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Original Article

Optimizing Spring-back and Spring-go in Vee-bending of SCGA340BHX Galvanized Steel: A Taguchi Approach

Hendri Susilo[1], Danang Supriyanto[1], Yogi Nur Widyartha[1], Khoirudin[1*], Sukarman[1*], Dodi Mulyadi[1], Ade Cepi Budiansyah[1], Afif Hakim[2], Ade Suhara[2], Nana Rahdiana[2], Agus Hananto[3]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Buana Perjuangan Karawang, Karawang, 41361, West Java, Indonesia

[2]Department of Industrial Engineering, Faculty of Engineering, Universitas Buana Perjuangan Karawang, Karawang, 41361, West Java, Indonesia

[3]Departmentof Informatic Engineering, Faculty of Engineering Technology, Asia E University, Subang Jaya, 47500, Selangor, Malaysia.

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ABSTRACT

Spring-back and spring-go are critical elastic recovery phenomena in sheet metal forming that affect the angular precision of bent components. This study investigates the influence of punch angle, die opening, and punch speed on these behaviors during the Vee-bending process of SCGA340BHX high-strength galvanized steel. A Taguchi design of experiments with an L8 orthogonal array was applied, and spring-back angles were measured and analyzed using the "smaller-is-better" signal-to-noise (S/N) ratio criterion. The results reveal that punch angle is the most influential parameter governing spring-back and spring-go tendencies, followed by die opening and punch speed. A punch angle of 50° and a die opening of 35 mm produced the highest average spring-back (3.03°), while spring-go behavior was observed primarily at higher punch speeds (35–40 mm/min). The study further confirmed the inverse relationship between bending force and spring-back, with lower forming forces correlating to greater elastic recovery. These findings provide a comprehensive understanding of the interdependence between geometric and kinematic factors in elastic recovery phenomena, offering quantitative insights for optimizing Vee-bending operations involving thin, high-strength steel.

*Corresponding author.
E-mail address: khoirudin@ubpkarawang.ac.id (K. Khoirudin), sukarman@ubpkarawang.ac.id (S. Sukarman)
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1. Introduction

Dimensional accuracy remains a fundamental requirement in metal-forming processes, particularly in high-precision sectors such as automotive manufacturing [1]. Two critical phenomena that affect dimensional consistency are spring-back and spring-go. Spring-back refers to the elastic recovery of a material after unloading, resulting in partial shape reversal toward its original form [2, 3]. Conversely, spring-go denotes a residual overshoot beyond the intended geometry, typically caused by non-uniform residual stress distributions and incomplete elastic recovery [4, 5]. Both mechanisms introduce challenges in maintaining geometric precision, potentially leading to misalignment, loss of structural integrity, and the need for expensive rework.

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Numerous strategies have been developed to mitigate spring-back, such as die geometry optimization, pressure compensation, and the implementation of numerical models for process correction [6-9]. These are particularly vital in cold-forming operations, where elastic effects dominate the post-deformation behavior [10]. Reports of spring-back phenomena span a variety of techniques, including deep drawing, roll bending, and vee-bending [11, 12]. One industrially relevant case is the vee-bending process applied in the production of muffler brackets for MPV-class vehicles, where dimensional stability directly influences assembly tolerance and functional performance, as shown in Figure 1.

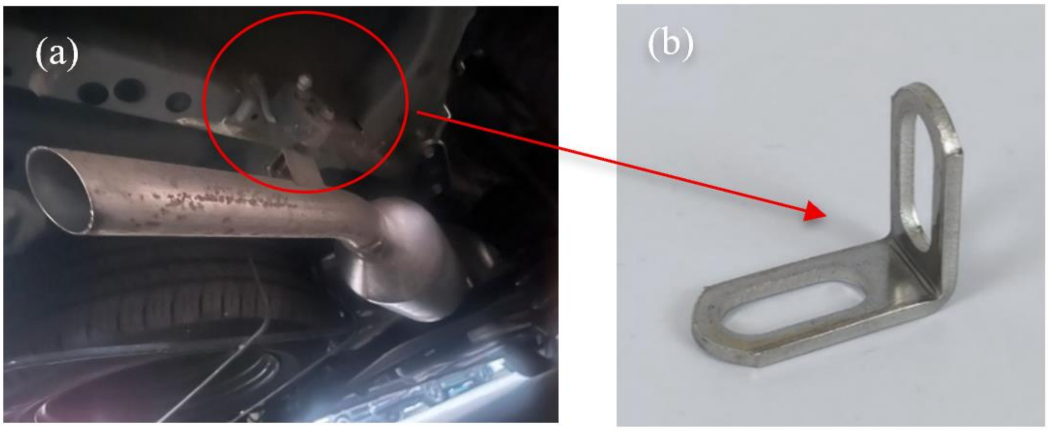

Figure 1. Application of the vee-bending process: (a) Position of the Vee-bending bracket, (b) Vee-bending bracket

The magnitudes of spring-back and spring-go are highly sensitive to multiple interrelated factors, including material strength, punch/die geometry, lubrication conditions, and process parameters such as punch speed and bending angle [13-15]. Techniques such as holding time control during punch displacement and hydroforming with regulated hydraulic pressure have shown promising outcomes in suppressing spring-back, with reductions of up to 26% at 20 MPa [16, 17]. In parallel, the Taguchi design of experiments (DOE) and finite element simulations have proven effective in systematically optimizing process variables to enhance forming precision [18, 19]. This literature review highlights various aspects of the vee-bending process for steel materials in different industrial contexts. The holding time after loading during the V-bending process is critical for reducing spring-back [14]. The spring-back effect in Ti-6Al-4V alloy during the rolling and vee-bending processes revealed that rolling resulted in less spring-back than conventional bending [15]. A study on stress distribution and its effect on spring-back in bending using hydroforming techniques was conducted by [20], who confirmed that hydraulic pressure is inversely proportional to the resulting spring-back. At 10 MPa, the spring-back was reduced by 8.9%, and at 20 MPa, it was reduced by 26%. Spring-back behavior in pipe bending using high-strength TA-18 and mid-strength Cr14Ni9Ti and TA-18 LF2M materials with diameters of 127 and 70 mm, respectively [21]. Their methodology involved both experiments and Finite Element (FE) simulations. The results revealed that accurate and efficient pipe bending depends on the mechanical properties of the materials and that the precision of FE modeling is heavily influenced by the material response modeling under load [21]. Vee-bending research on aluminum (A1100-O) materials was conducted using the Taguchi method. The process parameters included the bending radius, material thickness, and punch angle. The ANOVA results illustrate the influence of each process parameter on spring-back and spring-go, along with the calculated percentage contribution [19]. Vee-bending of Inconel 625 alloy using Taguchi optimization of temperature, punch speed, holding time, and rolling direction [18].

Despite these advancements, limited attention has been paid to the interplay between spring-back/spring-go and coating integrity in galvanized steels. This represents a critical research gap, particularly given the widespread application of galvanized materials in automotive body structures, where both formability and corrosion resistance are paramount. Galvanized steels, such as SCGA340BHX, produced by

Posco (coil number GA4997371), exhibit a favorable combination of mechanical strength (tensile strength: 361 N/mm², yield strength: 240 N/mm², elongation: ~38%) and corrosion protection through a zinc layer of 7–10 µm thickness. According to the JIS G 3315 standard, this steel benefits from bake-hardening effects and is widely employed in lightweight structural components [22, 23]. However, the integrity of the zinc coating is susceptible to degradation mechanisms during plastic deformation, including microcracking, delamination, and interfacial decohesion, owing to stress localization [24-26].

Numerous studies have addressed spring-back in metal forming; however, limited research has explored the concurrent occurrence of both spring-back and spring-go behaviors under varying punch angles, die openings, and punch speeds, particularly in the vee-bending of high-strength SCGA340BHX steel. This study investigates these interdependent phenomena using a Taguchi experimental design to systematically evaluate the influence of the forming parameters. The signal-to-noise (S/N) ratio analysis, based on the "smaller-is-better" criterion, revealed that the punch angle had the most significant impact on spring-back, followed by the die opening and punch speed. The experimental results demonstrated that spring-back tended to increase with wider die openings and larger punch angles, whereas spring-go occurred predominantly at higher punch speeds and 50° punch angles. These findings offer a clear understanding of how geometric and kinematic variables govern elastic recovery modes in Vee-bending and contribute new insights into the parameter-induced transition between spring-back and spring-go behaviors.

2. Methods

2.1. *Materials and equipment*

Several instruments were employed in this study, including a bevel protractor with an accuracy of 5 arcminutes for measuring bending angles and a Vernier caliper for linear dimensional measurements [13]. Fabrication of the punch and dies utilized equipment such as a heat treatment furnace, metal bucket for quenching, tongs for sample handling, wire-cut electrical discharge machining (WCEDM), and CNC milling machines. The heat treatment process involved carefully heating the tool steel to its austenitization temperature, followed by rapid quenching to achieve the desired hardness. WCEDM was utilized for the precise cutting of intricate shapes in the punch and die components. CNC milling machines were employed for final surface finishing and to ensure the dimensional accuracy of the fabricated tools.

The material investigated was SCGA340BHX galvanized steel sheet with a thickness of 0.65 mm, supplied by Posco Steel Manufacturing (coil number GA4997371). SCGA340BHX is widely applied in the automotive industry and in metal-forming processes owing to its good formability, relatively high tensile strength, and excellent deformability after bake hardening. Additionally, its zinc coating provides strong corrosion resistance. This steel grade complied with the Japanese Industrial Standard (JIS G 3115) [5]. The mechanical properties of the SCGA340BHX material used in this study are summarized in Table 1.

Table 1. Mechanical properties of SCGA340

Specification	Mechanical properties			
	T.S. (MPa)	**Y.S (MPa)**	**EL (%)**	**R-Value (%)**
JIS G 3315	≥340	235-295	≥28	1.5

SCGA340BHX steel sheets with a thickness of 0.65 mm and initial dimensions of 1219 mm × 2438 mm were cut into smaller specimens measuring 70 mm × 30 mm using a shearing machine. The dimensional accuracy of each specimen was verified using Vernier calipers. According to coil number GA4997371, the material exhibited a tensile strength of approximately 360 MPa. Each combination of experimental parameters was applied to the four specimens to evaluate the consistency and repeatability of the measured output variables. The specimen geometry and dimensions are shown in Figure 2.

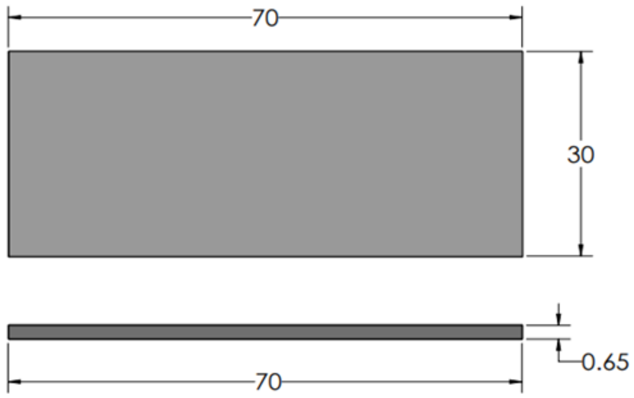

Figure 2. Geometry and dimensions of the sample

The V-die bending tools were manufactured from SKD-11 steel and heat-treated to attain a hardness of 55–62 HRC. Two types of vee-bending dies with different opening widths and heights were designed. The punch dies were fabricated with two bending angles (40° and 50°) and a bending radius of R1.0 mm. Figure 3 illustrates the vee-bending setup, where the forming process was carried out using a Mitutoyo Universal Testing Machine (M-UTM) equipped with a maximum load capacity of 10 kN.

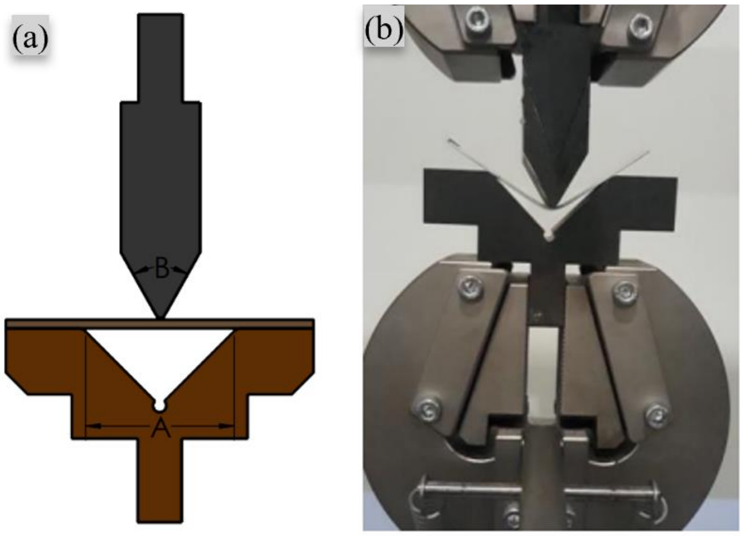

Figure 3. bending process performed using vee-bending dies: (a) vee-bending geometry, (b) testing schematic.

The bending force (F) was calculated to determine the required tonnage of the bending machine and the setting of the force on the production machine. The force required for the bending process depends on the geometry of the punch and die, as well as the strength, thickness, and length of the sheet metal being bent. The maximum bending force can be estimated using Eq.1 [27].

$$F = \frac{C_{bf} \times \sigma \times w \times t^2}{D} \quad (1)$$

where F is the bending force (N), C_{bf} is the die type constant, and the constant for the V-die type is 1.33 [28], σ is the tensile strength of the sheet metal (MPa), w is the width of the metal being bent (mm), t is the material thickness (mm), and D is the die opening dimension (mm). This test used bending forces with variations of 173.87 N and 202.85 N. The spring-back factor k_R is the ratio of the bending angle applied to the die (α_1) to the bending angle after the force is released (α_2) [29]. The spring-back factor was calculated using the following equation:

$$k_R = \frac{\alpha_2}{\alpha_1} = \frac{r_{i1}+0.5s}{r_{i2}+0.5s} \quad (2)$$

where r_{i1} and r_{i2} are the die radius and workpiece radius, respectively, in mm. The spring-back phenomenon during the vee-bending process is illustrated in Figure 4.

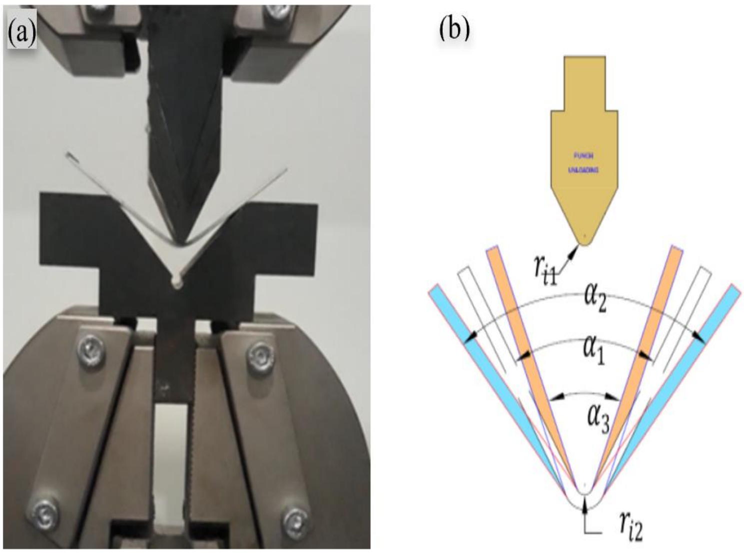

Figure 4. Spring-back phenomenon in the vee-bending process: (a) vee-bending process and (b) illustration of spring-back.

2.2. *S/N ratios*

The Taguchi analysis utilizes the concept of signal-to-noise (S/N) ratio to measure the performance of a process and ensure the stability of the obtained results [30]. There are three main categories of S/N ratios: smaller-the-better, larger-the-better, and nominal-the-best, each used according to the characteristics of the process being analyzed. The choice of S/N ratio type depends on the optimization objective, where smaller-the-better is used to minimize variability, larger-the-better is used to maximize the desired response, and nominal-the-best is used to achieve the optimal target value. These three characteristics are formulated in Equations 2, 3, and 4 and serve as the foundation for data processing to improve the manufacturing process quality [31].

Larger is better:

$$S/N\ ratio = -10 \log 10 \frac{1}{n_0} \sum_{i=1}^{n_0} \frac{1}{y_i^2} \quad (3)$$

Nominal is the best:

$$S/N\ ratio = -10 \log 10 \frac{\bar{y}^2}{s^2} \quad (4)$$

Smaller is better:

$$S/N\ ratio = -10 \log 10 \sum_{i=1}^{n_0} \frac{y_i^2}{n_0} \quad (5)$$

where n is the number of samples, $\bar{y}$ is the average response factor, y is the response factor, and s is the variance in the response factor. For material spring-back, values approaching zero were considered optimal. Therefore, the smaller-is-better characteristic was used in this study.

2.3. *Taguchi experiment parameters*

The Taguchi-based optimization method is a powerful optimization technique that differs from traditional practices because it can economically satisfy design optimization with a minimum number of experiments [32]. The Taguchi experiment was conducted by varying the following input variables: bending speed, V-die angle, and die opening length. The spring-back angle was used as the output variable. The experiment used a Taguchi experimental matrix with three input factors and a factorial design, as shown in Table 2.

Table 2. Taguchi Orthogonal Array Matrix

Code	Vee-bending parameters	Unit	Level			
			I	II	III	IV
A	Bending speed	mm/min	20	30	35	40
B	Punch angle	^{O} (degree)	40	50	-	-
C	Die opening	mm	30	35	-	-

3. Results and Discussions

3.1. *Force bending analysis*

The bending force in vee-bending plays a critical role in determining the material flow, stress distribution, and elastic recovery behaviors, such as spring-back and spring-go. In this study, force data were collected using a calibrated load cell integrated into the forming equipment (M-UTM), allowing real-time monitoring of the force–displacement response. These profiles provide insights into the deformation behavior, onset of plasticity, and development of residual stress during unloading.

The theoretical bending force was calculated using Equation 1 to establish the minimum force threshold based on the material properties and geometric parameters. For SCGA340BHX steel with a thickness of 0.65 mm and a bending width of 70 mm, the estimated forces for die openings of 30 mm and 35 mm were approximately 290.33 N and 249.17 N, respectively. These values fall well within the operational capacity of the M-UTM, ensuring that the vee-bending process is both accurate and safe. Although specific vee-bending parameters for this equipment are not always detailed in the literature, universal testing machines are widely recognized for their reliability in bending evaluations, including spring-back prediction and force-displacement analysis in high-strength steel sheets [4, 33]. Their precision in load control and displacement measurement enables consistent data acquisition, which is essential for validating material deformation behaviors. Additionally, UTM systems, such as the Mitutoyo model, have been utilized across various studies involving metal forming, fracture analysis, and material characterization [34, 35]. Thus, the use of M-UTM in this study ensures test validity while maintaining equipment safety margins. Furthermore, appropriate die selection remains crucial to balance the formability and dimensional accuracy, especially when forming thin, high-strength galvanized steel sheets.

3.2. *Spring-back and spring-go analysis*

The experimental results demonstrate that both the spring-back and spring-go behaviors are strongly influenced by key forming parameters, particularly the bending speed, punch angle, and die opening width. The elastic recovery phenomena were quantitatively evaluated using Equation 2. Eight experimental combinations were executed; each replicated four times to ensure repeatability and statistical reliability. As shown in Table 3, higher spring-back values were consistently associated with larger punch angles (50°) and wider die openings (35 mm). The highest average spring-back (3.03°) was recorded for run no. 2 (A1–B2–C2). This trend is consistent with established findings, which report that wider dies and larger punch angles reduce the contact area and localized plastic strain, thereby promoting elastic recovery. In contrast, the lowest spring-back value of 0.77° was observed for run no. 1 (A1–B1–C1), which was performed at a 40° punch angle, 30 mm die opening, and low punch speed. Notably, specimen S-3 in this experiment exhibited zero measurable spring-back, potentially indicating either perfect angular recovery or the onset of spring-go behavior.

Spring-go, defined as negative spring-back or overbending, was rarely observed during testing. The isolated case of zero spring-back in specimen S-3 suggests a possible transitional condition between elastic recovery and overbending, although further investigation with more refined angle measurements is necessary to confirm this. Experiments conducted at the highest bending speed (A4:40 mm/min) demonstrated greater variability in spring-back. For instance, run no. 7 (A4–B1–C2) showed a wide range of spring-back values from 0.70° to 3.47°, suggesting that higher strain rates may trigger instability or non-uniform elastic recovery during unloading. Additionally, a slight decreasing trend in the average spring-back was observed as the punch speed increased from 30 to 35 mm/min, indicating a potential correlation between the punch velocity and elastic behavior. These observations, as illustrated in Figure 5, highlight the delicate interplay between the forming parameters and elastic recovery mechanisms in the vee-bending of high-strength steels, underscoring the need for parameter optimization to ensure dimensional accuracy and process stability.

Table 3. Results of Taguchi experimental matrix.

Run. No.	Bending speed (mm/min)	Punch angle (°)	Die Opening (mm)	Spring-back (°)			
				S-1	S-2	S-3	S-4
1	A1 (20)	B1 (40.00)	C1 (30)	0.83	1.19	0.00	1.07
2	A1 (20)	B2 (50.00)	C2 (35)	2.91	4.01	2.39	2.81
3	A2 (30)	B1 (40.00)	C1 (30)	0.50	1.06	1.03	1.00
4	A2 (30)	B2 (50.00)	C2 (35)	2.44	2.54	3.39	3.21
5	A3 (35)	B1 (40.00)	C2 (35)	1.95	3.67	1.21	3.22
6	A3 (35)	B2 (50.00)	C1 (30)	2.63	2.37	3.16	4.47
7	A4 (40)	B1 (40.00)	C2 (35)	3.47	0.70	0.75	2.78
8	A4 (40)	B2 (50.00)	C1 (30)	2.03	2.96	3.51	2.93

In the third experimental run, conducted with the same die opening and punch angle (30 mm and 40°, respectively), but with an increased punch speed of 30 mm/min, all samples consistently exhibited positive spring-back. In contrast, six other experimental runs, namely run no. 2, 4, 5, 6, 7, and 8produced indications of spring-go behavior, characterized by a negative angular deviation beyond the intended bend angle. A closer analysis revealed a clear pattern: all tests involving a 50° punch angle consistently resulted in spring-go, irrespective of the punch speed or die opening width. This supports the hypothesis that increasing the punch angle decreases the effective bending radius and alters the stress distribution, resulting in excessive bending and a greater tendency for overbending upon unloading.

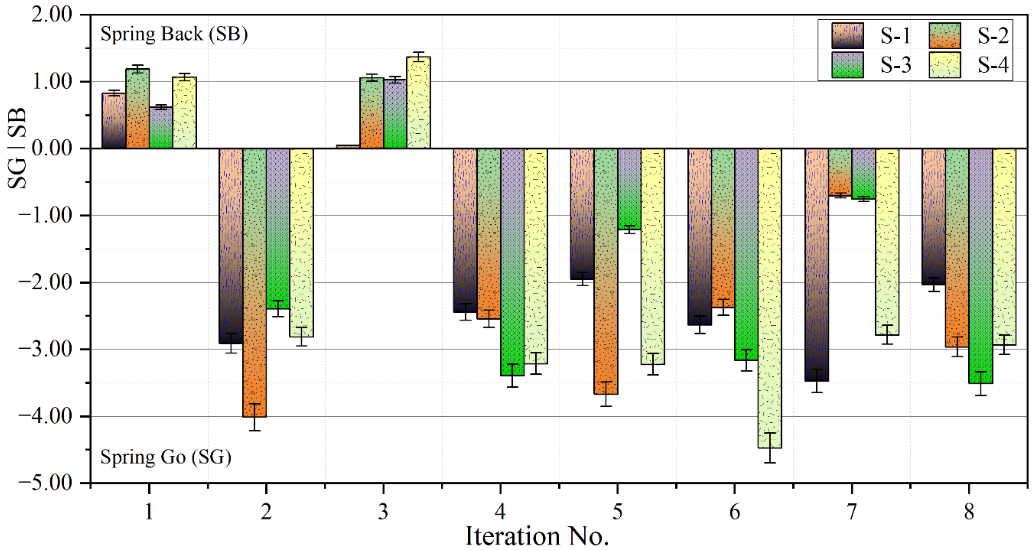

Figure 5. Spring-back and spring-go phenomenon on the 3 Vee-bending parameters tested

Furthermore, the punch speed demonstrated a strong correlation with the elastic recovery behavior. Spring-back was more frequently observed at lower punch speeds (20–30 mm/min), whereas spring-go appeared more frequently at higher punch speeds (35–40 mm/min). This trend is supported by findings in the literature, which indicate that low punch speeds allow more time for elastic energy dissipation, favoring recovery and thereby contributing to spring-back [36]. This aligns with earlier findings, where an increase in the punch angle, typically associated with higher speeds, corresponded to an increased likelihood of spring-go owing to the aforementioned mechanics [37]. Additional evidence from V-bending studies using polymer-based tooling shows that punch speed influences geometrical accuracy and surface deformation, which can alter spring-back angles and the effective bend radius [38]. Moreover, research on incremental forming processes has demonstrated that the application of ultrasonic vibrations can significantly reduce spring-back by promoting localized plasticity and reducing residual stress [39]. Overall, the results confirm that the interplay between the punch angle and punch speed plays a decisive role in dictating the transition between spring-back and spring-go behavior. An optimized balance of these parameters is essential to ensure dimensional stability and minimize post-forming corrections in vee-bending processes involving high-strength steel sheets.

3.3. *Interdependence of spring-back behavior and bending force parameters*

The experimental analysis revealed that, among the three main forming parameters (bending speed, punch angle, and die opening), the die opening had the most direct and substantial influence on the required bending force. Increasing the die opening from 30 to 35 mm led to a decrease in the theoretical bending force from approximately 268 to 230 N. This trend aligns with classical bending mechanics, where a wider die span reduces the constraint on the material, thereby lowering the force necessary to achieve plastic deformation. However, this reduction in the forming load corresponded to an increase in spring-back owing to the diminished plastic strain and confinement, which facilitated greater elastic recovery [40].

The punch angle, while contributing minimally to the forming force, played a critical role in controlling the spring-back behavior. Larger punch angles (e.g., 50°) reduce the contact area between the punch and workpiece, limiting localized plastic deformation and promoting elastic spring-back. This was evident in run no. 2 (A1–B2–C2), which showed the highest average spring-back of 3.03°, despite the lowest bending force. In contrast, smaller punch angles (e.g., 40°) induced deeper plastic zones and reduced elastic recovery, as observed in run no. 1 (A1–B1–C1), which exhibited the lowest spring-back value of 0.77° at a higher forming load of 268 N. These findings are consistent with previous studies demonstrating that optimizing the punch geometry and deformation paths in sheet metal forming can significantly reduce spring-back [41]. Effective control and reduction of spring-back can often be accomplished by optimizing the forming process through control parameters such as punch displacement and bending trajectory, aligning with the importance of precise punch angle selection [42].

Although the bending speed does not influence the theoretical force calculations, its effect on the deformation quality and elastic recovery is notable. Lower speeds (20 mm/min) produced a more controlled strain distribution and reduced elastic rebound, whereas higher speeds (40 mm/min) occasionally led to spring-go, likely due to insufficient stress relaxation under rapid loading conditions. This behavior may be explained by the strain-rate sensitivity of metals, where increased dislocation–phonon interactions at higher rates lead to elevated flow stress and potentially non-uniform deformation [43]. Recent studies have also suggested that punch trajectory control and tool material flexibility, enabled by approaches such as neural network-assisted systems and polymer-based punches, can contribute to more effectively managing spring-back [44, 45]. In summary, the choice of punch angle is a critical factor in the design of sheet metal forming processes. Smaller punch angles lead to greater plastic deformation, which positively affects the stability and quality of the deformation process by minimizing spring-back [40-42]. In summary, the interdependence between the forming force and spring-back behavior is primarily governed by the die opening and punch angle, with the bending speed exerting secondary effects. These results highlight the importance of selecting optimal parameter combinations to ensure dimensional accuracy and mechanical stability in the vee-bending of lightweight galvanized steels.

3.4. *S/N ratio analysis*

To quantitatively assess the influence of the process parameters on the spring-back behavior, a signal-to-noise (S/N) ratio analysis was performed. This method enables the identification of optimal parameter levels by evaluating the variability of the response relative to the desired output—minimized spring-back. The average S/N ratio for each parameter at its respective level was calculated. Parameters exhibiting greater variations in S/N values across levels were inferred to have a more significant impact on the response. Among the three evaluated parameters (bending speed, punch angle, and die opening), the punch angle and die opening exhibited the most substantial influence on the spring-back response, as evidenced by their wider S/N ratio spread. In contrast, the bending speed had a comparatively lower effect, particularly in the initial evaluation stages.

As illustrated in Figure 6, the optimal conditions for minimizing spring-back were identified at the highest levels of all three parameters: punch angle (50°), punch speed (40 mm/min), and die opening width (35 mm). This suggests that increasing both the punch angle and die width enhances the mechanical constraint on the material flow during bending, thereby reducing the residual elastic recovery.

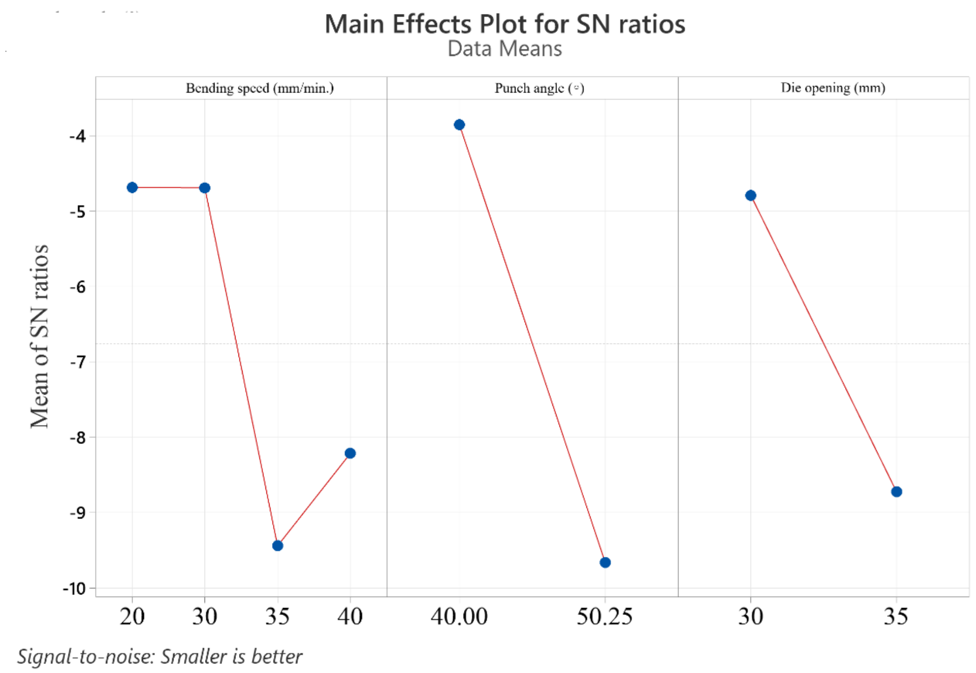

Figure 6. *Signal-to-noise (S/N) ratio for spring-back based on the "smaller-is-better" criterion.*

The punch angle was identified as the most influential factor governing the spring-back behavior, followed by the die opening width and bending speed. This finding aligns with the geometric principles of V-bending, where larger punch angles promote a tighter bend radius and induce greater localized plastic strain, resulting in a more stable plastic deformation zone that suppresses elastic recovery. In addition to the signal-to-noise (S/N) ratio analysis, mean response plots were generated to evaluate the average spring-back and spring-go values across each experimental level. For die opening, an overall decreasing trend in spring-go magnitude was observed as the die width increased, although minor deviations occurred owing to parameter interactions, as illustrated in Figure 6. Similarly, the average spring-back response decreased with increasing punch angle, reaching its lowest value at 50°, reaffirming the critical role of punch geometry in enhancing bending stability. These findings are consistent with prior research indicating that geometric refinement in blank or die design can effectively minimize the elastic recovery effects in sheet metal forming [11, 46].

The calculated and observed bending forces further support the interaction between the tooling geometry and material behavior. As the die opening increased from 30 to 35 mm, a noticeable reduction in the required bending force was observed, confirming that wider die gaps decreased the forming load but simultaneously contributed to greater spring-back [47, 48]. This trade-off highlights the importance of optimizing the punch angle and die opening to balance the forming effort and dimensional precision [48]. Although other studies have found that the material strength or strain rate may become dominant under different forming conditions [19, 46], within the conventional Vee-bending of SCGA340BHX galvanized steel, the punch angle and die opening remain the decisive parameters. These results offer a practical basis for controlling the spring-back and spring-go phenomena in lightweight steel components through precise adjustment of the forming parameters.

4. Conclusions

This experimental study on the vee-bending process of SCGA340BHX high-strength galvanized steel quantitatively examined the influence of the punch angle, die opening, and bending speed on the bending force, spring-back, and spring-go behaviors. The key quantitative findings are summarized as follows:

- The spring-back magnitude is primarily governed by the punch angle. The highest average spring-back of 3.03° occurred at a 50° punch angle, 35 mm die opening, and 20 mm/min speed (Run No. 2). Conversely, the lowest average spring-back of 0.77° was recorded at a 40° punch angle, 30 mm die opening, and the same low speed (Run No. 1).
- Spring-go behavior, characterized by negative angular deviation, was consistently observed in all test runs using a 50° punch angle, regardless of the die opening or speed. In particular, Runs 2, 4, 5, 6, 7, and 8 exhibited clear signs of spring-go, with individual specimens exceeding the set bending angle.
- A punch speed of 20–30 mm/min favored spring-back, whereas speeds of 35–40 mm/min increased the likelihood of spring-go. For example, Run No. 7 (40 mm/min) exhibited spring-back values ranging from 0.70° to 3.47°, indicating greater variability owing to the strain-rate sensitivity.
- The S/N ratio analysis confirmed that the punch angle had the most significant effect on spring-back variability, followed by die opening and bending speed. The optimal combination for minimizing spring-back was found at a 50° punch angle, 35 mm die opening, and 40 mm/min bending speed under the "smaller-is-better" criterion.
- A wider die opening (35 mm) reduced the bending force by up to 15% compared to 30 mm, but increased the average spring-back by more than 100%, emphasizing a clear trade-off between the forming load and angular accuracy.

These quantitative results offer a practical framework for parameter optimization in vee-bending processes, particularly when forming thin, high-strength steel sheets. The balance between punch geometry, forming speed, and die width is critical for minimizing post-process angular deviations and ensuring dimensional precision.

Author's Declaration

Authors' contributions and responsibilities

Hendri Susilo was responsible for conceptualization, methodology, formal analysis, and writing the original draft. **Danang Supriyanto** contributed to experimental design, instrumentation, and data visualization. **Khoirudin** supervised the project, administered the research activities, contributed to writing—review and editing, and acquired funding. **Sukarman** conducted the investigation, managed data curation and validation, and reviewed and edited the manuscript. **Dodi Mulyadi** supervised the project, administered the research activities, and contributed to writing—review and editing. **Yogi Nur Widyartha** handled the data processing and statistical analysis. **Ade Cepi Budiansyah** is involved in resource provision, material preparation, and quality control. **Afif Hakim** carried out data collection, laboratory testing, and documentation. **Ade Suhara** assisted with validation, technical support, and safety supervision. **Nana Rahdiana** contributed to conceptual review, scientific discussion, and manuscript editing. **Agus Hananto** performed formal analysis, comparative study, and literature review. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no conflicts of interest related to this study.

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