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Investigation effect of bending process parameters on springback of 416 stainless steel sheet using experimental and statistical approach

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ABSTRACT

The springback phenomenon is one of the most sensitive features in sheet metal forming. Inaccurate estimation of springback amount results in product failure and incorrect final dimensions. Dimensional accuracy is crucial when manufacturing brackets, joints, and structural parts that typically require L-shaped bending after machining, which are often made of stainless steel. Therefore, the main objective of this study is to strive for more accurate prediction and control of springback, given its crucial importance in the design of sheet metal forming tools. In the current work, the springback behavior of 416 stainless steel sheet was evaluated during the L-bending operations. Three rolling directions (0°, 45°, and 90°), sheet thicknesses (0.5 and 1 mm), and dwell time (0.5 and 2 min) were used to assess their impact on the springback phenomenon. The design of experiment was employed to analyse the experimental results using a full factorial design in Minitab software, and a regression model was constructed to predict the springback value. The analysis of variance is used to determine the most significant parameter of the springback value. The results showed that the rolling direction, sample thickness, and dwell time significantly affect the springback values during L-bending operations for samples made of 416 stainless steel. It was evident that the samples at an angle of 0° (parallel to the rolling direction) showed less springback compared to other directions due to the high homogeneity of the fibers and mineral tissues. It has also been demonstrated that increasing the sample thickness and dwell time up to 1 mm and 2 min, respectively generally results in a reduction in springback. The outcomes indicated that the effect of dwell time (0.5 and 2 min) is more pronounced in thinner samples of 0.5 mm and in the rolling direction, while its impact is less pronounced in thicker samples of 1 mm.

Keywords: springback, bending process, rolling directions, sheet thickness, dwell time, factorial design, analysis of variance, stainless steel sheet.

INTRODUCTION

Sheet metal bending is considered of great importance in keeping up with the growing developments of modern technology and industry today. It can be used in numerous applications such as aerospace and automotive industries, electronic component boards, drums, civil engineering applications, food cans, energy applications, medical, and many other fields [1, 2]. Some advantages of products manufactured using the sheet metal bending process can be listed as being more rigid, cheap, and easy to manufacture and join compared to other alternative products. The products having high strength and a high modulus of elasticity, as well as having an ideal strength-to-weight ratio [3]. However, a problem of variation in the bending angle from the desired shape, resulting from the springback phenomenon, leads to quality issues and increases the difficulties of the assembly process. Springback is defined as an error in terms of the size of manufactured solid components that reflects the elastic recovery of the component after unloading. The springback phenomenon presents economic challenges in manufacturing, as inaccuracies in products result in lower overall efficiency and poor quality [4, 5]. Moreover, the springback behavior of the part to be bent affects the dimensions of the bending die, which increases the cost of manufacturing the die when the springback compensation method is used. Therefore, it is necessary to estimate the springback value at the design stage [6]. To minimize the spring-back effect, parameters such as sheet thickness, material properties, tooling geometry, sheet anisotropy, bending force, bending method type, shape and size of the bent part, etc. require to be known [7]. Accurate angles and dimensions of products can be achieved by adjusting these parameters. There is no specific method that can be used in an acceptable manner through which the springback value can be measured for any type of metal used in sheet metal forming [8]. Therefore, many researchers have resorted to using many statistical, numerical, and analytical methods to predict the springback value for each type of metal sheet separately. Nasrollahi and Arezoo [9], and Feng and Wang [10] used the finite element method to characterize springback behavior. While, Thipprakmas et al. [11], Adnan et al. [12], and Maske and Sawale [13] used the Taguchi method to study the springback behavior. They reported that sheet thickness and bending angle have a significant influence on springback behavior during V-bending. The most important alloy used widely in sheet metal is steel due to its easy control and strengthening properties by heat treatments, cold working (strain hardening) or coating [14]. Stainless steel is one of the most widely used steel alloys in sheet metal. However, it suffers from a significant amount of springback due to its high strength compared to other alloys, such as aluminum or copper [15]. A significant amount of research has been conducted to investigate the parameters affecting springback, utilising various methods and techniques to minimise its value in steel alloys. Lin et al. [16] employed a new technique called "radial hydro bending" to form a high-strength steel tubular part, thereby modifying the stress state. The new method led to a reduction in the difference between axial stress during the bending process, thereby reducing springback by 95%. González et al. [17] show that the intermediate annealing processes can greatly reduce the springback and anisotropy of high-strength steels sheets. Matsugi et al. [18] showed that increasing the holding time reduces springback, while Karaağaç and Yıldırım [19] indicate that increasing the bending angle increases it. Akinlabi et al. [20] studied the effect of springback on formed steel sheets. It was found that the error rate due to springback is greater than 4%. It is revealed by Lal et al. [21] that the higher initial sheet thickness and increased blank holder force reduce the springback of the deformed part. Whereas, as the radius of the punch nose increases, the springback also increases. Spišák et al. [22] showed that materials with high strength properties (such as strain hardening) and small sheet thickness exhibit higher springback behavior. Hmood and Abbas [23] performed simulations under dry friction conditions and with lubrication of the active surfaces of specimens and tools. The results showed that increasing the coefficient of friction leads to an increase in springback behavior. Dametew [24] applied edge bending to observe its effect on springback.

Many researchers have investigated the effect of bending parameters on springback behavior. However, most of this research has focused on the V-bending process type, with only a few studies dedicated to L-bending, where the geometry and loading path influence stress distribution and the direction of springback. Furthermore, the interactions between rolling direction, sheet thickness, and dwell time, which represents the period during which pressure is applied to the workpiece and allows stress redistribution and relaxation, have not been thoroughly explored in existing literature. This study aims to address this deficiency by systematically investigating these factors in the L-bending of 416 stainless steel through a statistically robust full factorial design and regression modelling. The use of a full factorial design to analyze the data and develop a mathematical model to predict the elastic recovery value, in addition to evaluating the effect of dwell time, sheet thickness, and rolling direction, is considered one of the most original points of this research. Compared with previous research that focused on V-bending processes and the influence of individual factors, this research contributes to a deeper understanding of interactive factors and their simultaneous influence on springback. Hence, the research makes an important addition to the scientific literature by developing new tools and applications that can help improve the design of sheet metal forming processes and reduce errors resulting from elastic recovery.

RESEARCH METHODOLOGY

Springback theory

One common technique in sheet metal forming operations is bending. There are clear stress gradients between the tension and compression zones in bending processes because deformation is focused in a small area of thickness. Following load reduction, these localized gradients have a major impact on the development of residual stresses, which directly regulate the degree of springback. Bending material cross-sectional changes are depend upon material type, thickness, bending angle, and bending radius. An elastic recovery occurs after each plastic deformation. This phenomenon causes the plastically deformed workpiece's dimensions to alter when the load is released. In sheet metal bending operations, it is essential to consider the amount of springback to achieve the parts at the required angles and dimensions. The bending process generates compressive stresses in the internal deformation zone and tensile stresses in the external deformation zone of the sheet as shown in Figure 1. Because these forces are not equal, the compressive pressure difference force produces elastic energy. With this energy, the sheet metal reverts to its initial form. As a result, the ultimate bend radius will initially be larger than the intended bend radius as illustrated in Figure 2. More crucially, as the difference between inner and outer surface stresses increased, the amount of springback resulting from applied loads increases [6, 25]. All the factors that influence the deformation of the sheet metal during the production process also generally influence the springback. Two measurements are adopted to determine the back spring value, namely springback angle ($\Delta\alpha$) in degree and springback factor (Ks). The $\Delta\alpha$ represents the difference between the final bending angle (α_f) in degree obtained after lifting the punch and the initial bending angle (α_i) in degree as presented in Equation 1 [26].

$$\Delta\alpha = \alpha_f - \alpha_i \tag{1}$$

The *Ks* represents the relationship between the initial and final angles. When *Ks* = 1, it means no springback, and a value of 0 means total springback. The *Ks* can be represented mathematically by Equation 2 [27].

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

where: R_i – bend radius before springback (mm),
R_f – bend radius after springback (mm),
h – sheet thickness (mm).

Materials and methods

ASTM 416 stainless steel alloy, which is widely used in various industries due to its machinability, corrosion resistance, and high strength, was investigated in this work. The chemical composition which is determined by optical emission spectroscopy of the steel used was presented in Table 1. The dimensions of sheets used in this study are 130 mm length × 30 mm width, and these sheets were cut using a water jet machine (pressure of 350 MPa, and traverse speed of 120 mm/min) to eliminate the effect of heat and maintain their mechanical properties. The edges of all sheets have been ground to remove burrs. The sheets were cut in different directions (0°, 45°, and 90°)

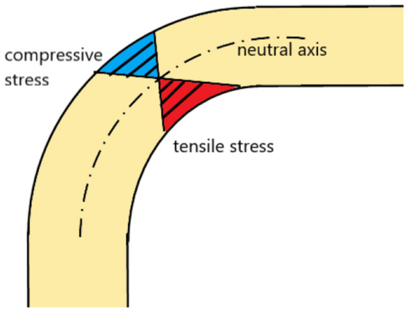

Figure 1. Types of stresses

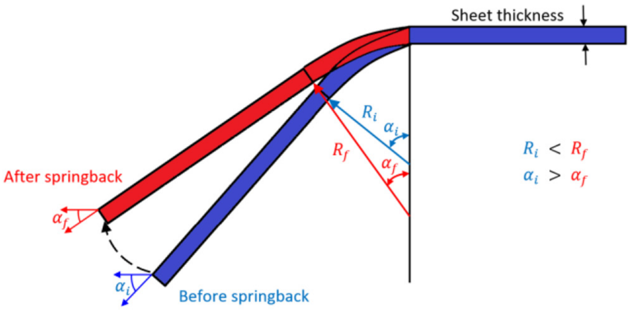

Figure 2. Springback in bending operation

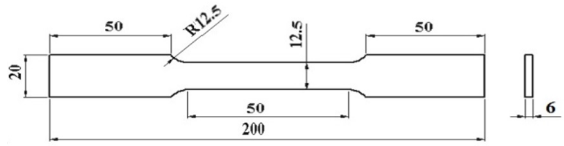

Figure 3. Tensile test sample dimensions

Figure 4. Tensile test samples with rolling direction

Table 1. Chemical composition for used stainless steel alloy

C %	Si %	Mn %	S %	Cr %	Ni %	Mo %	Cu %	P %	Al %	Fe
0.0874	0.0344	0.528	0.149	12.87	0.003	0.071	0.006	0.0055	0.006	Balance

Note: C – carbon, Si – silicon, Mn – manganese, S – sulfur, Cr – chromium, Ni – nickel, Mo – molybdenum, Cu – copper, P – phosphorus, Al – aluminum, Fe – iron.

of roll direction to evaluate the effect of material anisotropy on springback. In the current research, two sheet thicknesses of (0.5 and 1) mm was used. Standard tensile samples as shown in Figure 3 were prepared to determine the mechanical properties of 416 stainless steel alloys. The specimens were cut in the rolling direction at 0°(parallel), 45°(diagonal), and 90°(transverse) angles for tensile testing according to ASTM E8M standards as shown in Figure 4. For each direction, 3 tests were performed at room temperature using a computerized tensile tester (WDW-200E) with a maximum capacity of 100 kN. All tests were performed at a constant device speed of 20 mm/min.

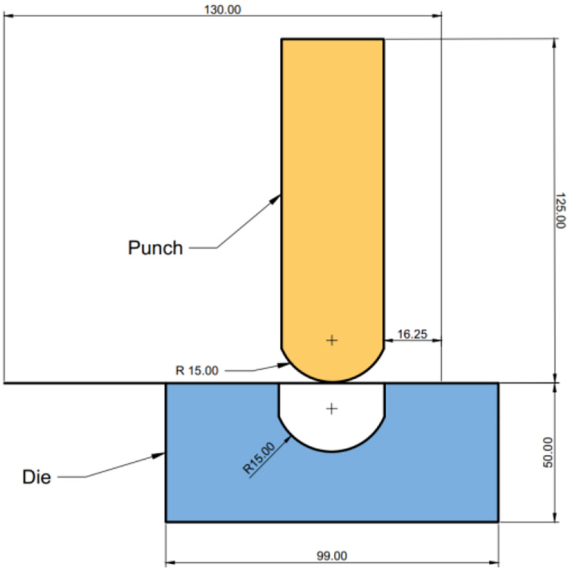

Figure 5. Die and punch dimensions

Experimental setup

L-shaped bending of the sheet specimens was performed using a 50-ton Instron machine. Specialized experimental instruments have been designed and manufactured to experimentally study the springback of 416 stainless steel sheets. Specialized tools consist of a semicircular bending die and a punch. All details and dimensions of the tools used are shown in Figure 5. The bending and punching die used in the experiments were made of tool steel to prevent damage that could occur to the punch and die surfaces during bending operations. To perform the bending process, the die assembly was mounted on the Instron machine, then the 416 stainless steel sheet specimen was placed on the die in the correct position before a punch load was applied until it was bent to the desired shape. After reversing the punching motion, the L-shaped sample is removed from the die. The experimental setup for the L-shaped bending process is shown in Figure 6. After the bending process, the edge of the sheet metal was not completely linear. The curve was produced on the edges of the metal sheets. The Springback angle was measured by drawing lines parallel to the bending edges during the measurement process. Each measurement was repeated three times and the average value of these measurements was taken. In the experiments, three samples were tested for each roll direction (0°, 90°, and 45°), sheet thickness (0.5, and 1) mm, and dwell duration (0.5 and 2) min.

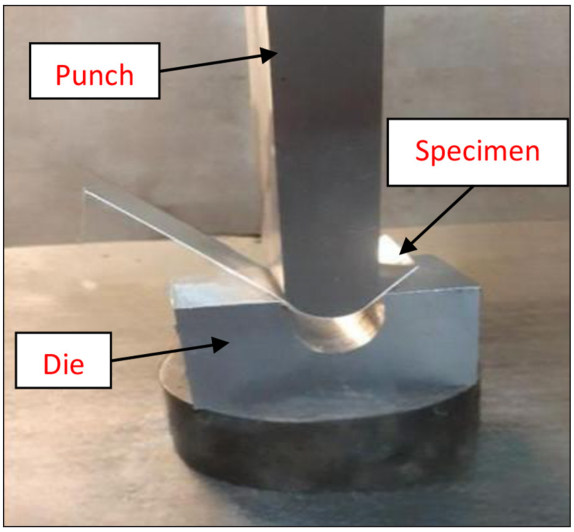

Figure 6. Experimental setup for the L-bending process and produced L-shaped sample

Factorial design

The present work aimed to develop a method that allows for reducing or eliminating springback from the design stage of the bending process. The optimal solution can be obtained using statistical modeling that provides a mathematical description of the effect of various process parameters on the geometry of the formed components. That's why we used a factorial design approach that can take a project with many sets of variables, and quickly boil it down to simple experiments that can be run one at a time and will determine the cheapest way to achieve the goal. Instead of looking at one variable at a time, a factorial design can test many variables simultaneously, so the number of tests can be appropriately small [27]. This method allows us to determine the relative importance of process parameters and their interactions in Springback. The factorial design in this study took into account three factors influencing the bending process. The method was implemented using Minitab19 software that allows the development of different factorial plans, analysis of variance, elucidation of different dependency functions, and optimization of the process. In this simulation case, it was considered that the most important influencing factors were sheet thickness and dwell time. The rolling direction of the sheet determines the modification of mechanical properties and thus changes the behavior of the material during the L-bending process. For this reason, the rolling direction is included in the list of parameters that affect the bending process. The process parameters are listed in Table 2. Each parameter has two levels of variation except roll direction which has three levels.

Table 2. Levels of variation for bending process parameters

Parameter	Level		
Rolling direction, θ (degree)	0	45	90
Dwell time, t (min)	0.5	2	–
Thickness, h (mm)	0.5	1	–

To maximize the efficiency of dependency functions with more reliable simulation results, a full factorial design was used. For the three process parameters with two and three levels of variation, 12 experiments were necessary. Table 3 and Figure 7 show full factorial design experiments with the process parameters used in this simulation. The dependency between the process parameters of the part is represented by response functions in the form of a second-order polynomial as presented in Equation 3. The experimental data

Table 3. Full factorial design of bending process parameters

No. of experiments	Rolling direction, θ (degree)	Dwell time, t (min)	Thickness, h (mm)
1	0	0.5	0.5
2	0	2.0	1.0
3	90	0.5	0.5
4	0	0.5	1.0
5	45	0.5	1.0
6	0	2.0	0.5
7	90	2.0	1.0
8	45	2.0	0.5
9	90	0.5	1.0
10	45	2.0	1.0
11	90	2.0	0.5
12	45	0.5	0.5

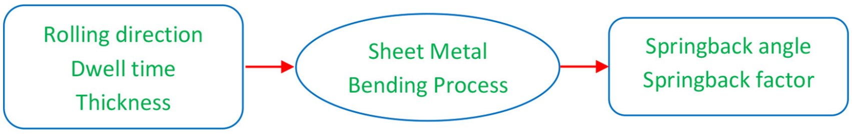

Figure 7. Bending process model

for determining the coefficients of the Equation 3 are listed in Table 3.

$$\begin{gathered}\Delta\alpha = a_o + a_1\theta + a_2t + \\ + a_3h + a_{11}\theta^2 + a_{22}t^2 + \\ + a_{33}h^2 + a_{12}\theta t + a_{13}\theta h + \\ + a_{23}th + a_{123}\theta th\end{gathered} \tag{3}$$

RESULTS AND DISCUSSION

Tensile test

The direction of rolling plays a major role in determining the mechanical properties of metal specimens, as these properties can change based on the angle at which the specimens are cut relative to the direction of rolling. Therefore, it is important to take this factor into consideration when designing and testing metallic materials to ensure optimal performance in various engineering applications. Figure 8 and Table 4 show the results of tensile testing for samples cut at different angles (0°, 45°, and 90°) relative to the rolling direction. The results show that the samples at an angle of 0º show the highest tensile strength and the highest elongation before breaking, followed by the samples at an angle of 45°, which show intermediate properties between the samples at an angle of 0° and 90°, while the samples at an angle of 90° showed the weakest properties. This is because materials that are cut parallel to the rolling direction benefit from fibers and tissues aligned in that direction, giving them a higher ability to withstand applied forces [28, 29]. While cutting the samples perpendicular to the rolling direction alters the material's response due to the crystalline structure resulting from rolling and the anisotropic plastic deformation, making the material less able to withstand applied forces.

Springback

The findings were examined in terms of the effects of rolling direction, sheet thickness, and dwell time on springback in the L-bending process. Understanding the effect of these parameters on springback is critical to optimizing L-bending processes for 416 stainless steel. Figure 9 shows the effect of the rolling direction and sheet thickness on the springback value, as it clearly shows that samples at an angle of 0° (parallel to the rolling direction) showed the lowest springback, while samples at angle of 45° and 90° to the rolling direction showed the highest springback. The reason 0° specimens exhibit better mechanical

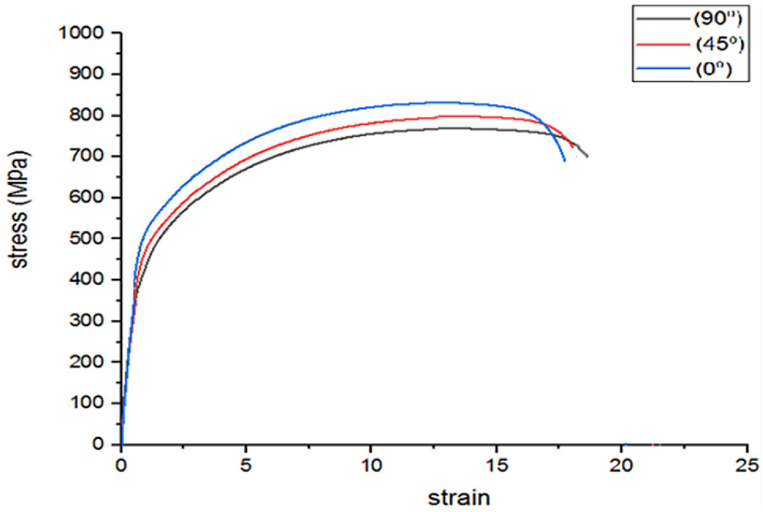

Figure 8. Stress-strain curves for rolling direction angles of 416L stainless steel

Table 4. Tensile properties of 416 stainless steel

Direction (degree)	Yield Stress, σ_y (MPa)	Ultimate Stress, σ_u (MPa)	Elongation (%)
0°	522 ± 5	840 ± 8	18 ± 0.5
45°	480 ± 4	800 ± 7	15 ± 0.4
90°	450 ± 6	760 ± 9	12 ± 0.6

properties is the more homogeneous stacking of fibers and mineral tissues, which allows better distribution of stresses. While in samples at an angle of 45° and samples at an angle of 90° (perpendicular to the direction of rolling), the springback is higher, as the fibers and metal tissues are oriented diagonally or vertically, which leads to an uneven distribution of stresses, which reduces their ability to withstand the stresses applied in this direction and makes them low flexibility and resistance to bending. Laurent et al. [30] have also documented this anisotropic effect, noting that alignment with the rolling direction decreases elastic recovery due to directional hardening.

At mean time, Figure 10 also shows the effect of thickness of the sample on the springback. It is clear from figure that thick samples have greater bending resistance and less springback, while thin samples show higher elasticity and greater springback. This is due to the fact that thin samples exhibit greater flexibility because the applied stresses are more widely distributed across a smaller thickness. Which leads to an increase in the value of springback due to the lack of resistance to bending. While thicker samples show less flexibility, as stresses are distributed across a greater thickness, which increases their resistance to bending. Hence a decrease in the value of springback due to increased resistance to bending. The higher bending stiffness of thicker sheets increases the plastic strain component and decreases the elastic recovery ratio, which is in agreement with the mechanics of bending theory. Similarly, Lal et al. [21] showed that increasing sheet thickness in materials

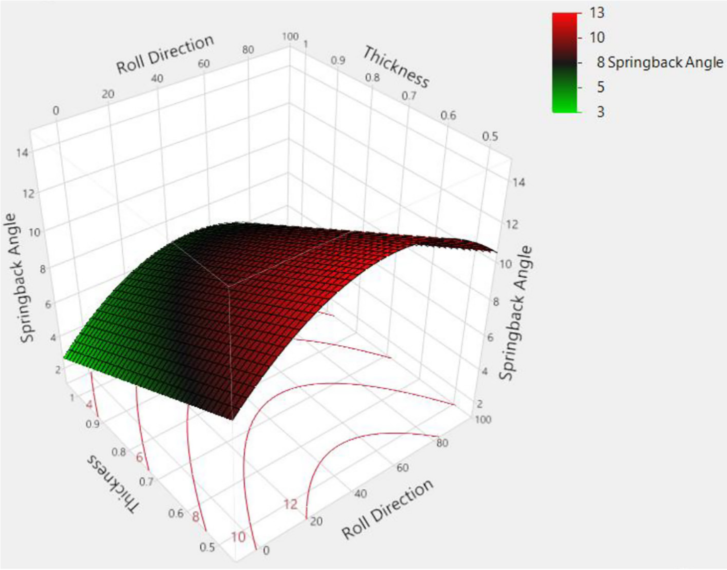

Figure 9. Relation between rolling direction, sheet thickness, and springback angle

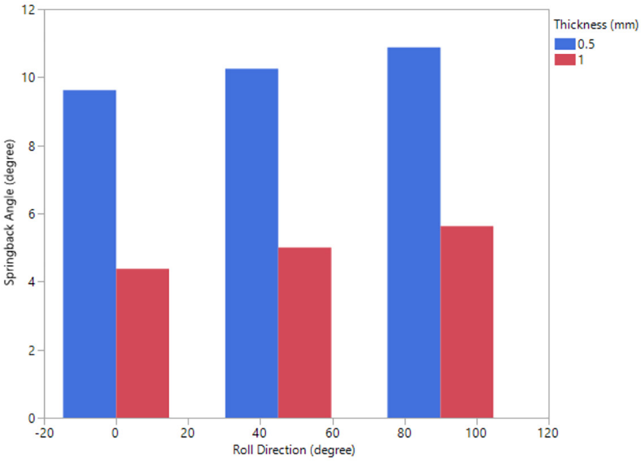

Figure 10. Relation between rolling direction and springback angle at sheet thickness of (0.5 and 1) mm

with a nonlinear work-hardening tendency results in lower springback because the plastic deformation zone penetrates deeper.

On other hand, Figure 10 demonstrates that there is no strong interaction effect between the rolling direction and the sheet thickness on the springback. The results showed that both factors affect springback independently, without a strong simultaneous interaction that significantly affects the final result.

The dwell time is the period during which the applied load is maintained before it is removed, and it also greatly affects the mechanical properties of the specimens during L-bending operations. Figure 11 shows that the shorter dwell time (0.5) min showed less effect on springback than the longer dwell time (2) min. For specimen conditions of (90° rolling direction and 0.5 mm thickness), the springback rate decreased by about 13.6% when using a dwell time of 2 min compared 0.5 min. This is due to the fact that the short dwell time does not have a significant impact on the material, as the fibers and mineral tissues have not been given enough time to relax or redistribute. As a result, the samples show properties similar to rapid load application. The long dwell time allows the material to redistribute and internal stresses to relax, resulting in improved elastic properties. The result is a decrease in springback and an increase in the elasticity of the material, as the fibers and mineral tissues can adapt to the applied stresses.

Figure 12 shows that the effect of dwell time on springback in the transverse direction (90°) is

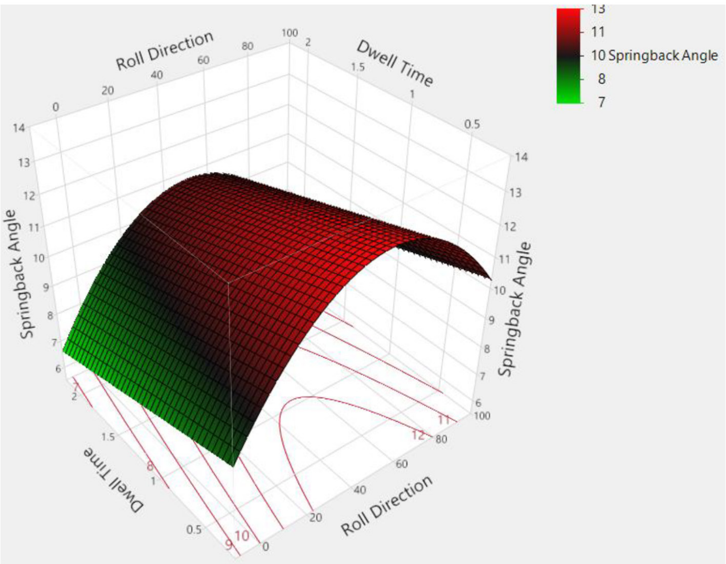

Figure 11. Relation between rolling direction, dwell time, and springback angle

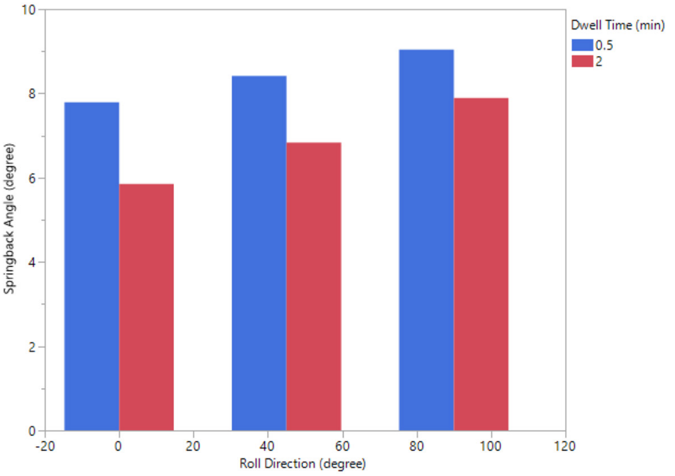

Figure 12. Relation between rolling direction and springback angle at dwell time of (0.5 and 2) min

less obvious compared to the longitudinal direction. Experimental values indicate that springback in the transverse direction does not decrease significantly with increasing stopping time, unlike the longitudinal direction. This decrease in the stopping time effect can be explained by the irregular crystal structure in the transverse direction. This makes residual stresses less evenly distributed, which reduces the effectiveness of dwell time in reducing springback. In the same context, Tekaslan et al. [31] revealed that extending the punch holding in stainless steel V-bending operations allows stress relaxation, which reduces elastic recovery. This is consistent with the observed decrease in springback with increasing dwell time.

Figure 13 shows the relationship between dwell time and sample thickness with springback. As previously explained, the figure shows a decrease in the value of springback with increasing sample thickness and dwell time. However, it was observed that in thick samples, the effect of dwell time is less obvious compared to thin samples. Experimental results have shown that samples with larger thickness show a lower value of springback regardless of the length of the dwell time. While thin samples show significant improvements in springback with increasing dwell time. The reason for this is that the larger thickness of the specimen leads to less local accumulation of residual stresses, and essentially benefits from equal stress distribution, making the temporal relaxation effect of the hold-up time less important. In thinner specimens, stresses are more concentrated, and thus springback benefits more from increased dwell time.

Regression model

Rolling direction (θ), dwell time (t), and thickness (h) were considered to develop mathematical models of springback angle. The relationship between the factors (θ, t, and h) and the response (springback angle $\Delta\alpha$) was obtained through a quadratic regression model. After analyzing the results and using the least squares method, the Minitab statistical program generated the model coefficients for every function. The values of the coefficients are shown in Table 5.

Regarding Table 5, it can be seen that all coefficients of the polynomial model are included except for the second-order terms, where t^2 and h^2 are omitted due to their lack of influence. The P values were determined as a 5% significant level from the springback analysis. It is shown that the variable terms with $P < 0.05$ are second-order terms for roll direction and first-order terms for thickness which are considered to have a greater influence on springback, while the P value for dwell time and interaction terms indicate less statistical significance for springback. According to the form of the functions presented in Equation 1, the final mathematical of second-order model for $\Delta\alpha$ was obtained as follows in Equation 4:

$$\begin{gathered}\Delta\alpha = 17.53 + 0.1\theta - 2.72t - 13.28h - \\ - 0.0011119\theta^2 + 0.0111\theta t + 0.0185\theta h + \\ + 2.22th - 0.0148\theta th\end{gathered} \tag{4}$$

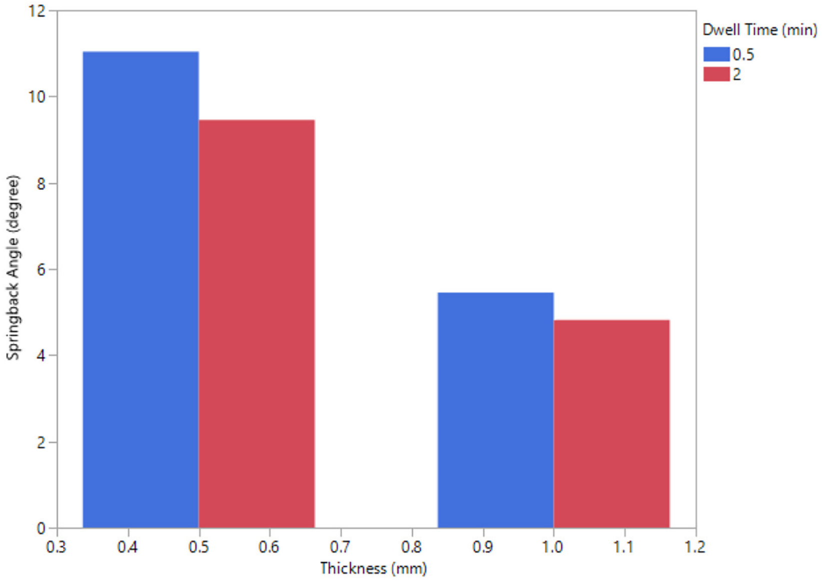

Figure 13. Relation between sheet thickness and springback angle at dwell time of (0.5 and 2) min

Table 5. Estimated coefficients of the regression model for springback

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	17.53	1.69	10.37	0.002	
θ	0.1000	0.0333	3.00	0.058	49.78
t	-2.72	1.16	-2.35	0.100	25.00
h	-13.28	2.13	-6.23	0.008	9.44
θ^2	-0.001111	0.000182	-6.11	0.009	13.00
θt	0.0111	0.0199	0.56	0.616	52.78
θh	0.0185	0.0367	0.50	0.649	43.44
th	2.22	1.46	1.52	0.226	31.94
θth	-0.0148	0.0252	-0.59	0.598	56.94

Note: SE – standard error of the coefficient, T – t-test, P – probability, VIF – variance inflation factor.

It can be observed from Equation 4 that the coefficient associated with t, the second order term θ^2, and the triple term θth are negative, indicating a decrease in $\Delta\alpha$ of the sheet metal with the increase of the above-mentioned parameter.

To test the global fit of the second-order regression equation, the values of regression statistics (R^2) were evaluated, as shown in Table 6. The values of R^2 and R^2 adjustment (adj) are 99.01% and 97.36%, respectively. The obtained second-order model for $\Delta\alpha$ was satisfied because the value of the coefficient of determination R^2 is high and close to 1 which indicates the strength of the interaction between the variables. Also, the value of R^2 agrees closely with R^2 adj, which is desirable [32]. In the second-order regression equation, the value of the coefficient of determination R^2 (adj) means that 97.36% of the change in the springback value is explained by independent variables.

Table 6. Model summary of springback (L-die)

Model summary			
Model	R-sq	R-sq (adj)	R-sq (pred)
1	99.01%	97.36%	86.16%

The adequacy of the model was also checked from the residual graphs as shown in Figure 14a and Figure 14b. From the normal probability graph of the remaining residues, it was shown that the data complied with the sample size rules and that all points clustered along a straight line, indicating that the errors were normally distributed.

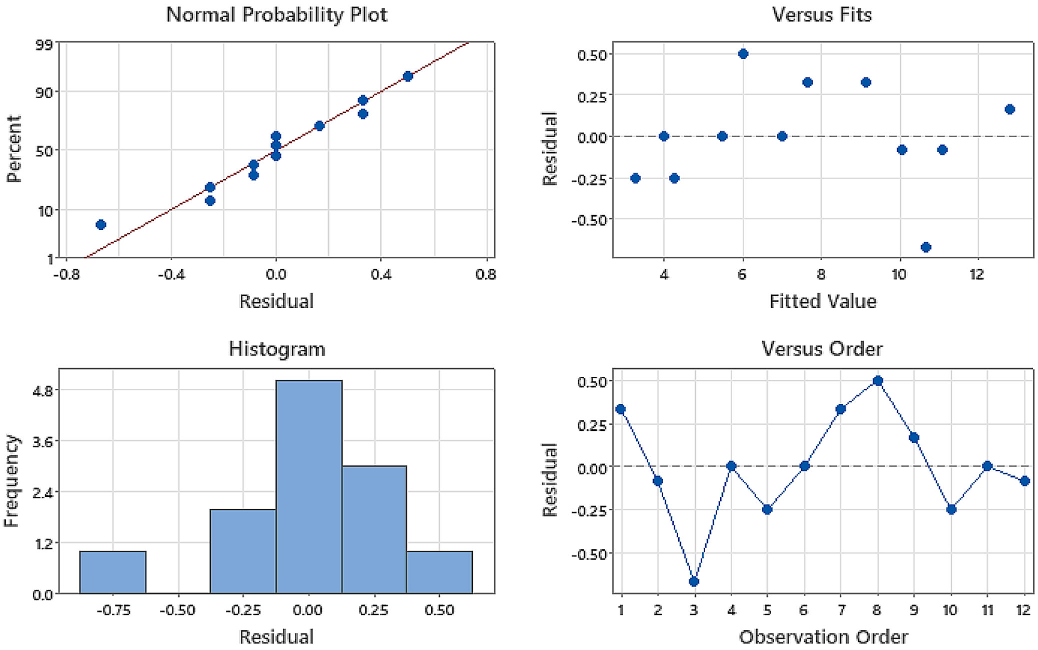

Figure 14. Plots of regression model for measured springback in L-shaped bending operation: (a) normal probability, (b) histogram, (c) versus fits, (d) versus order

Ideally, for residual charts, all points should lie randomly on either side of zero as in a recognizable pattern. Figure 14c and Figure 14d illustrates that all points lie on either side of zero, with no unstable variance or inconsistencies observed. This indicates that the residuals were randomly distributed with constant variances. Plotting the data against the residuals also shows the order of data collection and the patterns during the observation and at the points. Ideally, the residuals should be randomly distributed around the midline. Figure 14 clearly highlights that residuals that are close to each other are intercorrelated, indicating that they are not independent. Figure 15 represents a Pareto chart which indicated that the second-order term θ^2 and h intersects the red line (3.182), which means that they are the most important factors affecting the $\Delta\alpha$. A similar observation can be made on the combined factors such as t with θ, t with the interaction term ($t \times h$), and θ with the interaction term ($t \times h$) which also has a big impact on the springback.

Table 7 presents a comparison between experimentally measured values of $\Delta\alpha$ of the 416 stainless steel sheets, and the predicted values which obtained from second-order regression equation. This table demonstrates effectiveness of regression equation for predicating $\Delta\alpha$ based on parameters variation of the L shaped bending process. The regression method offer advantage for optimize forming processes by adjusting θ, t, and h which effect the properties of the product. In

Table 7. Experimental conditions and springback results for stainless steel (experimental and factorial method)

No.	Rolling direction, (degree)	Dwell time, T (mm)	Thickness, h (mm)	Measured springback, α_{exp} (degree)	Predicted springback, $\alpha_{predict}$ (degree)	Error (%)
1	0	2.0	0.5	8.0	7.6667	4.16667
2	0	0.5	0.5	10.0	10.0833	0.83333
3	45	2.0	0.5	10.0	10.6667	6.66667
4	45	0.5	1.0	7.0	7.0000	0.00000
5	90	2.0	1.0	4.0	4.2500	6.25000
6	90	0.5	1.0	5.5	5.5000	0.00000
7	90	2.0	0.5	9.5	9.1667	3.50877
8	45	2.0	1.0	6.5	6.0000	7.69231
9	45	0.5	0.5	13.0	12.8333	1.28205
10	0	2.0	1.0	3.0	3.2500	8.33333
11	0	0.5	1.0	4.0	4.0000	0.00000
Total error (%)						3.29089

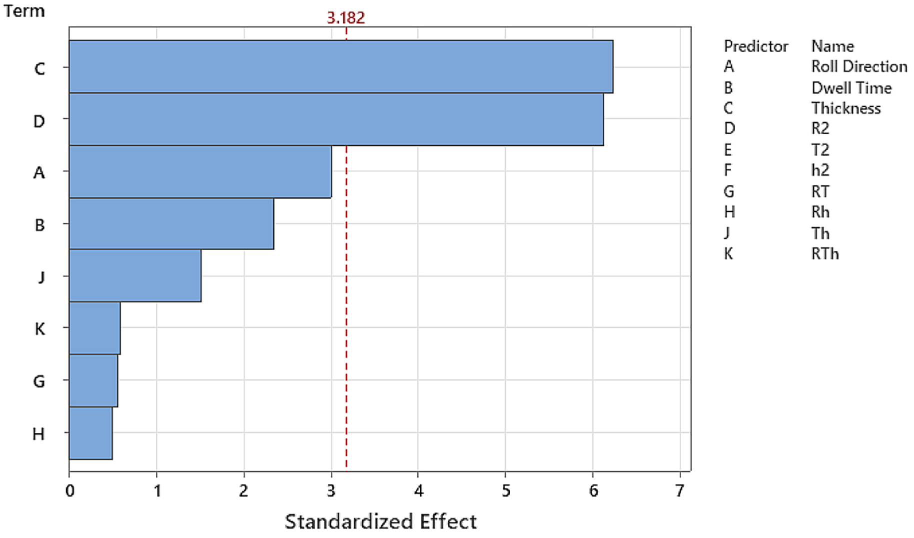

Figure 15. Effects of bending process parameters on springback

addition, errors between measured and predicted values of $\Delta\alpha$ and total error values are also given in Table 4. The error percentage (error %) and total error percentage (total error %) were calculated using Equation 5 and Equation 6 as follows:

$$Error(\%) = \left|\frac{\alpha_{predicted} - \alpha_{experimented}}{\alpha_{experimented}}\right| \times 100 \quad (5)$$

$$Total\ error(\%) = \frac{\sum_i^n Error_i}{n} \quad (6)$$

The results shown in Table 7 are graphically presented in Figure 16 which indicated that there is no big divergence between the predicted and experimental values of $\Delta\alpha$. The $\Delta\alpha$ values predicted by regression equation showed a slight difference from the actual experimental values. The finding suggests that the regression equation employed to measure the $\Delta\alpha$ of 416 stainless steel samples are effective and reliable. Experiment 9 obtained the highest values for $\Delta\alpha$, while experiment number 10 showed the lowest $\Delta\alpha$ among the experiments conducted. This statistical model provides a more accurate estimate of the $\Delta\alpha$ according to different values of the parameters studied. It also enables us to analyze the effect of these parameters on the springback behavior.

Analysis of variance

The adequacy of the model was verified using analysis of variance (ANOVA). This analysis is a tool for quantitatively evaluating the effect of independent variables on dependent variables. ANOVA can be used to determine the effect of individual variables in an experiment. The

Table 8. ANOVA results of regression model

Analysis of variance					
Term	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	8	107.979	13.4974	37.38	0.006
θ	1	3.254	3.2545	9.01	0.058
t	1	2.001	2.0008	5.54	0.100
h	1	14.000	14.0002	38.77	0.008
θ^2	1	13.500	13.5000	37.38	0.009
θt	1	0.113	0.1125	0.31	0.616
θh	1	0.092	0.0919	0.25	0.649
th	1	0.833	0.8333	2.31	0.226
θth	1	0.125	0.1250	0.35	0.598
Error	3	1.083	0.3611		
Total	11	109.063			

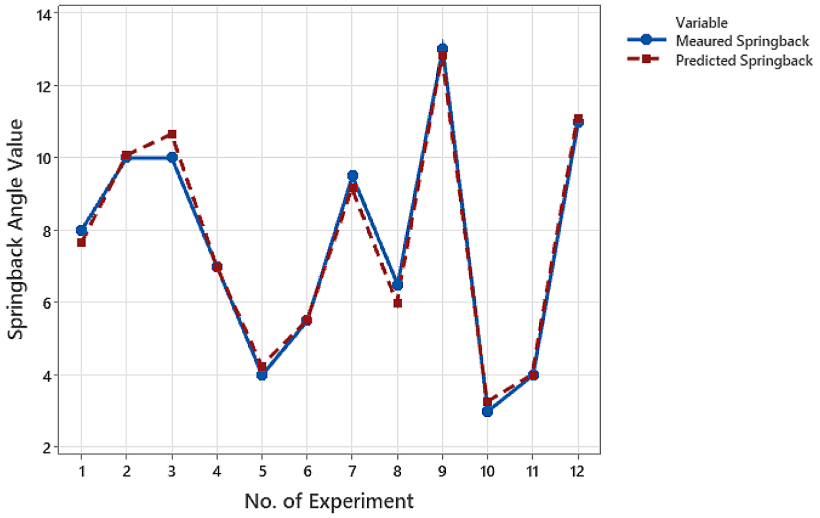

Figure 16. Comparison between measured and predicted values of experimental data for springback

ANOVA results are shown in Table 8. The F value is a tool to identify the parameter that has a significant impact on the response characteristic. The mean square deviation (MS) must be calculated as a result of the parameters to perform an F test. The F value for each parameter is calculated as the ratio between the MS and the mean square error. The F test, in statistical terms, provides a judgment about whether these estimates differ significantly at a given confidence level. This analysis was performed at a confidence level of 95% and a significance level of 5%. The influence of factors is determined by comparing F values; A larger value of F reflects a larger variation in the process parameter and the factor with the highest F value is considered to have the most influence on the result. After examining the results of ANOVA in Table 8, it was noted that the h had the largest effect in terms of F value, followed by θ^2 (F = 37.38). This result indicates that changing these parameters has a significant impact on the bounce rate.

CONCLUSIONS

The current work presents an experimental and statistical study of the effects of dwell time (0.5 and 2 min), sheet thickness (0.5 and 1 mm), and rolling direction (0°, 45°, and 90°) on the spring behavior of 416 stainless steel sheets during L-shaped bending processes. Many current published studies focus on V-bending processes, while L-bending processes remain largely unexplored despite the geometry differences between the two and their impact on stress distribution and springback. Furthermore, the combined effect and interaction effects of rolling direction, stasis time, and plate thickness on bending processes have not been thoroughly investigated. This work attempts to address this gap through a comprehensive experimental and statistical study of L-bending processes. The main results are summarized as follows:

- The rolling direction greatly affects the springback of 416 stainless steel samples. Samples bent along the 0° direction showed the lowest springback, while those bent along the 45° direction showed the highest springback.
- Sample thickness plays a crucial role in springback behavior. Thicker samples (1 mm) showed reduced springback compared to thin samples (0.5 mm). This can be attributed to the high stiffness and low flexibility of thick samples.
- Dwell time also affects springback, with longer dwell times (2 min) resulting in a decrease in springback. This decrease is likely due to the stress relief that occurs during the longer waiting period.
- The factors of roll direction and sheet thickness affect the springback independently, without strong simultaneous interaction that significantly affects the final result.
- The combined effects of rolling direction, sheet thickness, and dwell time were significant. Specifically, the combination of a roll direction of 0°, a sheet thickness of 1 mm, and a dwell time of 2 min resulted in the lowest springback values. Conversely, the combination of a rolling direction of 90°, a sheet thickness of 0.5 mm, and a dwell time of 0.5 min produced the highest springback values.

The results of the analysis of variance (ANOVA) indicated that the three factors and their interactions had a statistically significant effect on springback. This reinforces the importance of considering all factors simultaneously when optimizing bending processes. The predicted springback values obtained from the regression model closely matched the actual experimental results, indicating the reliability and accuracy of the statistical model. The correlation coefficient (R^2) was found to be high, indicating that the model explains a large portion of the variance in springback behavior. These results provide valuable insights for optimizing bending operations for 416 stainless steel sheets in different industries. By understanding the individual and combined influences of these parameters, manufacturers can better control springback, and improve the accuracy and quality of formed components.

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