current duration on springback in bending [11]. Additionally, there is research on predicting springback in V-bending using analytical and numerical methods [12]. Other studies investigate the effects of grain size and strain gradient to analyze microscale bending behavior and calculate springback angles [13]. There is also research on how the punch and die radius impact springback in air V-die bending [14].

Furthermore, a lack of research related to process parameters in springback exists. Investigating the influence of specific process parameters on springback behavior is an essential aspect that requires further attention in the existing body of literature. Several researchers have investigated springback using the Design of Experiment (DoE) method, as evidenced by studies documented in [15]-[18]. This methodology allows for a systematic exploration of various factors and their interactions in the bending process, providing valuable insights into the springback phenomenon. In this paper, the full factorial method and Analysis of Variance (ANOVA) in DoE are employed to examine the significance of various process parameters. Specifically, the focus is on investigating the impact of punch and die radii, as well as bending loads, in relation to the occurrence of springback during the bending process. In response to the previously highlighted issues, the experiment aims to refine the model for creating a more precise sheet plate bending tool, commonly known as the press tool. The objective is to enhance the tool's accuracy and performance, addressing challenges related to springback and bending load. Ultimately, this initiative seeks to offer manufacturers a more efficient and reliable solution for sheet metal bending. The experiment focuses on designing and constructing a high-performance press tooling structure with the goal of achieving more precise bending shapes. Emphasizing the enhancement of the press tool's structural design aims to deliver superior accuracy and efficiency during the sheet metal bending process. Additionally, the study explores the influence of punch specifications on springback and bending loads. By systematically varying punch parameters, including punch angle, radius, and travel, the aim is to comprehensively understand their impact on the bending process and optimize these specifications for reduced springback and bending loads. Subsequently, an optimization technique is employed to achieve punch parameters resulting in the least amount of springback and the smallest bending force.

This optimization process involves systematically adjusting punch specifications, utilizing methods such as Response Surface Methodology (RSM) or other optimization algorithms, with the ultimate goal of enhancing the precision and efficiency of the sheet metal bending process. Moreover, sheet plates are commonly made of stainless steel, a widely used material in the transportation and household products industries.

Stainless steel's durability, corrosion resistance, and versatility make it a popular choice for manufacturing various components, contributing to its prevalent use in diverse industrial applications.

This paper is divided into several sections. Section II offers a general overview of springback phenomena, while Section III explains the experimental setup for this research. In Section IV, the authors present the research and engage in discussion, while Section V delves into research conclusions.

II. Springback

During the experiment, springback is a phenomenon that can occur in the process. It arises due to the influence of several parameters with varying angles, such as punch and die radius, die gap, and punch travel [19]. General sheet metal bending is accomplished by creating V-shapes [16] and channel shapes (U-shapes) [20], utilizing a single-forming axis model. The accurate assessment of springback is fundamental for equipment design and ensures product durability [21]. Significant reductions in springback can be achieved by compressing the plate between the punch and die during the bending technique.

While the bending effect occurs in all bending operations, it is most easily measurable through Equations (1) and (2) below [22]:

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

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

where α_f represents the plate angle (°), α_i represents the die angle (°), R_f represents the plate radius, R_i represents the punch radius, Y is the yield strength (N/mm²), E represents the modulus of 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 at the school of mechanical engineering. The equipment used in the experiment included:

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

The research specimens are 1-millimeter and 2-millimeter stainless steel plates. In this study, the thickness of the plates has been adjusted to match the size of the punches and dies used.

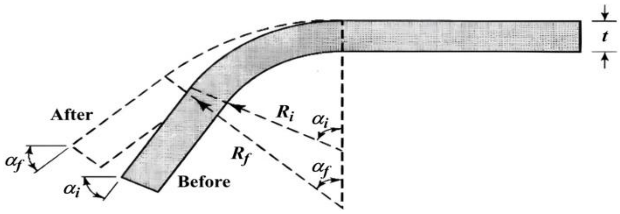


Fig. 1. The measurement of the springback effectt during the bending operation

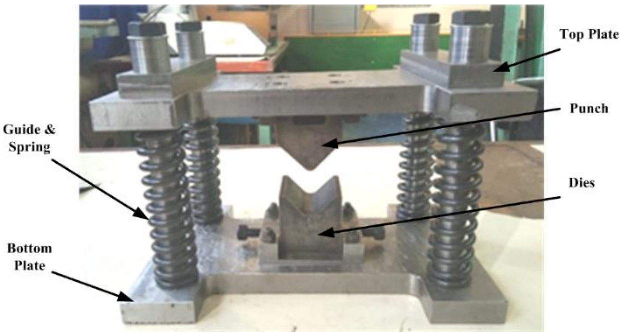


Fig. 2. A Press Equipment Set

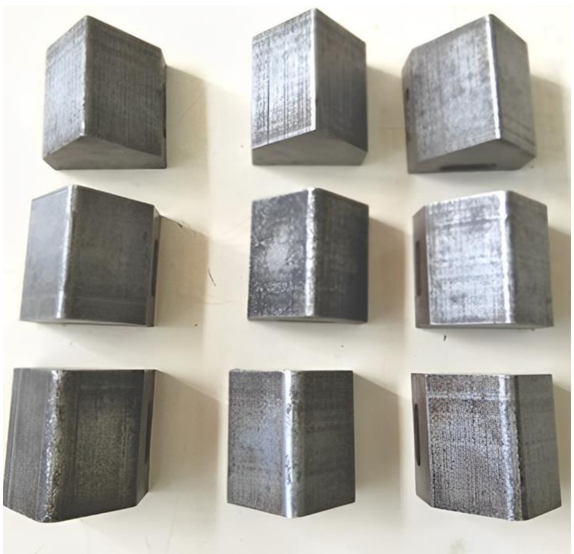


Fig. 3. A die set with varying angles and diameters

Fig. 4. Universal Testing Machine (UTM)

Therefore, the measurement method involves varied punch angles, radii, travel, and test specimens. The punch angle variations are set at 80°, 85°, and 90°. The punch radius variations are set at 2, 4, and 6 millimeters, while the punch travel varies between 18.5, 19, and 19.5 inches.

The test sample dimensions are 100 × 50 millimeters, with equivalent thicknesses of 1 and 2 millimeters. The parameter composition is determined to optimize the operation, as presented in Table I. The experimental plan was developed using Design-Expert software version 6.0.5 [23]. The observation data for each response were repeated three times for each parameter.

IV. Result and Discussions

IV.1. Punch Parameters' Effects on Springback

Table II presents the springback records obtained from the bending experiment results on sheet plates with two different thicknesses. The springback data, shown in Table II, represent the average values derived from three repetitions of springback measurements. As illustrated in Figures 5, springback records from the V-bending test of sheet plates are presented to analyze the relationship between springback and punch angle. Figures 5 demonstrate that the springback angle recorded for a 1-millimeter plate is proportional to the given punch angle, with the springback angle increasing as the punch angle increases.

TABLE I
PROCESS PARAMETERS

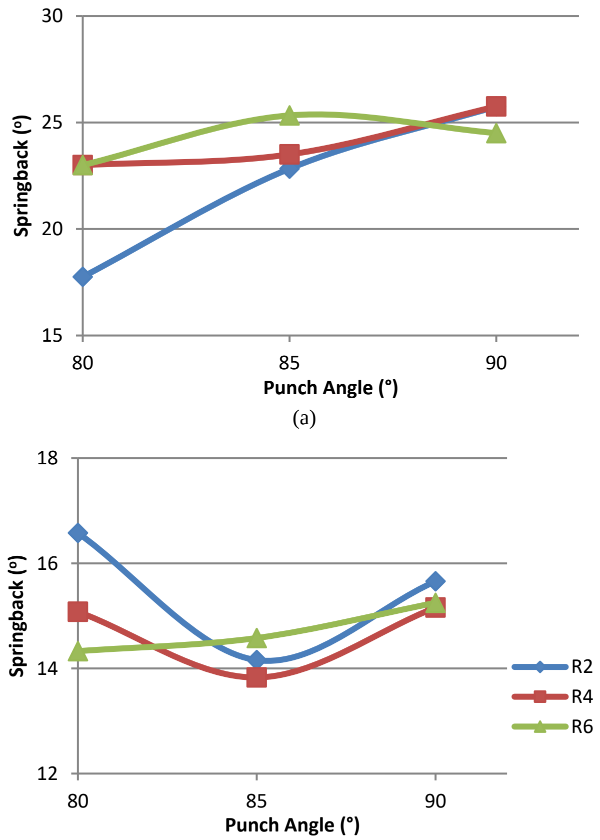
Parameters	Levels Low (-1)	Center (0)	High (+1)
Punch Radius (mm)	2	4	6
Punch Angle (°)	80	85	90
Punch Travel (mm)	18.5	19.0	19.5

For a 1-millimeter sheet plate with punch angle values of 80°, 85°, and 90°, the corresponding springback values are 19.19°, 22.22°, and 21.83° for a 2° radius, 20.5°, 22.97°, and 23.75° for a 4° radius, and 21.61°, 23°, and 22.97° for a 6° radius. Moreover, a punch test at the angle of 85° produces the minimum springback for a 2-millimeter plate. For the test angles of 80°, 85°, and 90°, the consecutive springback values are 15.05°, 13.44°, and 13.94° for a 2° radius, 13.75°, 12.28°, and 14.91° for a 4° radius, and 13.66°, 11.86°, and 12.3° for a 6° radius. The experimental results are generally aligned with previous research examining the impact of punch and die radius on stainless steel springback [14]. It was discovered that punch radius emerged as a major variable influencing the springback responses in V-die sheet plate bending. A case study testing a metallic sheet in V-shaped air bending discovered that the plate's characteristics significantly impact the bending process and the accurate estimation of spring using FE analysis [24]. For instance, the punch travel effect, as researched by [25], revealed that changes in the variable with a quasi-static value are influenced by punch travel and will affect its operations. This metamodel enables researchers to construct correction factors.

IV.2. Impact of Punch Variables on Bending Load

Table III presents the bending force data obtained from stainless steel bending test results. The bending load information in Table III represents the average values from three repetitions of the bending load tests.

Additionally, Figures 6 illustrate the data from the V-bending test results on sheet plates through an infographic diagram, demonstrating the relationship between bending force and punch angle.



(a)

(b)

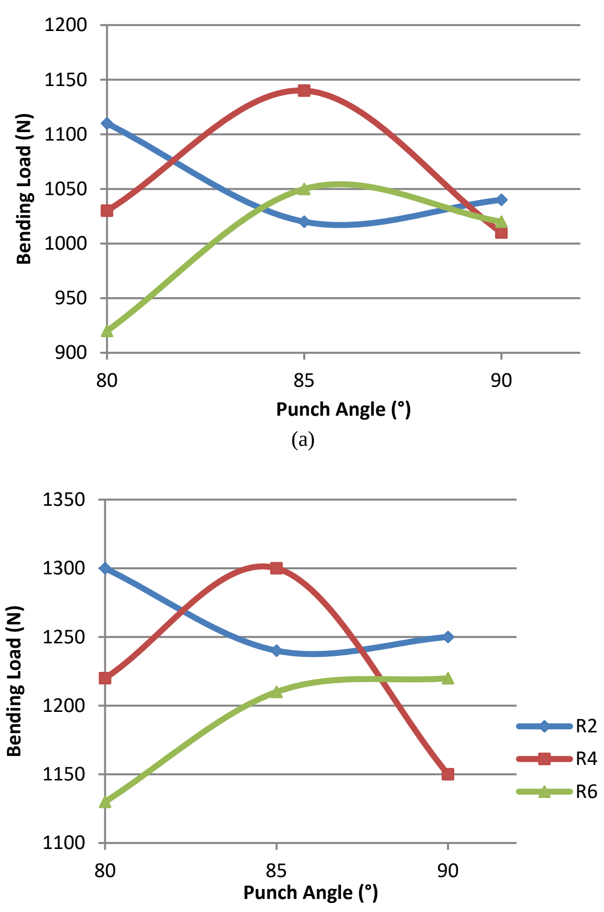
Figs. 5. Reverse graphic for distinct punch radius and angle for 1-mm (a) and 2-mm (b)

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
80	2	17.75	19.00	20.83	19.19	16.58	14.25	14.33	15.05
	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
85	2	22.83	22.66	21.16	22.22	14.16	13.25	12.91	13.44
	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
90	2	25.75	18.33	21.41	21.83	15.66	14.16	12.00	13.94
	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



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

Figures 6 illustrate the effects of varied punch radius and angles on bending load. The load values for a 1-millimeter plate with angle values of 80°, 85°, and 90° are as follows: 1170 N, 1036.67 N, and 1036.67 N for a 2° radius; 1046.67 N, 1146.67 N, and 1016.67 N for a 4° radius; and 936.67 N, 1063.33 N, and 1036.67 N for a 6° radius. For a 2-millimeter plate with angle values of 80°, 85°, and 90°, the corresponding load values are: 1303.33 N, 1273.33 N, and 1236.67 N for a 2° radius; 1256.67 N, 1383.33 N, and 1203.33 N for a 4° radius; and 1153.33 N, 1236.67 N, and 1400 N for a 6° radius. In [7], it was asserted that variations in the punch significantly influence the bending load, with die angles, die widths, and punch radius reported to affect springback and bending load differently.

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

Figure 7 illustrates the impact of material or sheet plate thickness on springback and bending load, using the previously presented data. The figure shows that variations in material size have an insignificant influence on springback responses and bending load values for both 1- and 2-millimeter thickness plates.

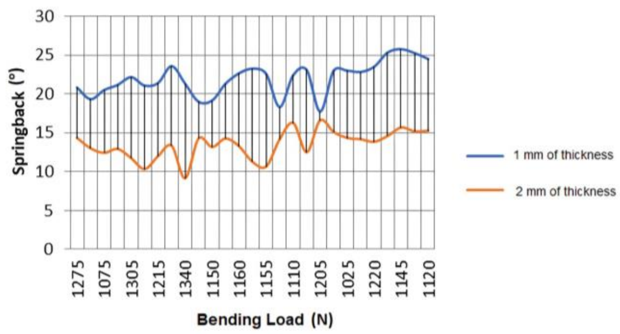


Fig. 7. Effect of material thickness variations on springback and bending load

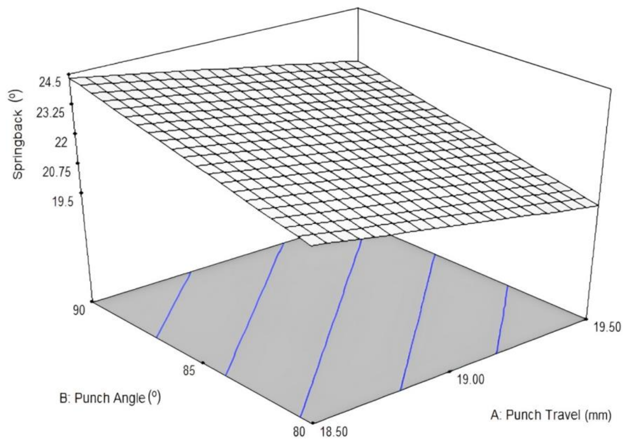


Fig. 8. 3D contour for springback

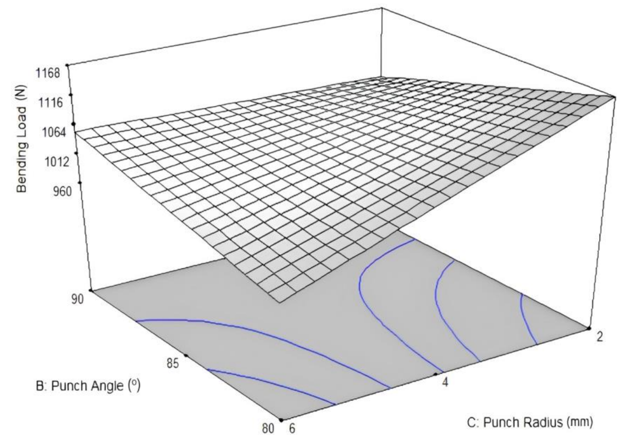


Fig. 9. 3D contour for bending load

IV.4. The Process of Optimization

The RSM was utilized to optimize the test results data through Design-Expert Software. DoE data analysis aids in evaluating the collected input and response data, generating a formula to determine the magnitude of the response, and facilitating the determination of optimal results. Scholars also employ this application to calculate the energy usage of metal bending operations [26] and 316L sheet plates [27]. Furthermore, the results of the optimization via DoE analysis are as follows. Utilizing the previously mentioned software and RSM, the authors conducted an ANOVA to examine the variations in punch angle and radius. The results for these two variables are presented in Table IV (springback) and Table V (bending load). The DoE analysis resulted in equations for both springback (Equation (3)) and bending load (Equation (4)).

These equations provide valuable insights into the relationships between the input variables and the corresponding responses:

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

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

Equation (3) emphasizes that punch angle has a more significant impact on springback than punch travel. The punch variables, specifically travel and angle, play a crucial role in determining the expected springback.

Furthermore, Equation (4) illustrates that punch variables, including angle and radius, significantly influence the bending load. This is determined by combining Equation (4) with punch variables, specifically angle and radius. As depicted in Figures 8 and 9, the DoE analysis presents 3D contours of the springback and bending load data models.

In addition, an optimization process will be conducted on the raw data, incorporating punch radius, angle, and travel to obtain springback and bending load data. Figure 10 depicts the highest prediction of the RSM at 0.82, offering comprehensive insight into the relationships between input and response data. The graphic optimization process involves constructing an overlay plot by combining contours of various response surfaces, as illustrated in Figure 11.

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		

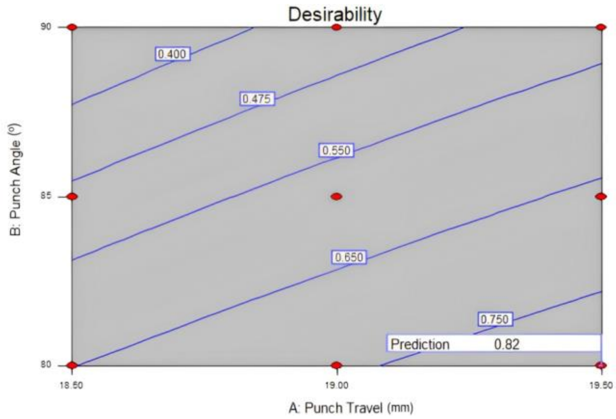


Fig. 10. Desirability after optimizing the data

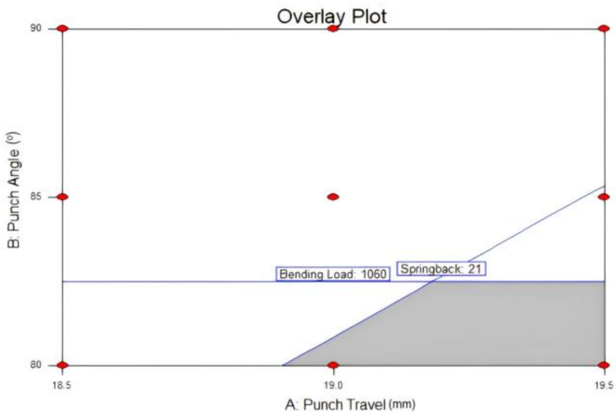


Fig. 11. Punch variables optimization to minimize the springback (maximum of 21°) and the bending load (maximum of 1060 N)

The shaded area within the overlay plot indicates the range of acceptable values for the dependent variables, serving as constraints for all desired outcomes. 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 while keeping the bending load below 1060 N.

IV.5. The Confirmation Analysis

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

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

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

The predicted values, actual experiments, residuals, and percentage errors are presented in Tables VII and VIII. The percentage errors between the actual and predicted values for springback and bending load are as follows:

- Springback=~ -1.99 to -3.18 %;
- Bending Load=~ 2.291 to 3.81 %.

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

To minimize springback in the V-bending plate process, various factors can be analyzed. These include the design of the punch and die using FA [28], [29], parameters such as thickness, width, and bend angle [30], and the temperature factor during heating during bending [31].

V. Conclusion

In this study, the authors explore the springback and bending load reactions of two steel plates with varying thicknesses. The authors' aim is to comprehend the influence of different plate thicknesses on these mechanical behaviors. The main goal is to evaluate how various punch variables impact springback and bending loads, with the intention of refining their calculation. The objective is to obtain punch values that result in minimal springback and bending loads. This study encompasses sheet plate thicknesses of 1 and 2 millimeters. Testing parameters were specified for each variable, including punch angle (80, 85, and 90 degrees), punch radius (2, 4, and 6 millimeters), and punch travel (18.5, 19, and 19.5 millimeters). The results of a V-bending test performed on stainless steel and analyzed with the RSM technique imply the following: Punch angle and travel parameters significantly contribute to springback, while angle and radius are both associated with the bending load. Both RSM and DoE analyses are crucial approaches for achieving precise analysis and optimal bending outcomes.

The mathematical models developed to predict various punch parameters are statistically valid for plates of all thicknesses. The study suggests further work to investigate a wider range of plate dimensions, including size and thickness. Additionally, die sets, which can be employed for mass production of various plate types, are ready for patent protection and commercialization at the medium-industrial level.

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