Springback in V-bending: Role of loading, force holding time, and heat treatment

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Abstract

This study investigated the effects of bending load, load holding time, and heat treatment on springback in aluminum, mild steel, and stainless steel during V-bending operations. Experiments were conducted using a universal testing machine equipped with a 90° V-die to measure springback under varying loads, holding times, and heat treatments (annealing, normalizing, and quenching). The results indicate that increased loading and holding time reduce springback, with aluminum exhibiting the highest and stainless steel the lowest. Heat treatment significantly influences springback, with annealing proving most effective in minimizing springback and enhancing dimensional stability. Error analysis confirmed the reliability of the results, with deviations within 2-3% of the mean. The study concludes that optimizing these parameters can improve process reliability and product quality in metal-forming. However, factors such as tool wear, lubrication, and environmental conditions were not considered in this study.

Keywords: Sheet metal forming; V-bending; springback; applied force; load holding time; heat treatment.

1. Introduction

Sheet metal forming encompasses a diverse array of techniques designed to transform flat metal sheets into specified geometries. This is achieved through both conventional and innovative methodologies, as well as non-standard tooling solutions, which offer unique advantages. The selection of the most appropriate method depends on criteria related to material and forming techniques. V-bending, as one of the bending processes, is a commonly used sheet metal forming technique in several industries [1, 2]. It is a prevalent technique within bending processes and is widely utilized across industries such as automotive, aerospace, and electronics manufacturing. The process involves shaping sheet metal by pressing it into a V-shaped die using a punch with a corresponding profile, thereby producing angular bends with precise geometries. These bends are favored in high-precision sectors due to their adaptability, operational efficiency, and ability to fabricate intricate components with minimal material waste [3, 4]. V-bending localizes deformation to the bending zone, leaving the rest of the sheet unaffected. This feature enables the production of complex geometries with high precision. However, springback is a typical phenomenon where the material partially reverts to its original shape after unloading-posing a persistent challenge, often resulting in deviations from the intended bend angle. Springback is influenced by material properties (e.g., elasticity, anisotropy), component dimensions, forming techniques, and surface characteristics of the bending interfaces [5-7]. Additionally, factors such as bending force magnitude/direction, workpiece orientation, tool geometry, and strain-hardening capacity significantly affect its magnitude. Extensive research on springback in V-bending operations has led to predictive models and mitigation strategies. Studies highlight loading parameters (e.g., punch stroke, applied load) as critical determinants of springback behavior, with punch stroke exerting greater influence than punch offset [8, 9]. Experimental investigations on high-strength steels have demonstrated how variations in load magnitude and duration alter springback across components with differing bend angles [10]. Optimizing these parameters is essential to minimize deviations, supported by statistical analysis of variance (ANOVA) to quantify the effects of material thickness, specimen width, bend angle, and machine settings [11, 12]. In addition to the applied load, load-holding duration has emerged as a pivotal factor, with prolonged holding times correlating with reduced springback. This parameter is integral to finite element analysis (FEA) models for enhancing prediction accuracy [13-15].

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Empirical studies on materials such as aluminum, brass, carbon steel [16], cold-rolled steel (DC01) [17], and advanced high-strength steels (DP280-440, DP340-590, DP400-780) [18] consistently confirm that extended loading durations diminish springback. However, nonlinear relationships between holding time and springback were observed in FEA simulations of advanced alloys like MP980 and AA6022-T4 [19]. For instance, Karaa?aç's fuzzy logic model revealed that increasing holding time by 10 seconds reduced springback in aluminum alloys AL1050-0 and AL5754-0 without inducing surface defects [17].

Heat treatment further modulates springback by altering material microstructure and mechanical properties. Annealing parameters, including temperature, duration, and cooling rate, directly influence springback patterns [20]. Moreover, the time elapsed between heat treatment and forming operations affects shape changes. The interplay between work hardening and heat treatment-induced stress distributions determines springback magnitude, with anisotropy playing a pivotal role [21, 22]. The timing between heat treatment and forming operations also affects dimensional stability, as work hardening interacts with thermally induced stresses to determine final geometries [23, 24]. Adjustments to bending radius, sheet thickness, and springback angle can thus be achieved through tailored thermal processing, underscoring the need for a holistic understanding of these variables. Existing literature underscores that effective springback control hinges on material elasticity, tooling design, and process parameters. Mitigation strategies such as overbending, underbending, and counterforce application are widely employed. Key levers for optimization include load magnitude and/or duration adjustments and heat treatment customization. While advanced numerical simulations provide insights into springback dynamics, prior studies have predominantly analyzed bending force, load duration, and heat treatment in isolation. Although these factors have been extensively studied individually, their interactions and combined influence on springback remain largely unexplored. Therefore, a thorough investigation into their synergistic impact is essential.

This study aims to evaluate the combined impact of bending force, load duration, and heat treatment on springback for widely used materials-mild steel, stainless steel, and aluminum alloys. Additionally, the study will compare the springback characteristics of these different materials to better understand their behavior.

2. Methodology

2.1 Experimental setup

This experimental investigation was conducted using a Universal Testing Machine (UTM - SM 1000) to perform V-bending operations. The setup comprised a hydraulic system, an electronic data logger, and custom-designed bending attachments, including a single V-shaped punch and a 90° V-angle die. Specimens were clamped onto the die, and bending was performed without lubrication at ambient temperature. Post-bending, the final bend angle was measured using a digital bevel protractor, and springback was quantified as the deviation from the initial 90° bend angle. Calibration and implementation protocols for the setup followed established procedures [25]. A photographic illustration of the experimental configuration is provided in Figure 1. The resulting data was systematically tabulated and analyzed to arrive at meaningful conclusions.

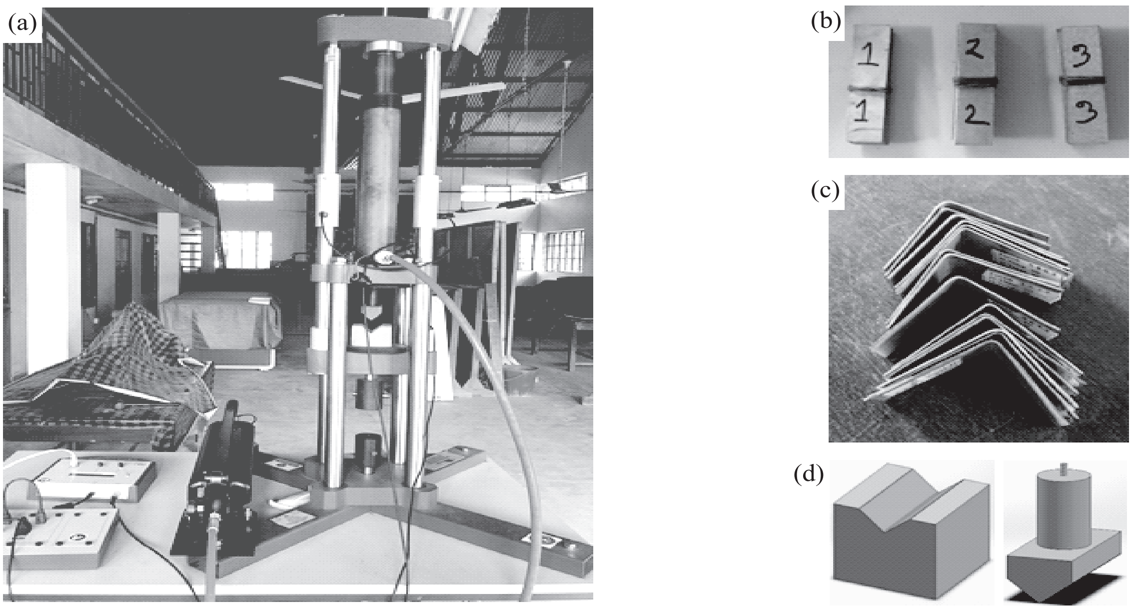


Figure 1. Experimental setup: (a) pictorial view UTM (Model SM 1000), (b) sample specimen, (c) specimens after V-bending, and (d) a set of die and punch used for V-bending.

2.2 Materials and parameters

The experiment utilized three types of materials that include mild steel (AISI 1040), aluminum (AA 3003) alloy, and stainless steel (AISI 403). These materials were chosen for their distinct mechanical properties, including yield strength, hardness, and recrystallization temperatures. Table 1 summarizes the basic physical properties and the recrystallization temperatures of the selected materials. These materials exhibit a range of behaviors in terms of ductility, strain hardening, and thermal response, enabling a comparative analysis of springback under varying conditions. A total of 108 specimens were prepared for the study, with 36 specimens for each material, and each specimen measuring 80×20×0.8 mm. The compact dimensions were selected to ensure precise angular measurements and compatibility with the testing apparatus. The die and punch were designed using SolidWorks® software and fabricated in a local workshop to maintain dimensional accuracy.

Table 1: Basic physical properties and the recrystallization temperature of selected materials

Material	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Hardness (Brinell)	Recrystallization temperature (°C)
Mild Steel (AISI 1040)	415	620	190 – 210	211	400 – 700
Aluminum (AA 3003)	130	165	70 – 80	35	260 – 350
Stainless steel (AISI 403)	415 570	530 –780	193 – 200	190 – 240	650 – 700

To address the research gap concerning the underexplored synergistic effects of bending force, load duration, and heat treatment, the experimental design incorporated:

- Applied load: 2, 5, and 8 kN (spanning light to heavy forming conditions).
- Holding time: 0, 30, and 60 seconds (to evaluate transient vs. prolonged load effects).
- Heat treatment: Three distinct heat treatment processes, such as: (1) annealing, includes heating the material above its recrystallization temperature, soaking, holding the material at this temperature for a certain time, and cooling, allowing the materials to cool slowly. The aim is to enhance ductility and reduce hardness by heating the material above its recrystallization temperature; (2) normalizing includes heating the material above its recrystallization point, soaking, and cooling to form fine grains. The aim is to improve ductility; and (3) quenching, which involves heating the material to an elevated temperature, followed by rapid cooling to preserve certain mechanical properties and hardness.

In this study, heat treatment was conducted using a Thermolyne Furnace 6000. The specimens were heated to specific temperatures tailored to their recrystallization temperatures. Due to the varying recrystallization temperatures of the materials, different heating durations were employed to reach and maintain the desired temperatures. Specifically, the furnace was set to 350 °C for aluminum alloy (AA 3003), 600 °C for mild steel (AISI 1040), and 700 °C for stainless steel (AISI 403).
Previous studies primarily examined bending force, load duration, and heat treatment as isolated factors, neglecting their interdependent effects on springback. To bridge this gap, the experimental framework systematically evaluates the combined parameter interactions through a factorial design. All permutations of the parameters- load (2, 5, 8 kN), holding time (0, 30, 60 s), and heat treatment (no heat treatment, annealed, normalized, quenched) -were tested.

Material-specific synergies were analyzed by testing mild steel, aluminum alloy, and stainless steel to understand how material properties influence the interplay between mechanical and thermal parameters. The inclusion of advanced alloys, such as stainless steel facilitates an assessment of deviations from linear springback trends observed in conventional materials. This holistic approach provides deeper insights into how the interactions between force, time, and thermal history influence springback, addressing the critical gap in existing literature.

2.3 Uncertainty Assesment

Error analysis is a crucial component of experimental research, focusing on the assessment and quantification of uncertainties in measurements and results. Its primary purposes are to identify potential sources of error during experiments, enhance reliability, and validate the experimental findings. To enhance the accuracy of the experimental outcomes, both systematic errors and random errors were addressed. Systematic errors were minimized through proper calibration of instruments, careful experimental design, and accurate data logging. Random errors were reduced by ensuring material consistency, precise specimen preparation, strict furnace temperature control, and replication when necessary. Additionally, three sets of data were collected for each experiment to further reduce errors and ensure reliable results.

3. Data Analysis and Results

Following the experiment, data were analyzed using MS Excel®, and various graphs were generated using SigmaPlot® 15.0. The effect of different parameters on springback are presented under four distinct headings, as outlined below.

3.1 Effect of loading on springback

Figure 2 reveals a consistent trend across the three metals investigated: mild steel, aluminum, and stainless steel. An increase in applied force resulted in a corresponding decrease in springback. This observation drawn from a dataset comprising nine experimental springback values for three force levels, which were subsequently averaged. A significant reduction in springback was observed starting at a force level of 2 kN, as demonstrated by plotting mean springback against varying force levels. This trend clearly indicates an inverse relationship between the applied bending force and the magnitude of springback.

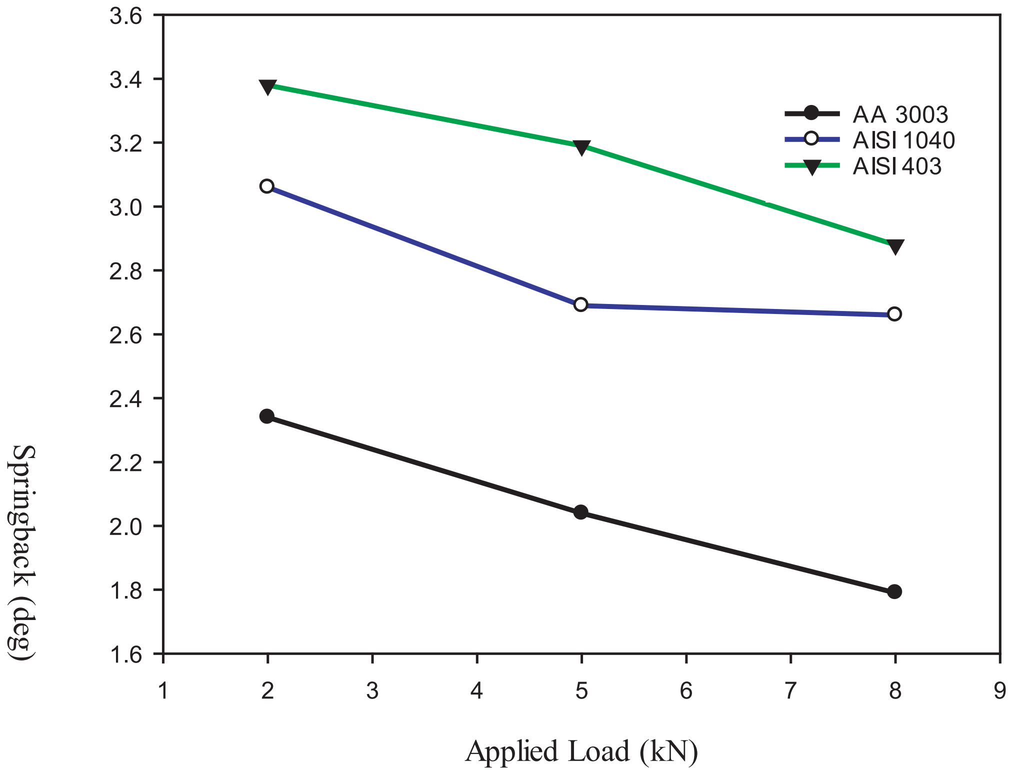


Figure 2. Effect of loading on the springback for mild steel, aluminum and stainless steel.

Under a minimal load of 2 kN and a 30-second holding time, stainless steel exhibited the highest springback angle at 3.38°, followed by mild steel (3.06°) and aluminum (2.34°). Conversely, under the maximum load of 8 kN and a 30-second holding time, the lowest springback angles were recorded: 2.88° for stainless steel, 2.66° for mild steel, and 1.79° for aluminum. A notable distinction in springback behavior among the materials was observed at a load of 5 kN and a 30-second holding time.

3.2 Effect of load holding time on springback

The duration for which a forming load is maintained on a workpiece, referred to as load holding time or dwell time, significantly influences the springback of a material. As illustrated in Figure 3, a consistent reduction in springback angle was observed across mild steel, aluminum, and stainless steel as the load holding time increased. However, the extent of springback varied considerably among these materials. For stainless steel, the springback angle was 3.37° under an applied load of 5 kN with immediate load removal, decreasing to 3.19° and 3.08° for dwell times of 30 and 60 seconds, respectively. Aluminum exhibited a more pronounced reduction, with springback angles of 2.33°, 2.04°, and 1.86° for the same load and time increments. Mild steel showed a less dramatic decrease, starting at 3.19° and reaching 2.69° and 2.61° for the 0, 30, and 60 second intervals, respectively. Notably, both stainless steel and mild steel consistently demonstrated higher springback values compared to aluminum under all conditions.

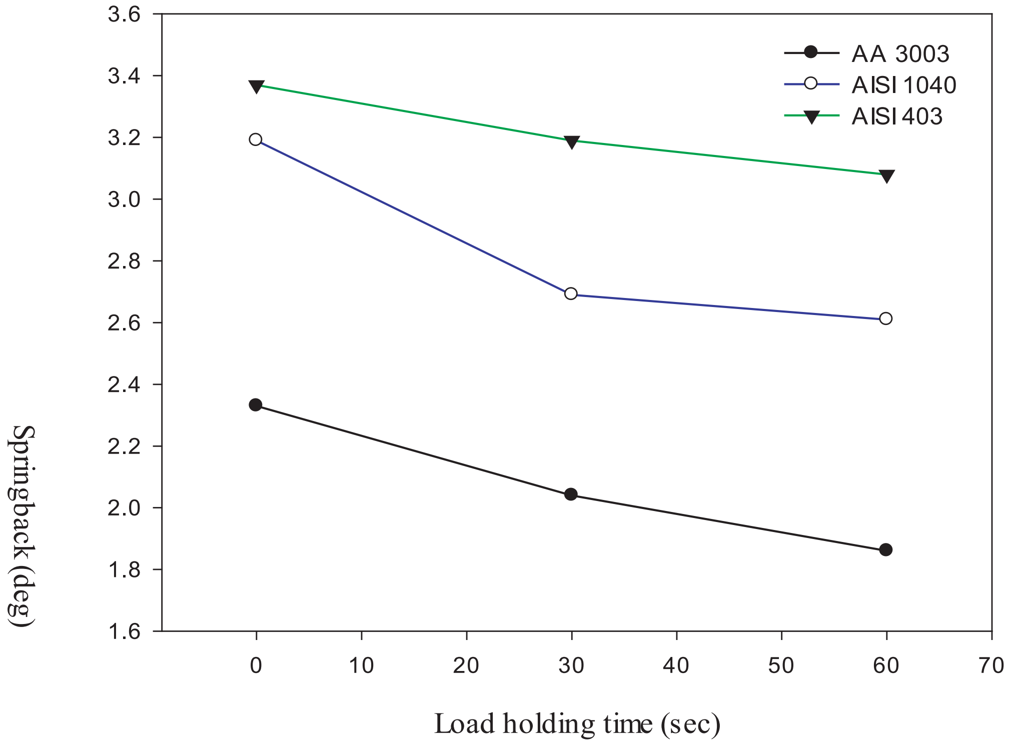


Figure 3. Effect of loading on the springback for mild steel, aluminum and stainless-steel.

3.3 Effect of heat treatment on springback

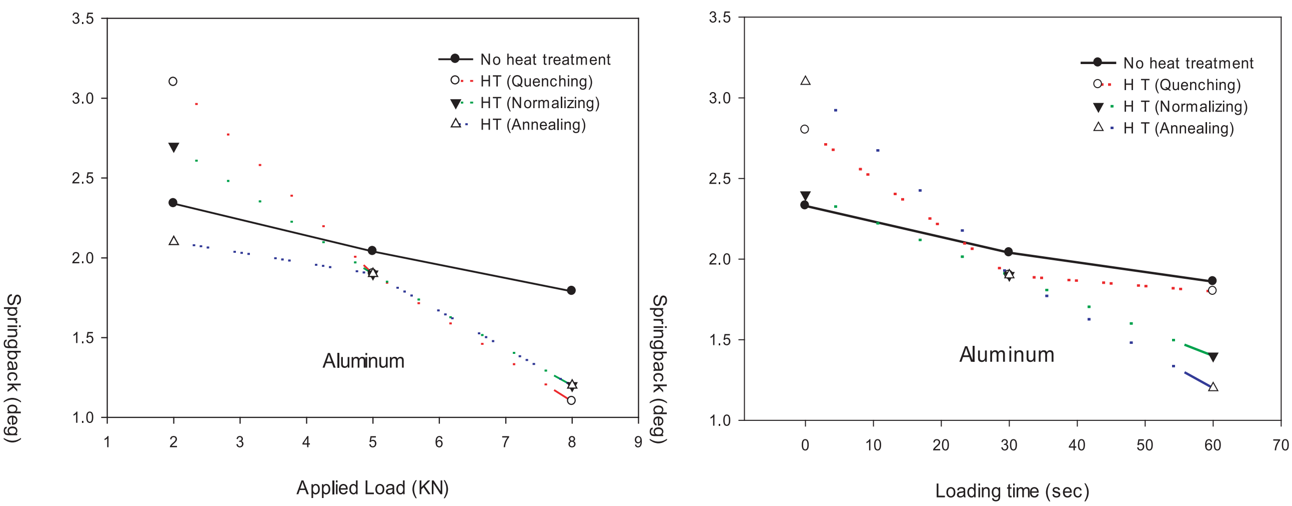
Heat treatment processes significantly alter the mechanical properties of metals, thereby influencing their springback behavior. Figure 4 illustrates the effects of various heat treatments-annealing, normalizing, and quenching, compared to no heat treatment on the springback of mild steel, aluminum, and stainless steel.

As depicted in Figure 4(a), heat treatment has a substantial impact on the springback behavior of aluminum alloys, specifically AA 3003, during metal forming. Without heat treatment, the springback angles for applied loads of 2, 5, and 8 kN with a 30 second holding time were 2.34°, 2.04°, and 1.79°, respectively. However, when heat treatments were applied, the springback angles changed significantly. For quenching, the angles were 3.10°, 1.90°, and 1.10°; for normalizing, 2.70°, 1.90°, and 1.20°; and for annealing, 2.10°, 1.90°, and 1.20° for applied loads of 2, 5, and 8 kN, respectively.

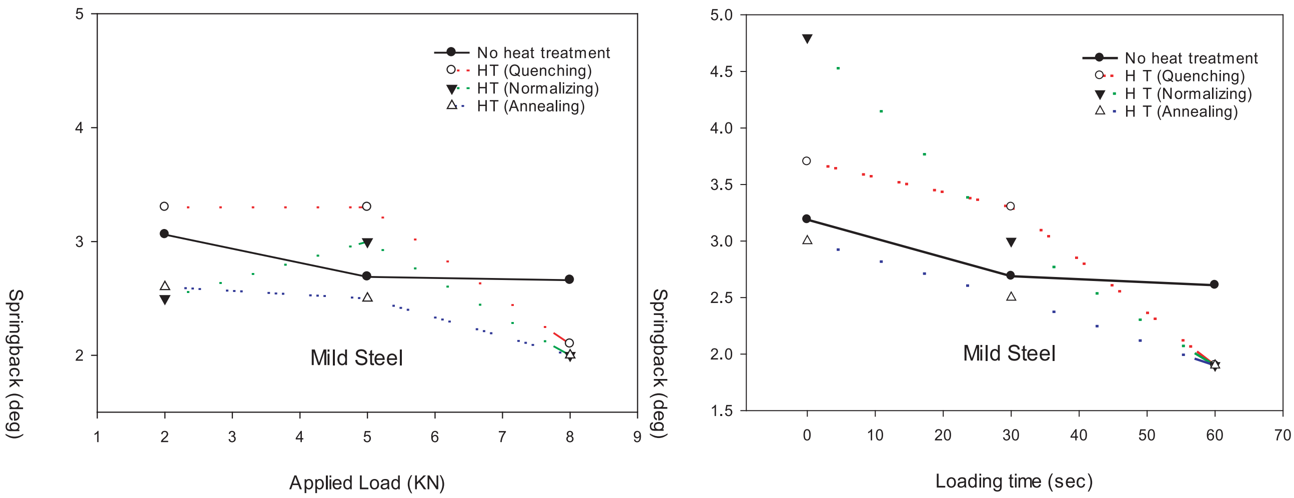
When considering the combined effects of the applied load and load holding time, the springback values for a 2 kN load without heat treatment were 2.33°, decreasing to 2.04° and 1.86° for 30 and 60 second holding times, respectively. With heat treatments, the recorded springback angles for a 2 kN load were 2.80° for quenching, 2.40° for normalizing, and 3.10° for annealing. For higher applied loads of 5 kN and 8 kN, springback values consistently decreased across all heat treatments. Table 2 summarizes the springback characteristics of mild steel and stainless steel under various heat-treatment conditions. The influence of heat treatment on springback behavior in mild steel and stainless steel during the forming process is illustrated in Figures 4(b) and 4(c). The optimal (best) heat treatment depends on specific application requirements. In this study, quenching resulted in higher springback compared to normalizing and annealing, with normalizing and annealing producing relatively lower springback values. Overall, the study demonstrates that heat treatment processes, particularly quenching, normalizing, and annealing, play a crucial role in modulating springback behavior across different metals. Quenching generally leads to higher springback, while normalizing and annealing result in comparatively lower values.

Table 2 Springback of Aluminum, mild steel and the stainless steel under different heat-treatment conditions.

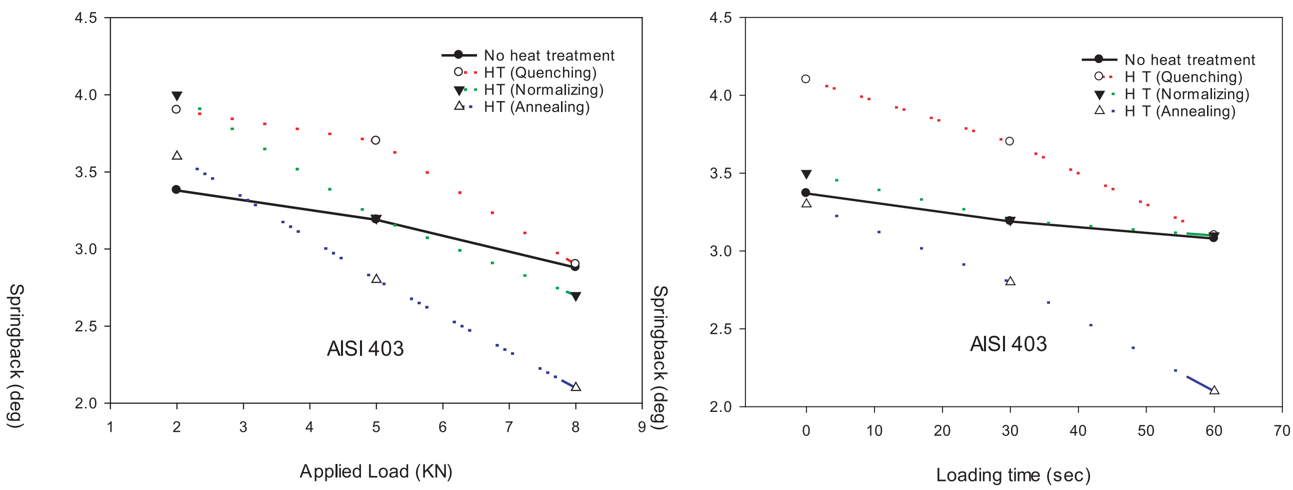
Applied load (kN)	No heat treatment	Quenching	Normalizing	Annealing	Holding time (sec)	No heat treatment	Quenching	Normalizing	Annealing
Aluminum (AA 3003) alloy with holding time 30 sec;					with applied load of 5 kN				
2	2.34°	3.10°	2.70°	2.10°	0	2.33°	2.80°	2.40°	3.10°
5	2.04°	1.90°	1.90°	1.90°	30	2.04°	1.90°	1.90°	1.90°
8	1.79°	1.10°	1.20°	1.20°	60	1.86°	1.80°	1.40°	1.20°
Mild steel (AISI 1040) with holding time 30 sec;					with applied load of 5 kN				
2	3.06°	3.30°	2.50°	2.60°	0	3.19°	3.70°	4.80°	3.00°
5	2.69°	3.30°	3.00°	2.50°	30	2.69°	3.30°	3.00°	2.50°
8	2.66°	2.10°	2.00°	2.00°	60	2.61°	1.90°	1.90°	1.90°
Stainless steel (AISI 304) with holding time 30 sec;					with applied load of 5 kN				
2	3.38°	3.90°	4.00°	3.60°	0	3.37°	4.10°	3.50°	3.30°
5	3.19°	3.70°	3.20°	2.80°	30	3.19°	3.70°	3.20°	2.80°
8	2.88°	2.90°	2.70°	2.10°	60	3.08°	3.10°	3.10°	2.10°



(a) Impact of non-heat treated and heat-treated aluminum alloy.



(b) Impact of non-heat treated and heat-treated mild steel.



(c) Impact of non-heat treated and heat-treated stainless steel.

Figure 4. Comparative analysis of springback behavior for non-heat-treated materials and those subjected to annealing, normalizing, and quenching in aluminum, mild steel, and stainless steel.

3.4 Uncertainty Assessment

To ensure the reliability of the data, each data point was derived by averaging three independent experimental trials. The resulting values were plotted against their deviation from the mean, as illustrated in Figure 5. This assessment demonstrates a consistent pattern with minimal variability across the experimental datasets. The maximum deviation from the mean was a modest 2%, with only two data points exceeding this threshold but remaining below 3%. These results collectively indicate a high degree of experimental precision and reproducibility.

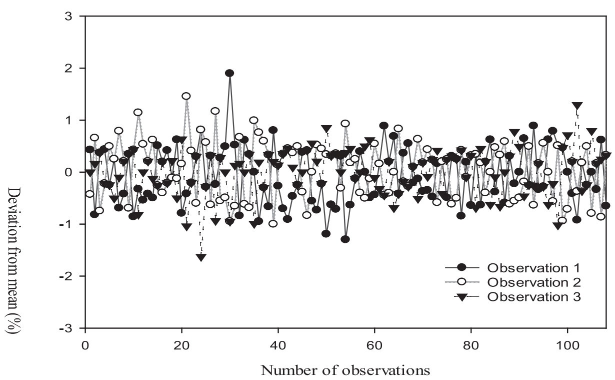


Figure 5 Deviation from average value of data.

4. Discussion

Springback refers to the tendency of a material, whether metallic or non-metallic, to partially return to its original shape after undergoing deformation during processes such as bending. Experimental studies have been conducted to evaluate how factors such as applied load, load holding time, and heat treatment processes influence the springback angle in V-bending operations.

Figure 2 demonstrates that an increase in applied load leads to a reduction in the springback angle for all three materials studied-mild steel, aluminum, and stainless steel. This phenomenon can be attributed to the physical properties of materials, including yield strength, Young's modulus, strain hardening behaviour, the Bauschinger effect, and the plastic strain ratio, as well as the deformation mechanisms involved in bending. During deformation, materials initially undergo elastic deformation, followed by plastic deformation as the load increases. Higher applied loads cause greater yielding, resulting in more significant changes in internal stress distribution. Consequently, a larger proportion of the deformation becomes permanent, reducing the springback effect. Material thickness, bending radius, and the tooling also interact in complex ways to influence permanent deformation. Generally, materials with higher yield strength and hardness exhibit greater springback angles compared to more ductile metals. For instance, stainless steel, with its higher yield strength and hardness, displayed the highest springback angle among the tested materials, followed by mild steel and aluminum under identical conditions.

Figure 3 highlights the significant impact of load holding time, or dwell time, on the springback angle in aluminum, mild steel, and stainless steel. When a load is applied and removed quickly, the material primarily undergoes elastic deformation, resulting in a predictable and consistent springback angle. In contrast, load holding times allow for additional effects such as stress relaxation and localized heating, which can reduce the material's yield strength and lead to a smaller springback angle. Time-dependent phenomena like creep can also induce further deformation during the load holding period, reducing the material's ability to fully return to its original shape.

The springback effect varies among mild steel, aluminum, and stainless steel due to their distinct material properties. Aluminum, with its lower yield strength and higher ductility, exhibits a larger springback effect and is particularly sensitive to load holding time and time-dependent behavior. Mild steel shows moderate and relatively predictable springback, with sensitivity to strain-hardening and load holding time effects. Stainless steel, on the other hand, demonstrates lower springback due to its higher yield strength and stiffness, exhibiting complex interactions related to work hardening and stress relaxation.

Heat treatment processes significantly influence the physical properties of materials, including yield strength, hardness, and ductility. Each heat treatment method imparts distinct characteristics to the material, tailoring its performance for specific applications. Annealing optimizes hardness, ductility, and grain structure, making materials more suitable for various applications. Normalizing refines the grain structure, enhancing toughness and homogeneity. Quenching increases hardness and strength but may introduce brittleness.

Figure 4 presents a comparative analysis of springback behavior in non-heat-treated materials versus those subjected to annealing, normalizing, and quenching across aluminum, mild steel, and stainless steel. This analysis highlights the impact of different heat treatment processes on the springback characteristics of these materials. Longer loading times lead to a reduction in springback, indicating that the material has more time to adjust to the stress, reducing its tendency to return to its original shape.

From Figure 4(a), aluminum with no heat treatment typically exhibits a moderate springback, whereas annealing consistently results in least springback, indicating better formability and less tendency to revert to the original shape. Quenching initially shows the most springback, but this effect diminishes with increasing load and time. Normalizing shows a steady reduction in springback, similar to quenching but at slightly lower values. It can be concluded that both applied load and loading time reduce springback in aluminum, with annealing being the most effective heat treatment to minimize springback.

Similarly, Figures 4 (b) and (c) depict the relationship between the springback of mild steel and stainless steel and two variables: applied load (left plot) and loading time (right plot). The graphs clearly show that heat treatment reduces springback in both mild steel and stainless steel, improving their resistance to deformation. Untreated mild steel shows greater springback, while heat-treated materials exhibit lower springback due to increased strength and better shape retention. Among the heat-treated conditions, annealing (blue lines) consistently yields the lowest degree of springback, providing the best shape retention and formability. Normalizing performs better than no heat treatment but is less effective than annealing. Quenching (red line) generally results in the lowest springback, effectively increasing the material's hardness and reducing its elasticity.

The selection of the optimum heat treatment process depends on the specific application requirements. For scenarios demanding both strength and minimal springback, quenching is the preferred method. Conversely, if the focus is on enhancing ductility and formability, annealing may be a more appropriate method. Normalizing offers a balanced compromise between these properties. Among the heat-treatment options examined, annealing stands out as the most effective for reducing springback across all the materials tested, conferring the highest degree of dimensional stability after forming or load removal.

While this study provides valuable insights into the effects of applied load, load holding time, and heat treatment on springback, certain limitations must be acknowledged. The experiments were conducted under controlled laboratory conditions, which may not fully replicate real-world manufacturing environments. Additionally, the study focused on three specific materials-mild steel, aluminum, and stainless steel-and may not be directly applicable to other materials or complex geometries. The influence of additional factors, such as tool wear, lubrication, and environmental conditions, was not considered. Future research could address these limitations by incorporating a broader range of materials, exploring more complex forming processes, and investigating the combined effects of multiple variables on springback behavior.

5. Conclusion

In summary, controlling springback in metal-forming operations requires a precise balance of applied load, loading time, and appropriate heat treatment. A thorough understanding of the interplay between these factors is essential for enhancing process reliability and product quality. The key findings of this study are summarized as follows:

- An increase in applied load results in a reduction of springback across all materials. Aluminum exhibits the highest springback, mild steel demonstrates moderate springback, and stainless steel shows the least springback, necessitating higher forces to achieve the desired bending angle.
- Prolonged load holding time leads to a decrease in springback for all materials. Mild steel experiences the most significant reduction, aluminum shows a moderate decrease, and stainless steel displays the least reduction, primarily due to increased plastic deformation over extended durations.
- As load holding time increases springback decreases for all materials, with mild steel showing the most reduction, aluminum a moderate reduction, and stainless steel the least, due to increased plastic deformation over longer durations.
- Heat treatment plays a critical role in modulating springback. Quenching tends to increase springback, while annealing effectively reduces it. Higher applied loads and longer load holding times further minimize springback, with annealing emerging as the most effective treatment for achieving dimensional stability.
- The experimental data demonstrate a high level of accuracy, with deviations from the mean value remaining within 2% to 3% range, confirming the reliability of the results.

Future research should focus on optimizing the interplay between applied load, loading time, and heat treatment processes to further mitigate springback in diverse materials. Investigating the microstructural changes induced by these parameters could provide deeper insights into their influence on springback behavior. Additionally, exploring advanced materials, such as alloys and composites, with varying compositions or treatments could broaden the understanding of springback in more complex scenarios. Finally, integrating computational modeling with experimental approaches may enable more accurate prediction and control of springback, leading to improved process reliability and product quality in metal-forming operations.

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Author contributions

Author contributions

M. A. Karim: Conceptualization, Methodology, Data curation, Formal analysis, Project administration, Funding acquisition, Supervision and Writing- original draft; M. A. H. Mithu: Conceptualization, Methodology, Data curation, Formal analysis, Writing- review and editing; R. Ahmed: Data curation, validation, software, visualization; T. I. Rajon: Data curation, validation, software, visualization.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data relevant to this research has saved in Mendeley Data, available in: Karim, Mohammed A (2024), "Springback in V-bending: Role of Loading, force holding time, and heat treatment", Mendeley Data, V1, doi: 10.17632/3xkycn4xz7.1

Research Highlights

1. Higher applied load reduces springback; aluminum shows the highest, stainless steel the least.
2. Increased load holding time decreases springback, with mild steel most affected, stainless steel least.
3. Heat treatment alters springback; annealing minimizes it, enhancing dimensional stability in formed metals.
4. Error analysis shows deviations within 3% of the mean, ensuring satisfactory accuracy in springback prediction.

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