Journal of Chemical Health Risks

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JCHR (2025) 15(3), 2146-2153 | ISSN:2251-6727

# Finite Element Analysis of Springback Behavior in SPCC Double-Layer Sheets During L-Die Bending: Influence of Die Radius, Clearance, and Plate Length

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***(Received: 16 March 2025 Revised: 20 April 2025 Accepted: 15 June 2025)***

**KEYWORDS**

double-layer metal sheet, SPCC steel, springback, L-die bending, Abaqus, finite element simulation, die geometry, elastic recovery

**ABSTRACT:**

This study investigates the influence of key geometric parameters—specifically die radius, punch–die clearance, and sheet length—on the springback behavior of double-layer SPCC steel sheets during L-die bending. Utilizing finite element method (FEM) simulations implemented in Abaqus, the research replicates the bending process to predict elastic recovery post-deformation. The simulated configurations mirror experimental setups referenced in a prior benchmark study for comparative validation. The numerical results reveal that the springback response in SPCC double-layer sheets is similarly sensitive to variations in die geometry and blank dimensions as observed in the referenced copper-aluminum layered material. Notably, increasing the die radius or decreasing the punch–die clearance significantly reduces elastic recovery, whereas longer sheet lengths result in greater springback. These trends highlight the importance of precise die design in minimizing geometric deviations after forming, especially in layered sheet metal applications. The findings contribute to an improved understanding of post-forming behaviors in advanced multilayer sheet materials and support the optimization of tooling configurations for enhanced dimensional accuracy in industrial forming processes.

## 1. Introduction

Springback is a critical challenge in sheet metal forming processes, particularly in precision bending operations, where deviations from the desired geometry can significantly affect product quality and dimensional accuracy. This elastic recovery, which occurs after unloading, is influenced by various factors such as material properties, tool geometry, sheet thickness, and contact conditions between the die and the workpiece [1,2]. In recent years, the advancement of high-precision forming in the automotive, aerospace, and electronics industries has heightened the demand for accurate prediction and control of springback, especially for thin and multilayered metal sheets.

SPCC (Steel Plate Cold Commercial) is widely used in these industries due to its excellent formability and low cost. However, when processed in multilayer configurations—such as in double-layer sheets—the complexity of deformation mechanisms increases significantly. Interfacial interactions, differential strain distribution, and the constraint effects between the layers contribute to unpredictable springback behavior, which is not well understood in the existing literature [3,4]. Most previous studies have focused on monolayer sheet bending, while the behavior of laminated or multi-layered sheets remains underexplored.

Furthermore, L-die bending, a commonly used forming method for achieving sharp angles and complex profiles, presents unique challenges in managing springback due to its high stress concentration and non-

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JCHR (2025) 15(3), 2146-2153 | ISSN:2251-6727

uniform strain distribution [5]. Parameters such as die radius, punch-die clearance, and sheet length play a critical role in the springback response but have been mostly investigated in the context of single-layer materials [6]. The effects of these geometrical and dimensional parameters on the springback behavior of double-layer SPCC sheets remain largely unknown.

Recent developments in finite element analysis (FEA) have enabled more accurate simulations of the bending process, offering valuable insights into stress-strain evolution and elastic recovery during unloading [7,8]. However, the application of such techniques to the study of springback in layered sheet systems is still in its infancy. Thus, there is a pressing need to systematically analyze how tool design and sheet dimensions influence the springback in multi-layer systems.

This study addresses this research gap by conducting a comprehensive finite element analysis of springback behavior in SPCC double-layer sheets subjected to L-die bending, focusing on the influence of die radius, clearance, and sheet length. The novelty of this work lies in:

- Investigating the interaction between geometric parameters and interlayer deformation mechanisms in a double-layer sheet configuration;
- Applying a validated FEA model to quantitatively predict and analyze springback behavior in a layered system;
- Providing design recommendations for minimizing springback through optimized tooling and sheet dimensions.

By advancing the understanding of springback in multilayer SPCC sheets under L-die bending, this research contributes to the development of more accurate and reliable forming technologies for next-generation lightweight structural components.

## 2. Materials and Simulation

### 2.1. Material Specification

The material used in this study is SPCC (Steel Plate Cold Commercial), a cold-rolled low-carbon steel widely applied in precision sheet metal forming due to its excellent surface finish, dimensional stability, and cost-effectiveness. Produced under the JIS G-3141 Japanese Industrial Standard, the third letter “C” in SPCC denotes its cold-rolled processing. SPCC is characterized by high formability and moderate strength, making it particularly suitable for components requiring tight dimensional tolerances and surface aesthetics [1].

In this study, a double-layer configuration of SPCC was modeled to explore the effects of interlayer behavior on springback during L-die bending—an area largely underexplored in current literature. Each layer was modeled individually, with material contact interactions included to capture the nuanced response during plastic deformation and elastic recovery. The mechanical properties of SPCC used in the finite element simulations are presented in Table 1.

Table 1. Mechanical Properties of SPCC Material

| Property | Value |
|---|---|
| Density | $7.8 \times 10^{-6}$ kg/mm³ |
| Elastic modulus (Young’s modulus) | 210,142 MPa |
| Poisson’s ratio | 0.3 |
| Stress-strain relationship | $\sigma = 166 + 210.142 \times (1 - \exp(-41.452 \times \varepsilon))$ |

The nonlinear stress-strain curve was defined by an exponential hardening function to simulate the elastic-plastic transition accurately. This constitutive model enables precise prediction of springback, which is highly sensitive to the unloading modulus and material strain hardening behavior.

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JCHR (2025) 15(3), 2146-2153 | ISSN:2251-6727

2.2. Finite Element Modeling and Boundary Conditions

To analyze springback phenomena in L-die bending of SPCC double-layer sheets, a finite element model was developed using ABAQUS/Explicit. The 3D model includes a punch (upper tool), die (lower tool), and a blank holder, with frictional contacts defined at all interfaces to realistically capture interfacial forces between the two sheet layers and the tooling (Fig, 1) Each sheet layer was modeled individually to account for contact-induced stress redistribution during bending and unloading.

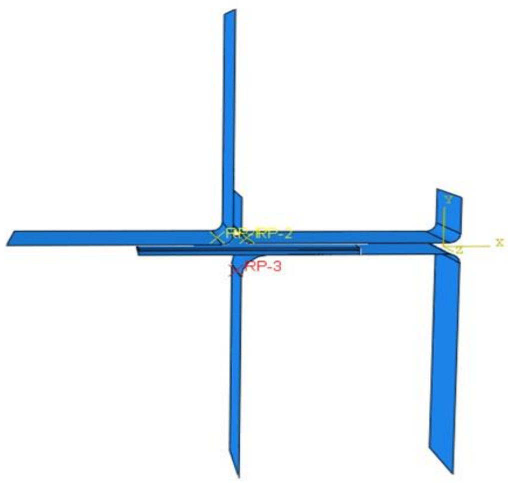


Fig.1: The 3D model in L-die bending of SPCC double-layer sheets

Three key geometric parameters were varied:

- Die radius: 3 mm, 5 mm, and 7 mm
- Sheet length: 40 mm, 60 mm, and 80 mm
- Punch-die clearance: 0.1 mm, 0.2 mm, and 0.3 mm

Table 2. Tool Dimensions

| Component | Height (mm) | Length (mm) | Width (mm) | Corner Radius (mm) |
|---|---|---|---|---|
| Blank holder | 10 | 40 | 20 | 2 |
| Die | 50 | 40 | 20 | 3, 5, 7 |
| Punch | 50 | 40 | 25 | 2 |

Table 3. Sheet Geometry

| Layer | Length (mm) | Width (mm) | Thickness (mm) |
|---|---|---|---|
| SPCC Top Layer | 40, 60, 80 | 20 | 0.5 |
| SPCC Bottom Layer | 40, 60, 80 | 20 | 0.5 |

The simulation process was divided into three key steps to replicate the bending and springback process:

- Step 1 – Contact Establishment: The blank holder is lowered at a constant velocity (1 mm/s) until it contacts the top SPCC layer.
- Step 2 – Bending: The punch moves downward to deform the double-layer sheet into the die cavity until full contact with the die radius is established.
- Step 3 – Unloading: The punch is retracted to its original position, enabling the springback of the deformed sheets.

Table 4. Boundary Conditions for Simulation Steps

| Component | Step 1 | Step 2 | Step 3 |
|---|---|---|---|
| Die | $U_1 = U_2 = 0$ | $U_1 = U_2 = 0$ | $U_1 = U_2 = 0$ |
| Punch | $U_1 = 0$ | $U_1 = 0$; $U_2 = -50$ | $U_1 = 0$; $U_2 = 50$ |
| Blank Holder | $U_1 = U_2 = 0$ | $U_1 = U_2 = 0$ | $U_1 = U_2 = 0$ |

In all simulations, a friction coefficient of 0.1 was applied to the interfaces to reflect realistic contact interactions between tool and sheet, and between the sheet layers. Mesh sensitivity analyses were performed

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to ensure convergence, with finer mesh zones concentrated near the bend region to capture high-gradient stress fields.

## 3. Results and Discussion

The results of the finite element simulations demonstrate a clear and quantifiable relationship between the elastic springback of the SPCC dual-layer steel sheet and the key geometric parameters involved in the forming process—namely the die radius, the punch-die clearance, and the sheet length. The simulations were systematically designed to isolate the effects of each variable while maintaining the others constant, providing a clear insight into their individual and combined influences on post-deformation recovery behavior.

### 3.1. Effect of Die Radius on Springback Behavior

As illustrated in Figure 2, the effect of die radius on the springback behavior of dual-layer SPCC sheet metal was investigated under controlled geometric conditions. Specifically, the sheet length was held constant at L = 60 mm, and the punch–die clearance was fixed at C = 0.2 mm to ensure consistent boundary constraints across simulations. The die radius R was systematically varied through three representative values: 3 mm, 5 mm, and 7 mm, which span a practical range commonly encountered in industrial sheet metal forming operations.

The simulation results exhibit a distinct and consistent trend: increasing the die radius significantly reduces the magnitude of elastic springback observed after unloading. This behavior can be primarily attributed to the mechanics of deformation: a larger die radius produces a gentler bending profile, resulting in lower localized plastic strains and more uniform stress distributions throughout the deformed region. Consequently, the elastic strain energy stored during bending is minimized, which in turn reduces the recovery deformation during unloading.

In contrast, a smaller die radius induces more severe local curvature, leading to higher stress concentrations at the bending zone and a greater accumulation of plastic deformation. When the forming load is removed, this concentrated elastic energy is released, resulting in a more significant rebound of the material—i.e., increased springback.

These findings align with the fundamental principles of bending mechanics and stress redistribution but further contribute to the field by demonstrating these effects within a dual-layer configuration of SPCC sheet metal, a material setup that is not extensively covered in existing literature. The multi-layer approach introduces additional complexity due to interfacial friction, constraint mismatch, and non-uniform through-thickness stress gradients, making these results particularly valuable for researchers and engineers working on layered material systems in precision forming applications.

The outcomes presented in this study offer not only theoretical validation but also practical guidance for die design and process parameter selection in cold forming processes, where minimizing springback is critical for maintaining dimensional accuracy.

| R | FEM | EXP | SPCC | % |
|---|---|---|---|---|
| 3 | 1.55 | 1.5 | 1 | 33.33 |
| 5 | 3.7 | 3.8 | 3.1 | 18.42 |
| **7** | **4.7** | **5** | **4.5** | 10.00 |

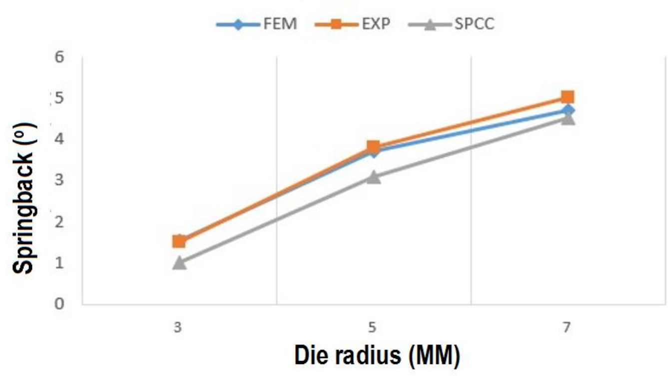


Fig. 2 Effect of Die Radius on Springback Behavior

### 3.2. Effect of Punch–Die Clearance on Springback Behavior

As illustrated in Figure 3, the next phase of the investigation focused on analyzing the influence of

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JCHR (2025) 15(3), 2146-2153 | ISSN:2251-6727

punch–die clearance on the springback behavior of the dual-layer SPCC sheet metal. In this series of simulations, the die radius was held constant at R = 5 mm and the sheet length was fixed at L = 60 mm, to isolate the effects of the clearance variable. Three distinct punch–die clearance values were examined: C = 0.1 mm, 0.2 mm, and 0.3 mm.

The simulation results reveal a clear inverse relationship between clearance size and springback magnitude. When the clearance was set at C = 0.1 mm, the SPCC sheet experienced the most pronounced springback. This is due to the higher contact force and constraint effect imposed by the closely spaced die and punch, which results in greater plastic deformation and elastic energy storage during the forming stage. Upon unloading, this stored elastic energy is released more abruptly, manifesting as a larger elastic recovery.

As the clearance increases to 0.2 mm and 0.3 mm, the degree of springback decreases. This reduction is attributed to a decrease in material constraint and contact stress, as the gap between punch and die allows for a less aggressive forming contact. With the reduction in contact intensity, the stress gradients across the sheet thickness are moderated, leading to a smoother stress redistribution and diminished elastic rebound.

These findings are consistent with classical forming mechanics, but they gain additional relevance in the context of dual-layer SPCC sheet forming, which inherently presents more complex interfacial mechanics. The interaction between the two SPCC layers under varying clearance conditions adds a novel dimension to the analysis—particularly in terms of how frictional behavior, interlayer slipping, and composite stiffness influence springback. To the best of the authors' knowledge, such a systematic investigation of clearance effects in multi-layer sheet forming configurations has not been widely reported, thereby highlighting the originality and practical significance of the present study.

Moreover, from an industrial perspective, these results offer actionable insight into the optimization of tooling tolerances for springback control. The findings suggest that tighter clearances, while offering better control of geometry during forming, may inadvertently increase springback, especially in layered material systems. Thus, a balance must be carefully maintained between dimensional conformity and post-forming stability.

| C | FEM | EXP | SPCC | % |
|---|---|---|---|---|
| **0.1** | **2.6** | **2.7** | **2.2** | 18.52 |
| 0.2 | 3.7 | 3.8 | 3.1 | 18.42 |
| 0.3 | 4.53 | 4.8 | 4.2 | 12.50 |

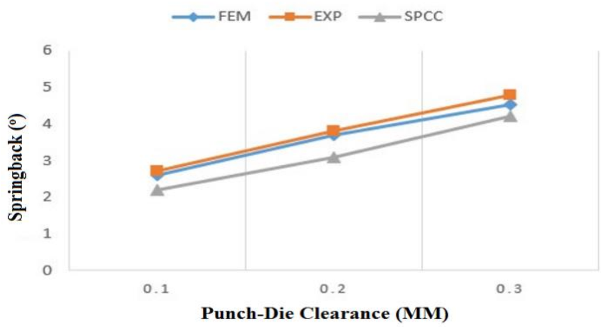


Fig. 3 Effect of Punch-Die Clearance on Springback Behavior

3.3. Effect of Sheet Length on Springback Behavior

To investigate the effect of sheet length on the springback behavior of SPCC sheet metal, simulations were performed with the die radius (R = 5 mm) and punch–die clearance (C = 0.2 mm) held constant. Three sheet lengths were selected for analysis: L = 40 mm, 60 mm, and 80 mm. This allowed for a focused evaluation of how geometric scale influences elastic recovery after plastic deformation in a dual-layer forming configuration.

The simulation results, presented in Figure 4, show a progressive increase in springback magnitude with increasing sheet length. The shortest specimen (L = 40 mm) exhibited minimal elastic recovery after unloading, while the longest sheet (L = 80 mm) demonstrated the most pronounced springback behavior. This phenomenon can be attributed to two key factors: (i) greater material flexibility in longer sheets, which reduces overall structural stiffness, and (ii) a larger deformation region, which enables a broader stress distribution across the material's length during bending. These conditions contribute to a higher release of stored elastic strain energy during unloading.

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JCHR (2025) 15(3), 2146-2153 | ISSN:2251-6727

| L | FEM | EXP | SPCC | % |
|---|---|---|---|---|
| 40 | 4.7 | 4.3 | 4 | 6.98 |
| **60** | **3.7** | **3.8** | **3.1** | **18.42** |
| 80 | 3.6 | 3.7 | 2.8 | 24.32 |

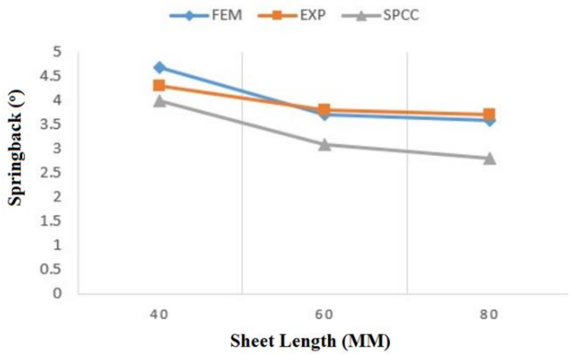


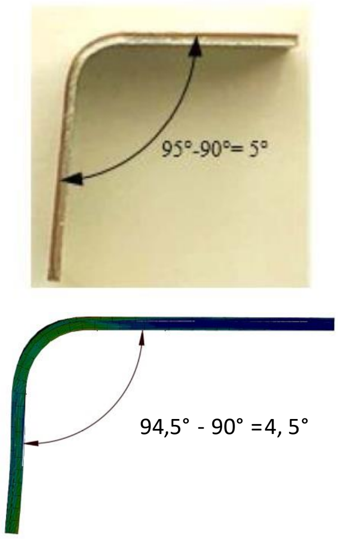

Fig. 4 Effect of Sheet Length on Springback Behavior

Conversely, shorter sheets are geometrically more constrained and possess higher global stiffness, which restricts the magnitude of both plastic strain and subsequent elastic rebound. These observations suggest that springback sensitivity is significantly influenced by the effective deformation length, which becomes a critical parameter in the design and simulation of sheet metal forming processes involving variable sheet dimensions.

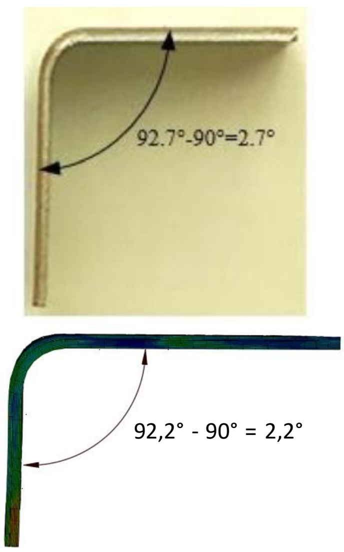
A comprehensive comparison of simulation results is presented in Figures 5. In addition to internal analysis, a comparative evaluation was conducted against existing experimental data and published FEM simulations performed on aluminum–copper composite sheets. The comparison revealed general consistency in the springback trends, reinforcing the validity of the modeling approach. However, a notable discrepancy in the magnitude of springback—up to 33.33%—was observed, particularly in simulations involving extreme values of die radius and clearance.

This deviation can be explained by differences in mechanical properties between SPCC steel and the aluminum–copper alloys used in reference studies. SPCC steel, with its higher yield strength and elastic modulus, responds differently to elastic unloading, resulting in stiffer springback behavior. The use of SPCC in a dual-layer configuration, as explored in this study, further amplifies the divergence due to increased bending resistance and reduced interlayer sliding compared to more ductile alloy systems.

This section underscores the novel contribution of the present work, which lies in systematically quantifying the influence of sheet length on springback in the context of multi-layered sheet forming, an area that has been underexplored in prior literature. The insights obtained here provide a foundation for optimizing blank size selection and process design in precision sheet forming operations, especially where tight tolerance control is required post-forming.




a) L=60mm;C=0,2mm; R=7mm



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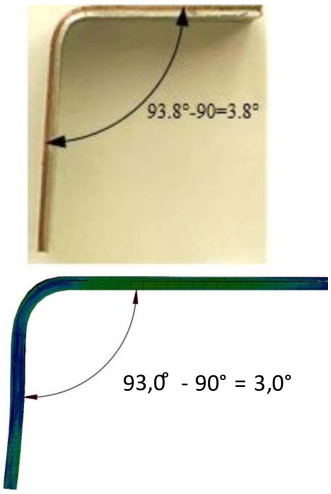
b) L=60mm;C=0,1mm; R=5mm




c) L=60mm;C=0,2mm; R=5mm

Fig. 5 Comprehensive comparison of simulation results

4. Conclusion

This study presents a comprehensive finite element simulation-based investigation into the springback behavior of SPCC sheet metal under varying geometric and process parameters, specifically focusing on die radius, punch–die clearance, and sheet length. The research was conducted within a dual-layer forming configuration, introducing a relatively underexplored context that mirrors multi-material or layered sheet forming applications in precision manufacturing.

The key findings can be summarized as follows:

- Die Radius: A larger die radius leads to reduced springback due to smoother bending profiles and lower residual stress gradients. Conversely, smaller radii induce sharper plastic deformation, amplifying elastic recovery during unloading.
- Punch–Die Clearance: A tighter punch–die clearance increases springback, likely due to elevated material constraint and contact stress during forming. Increased clearance allows for reduced contact forces, minimizing the stored elastic energy that contributes to rebound.
- Sheet Length: Longer sheets exhibit more pronounced springback behavior, driven by increased flexibility and a broader deformation zone. Shorter sheets, being more geometrically constrained, limit the extent of elastic recovery.

A comparative analysis with previous experimental and FEM data (involving aluminum–copper alloys) validates the general trends observed in this study, while also highlighting material-dependent deviations in springback magnitude—up to 33.33% in extreme configurations. This discrepancy reinforces the importance of material selection in predictive modeling and underscores the mechanical distinctions of SPCC steel, such as higher stiffness and yield strength, which contribute to unique elastic recovery characteristics.

The novelty of this work lies in its integrated examination of geometric effects on springback within a dual-layer sheet configuration, using a material (SPCC) that is highly relevant in automotive and electronics manufacturing. The simulation framework developed here can serve as a valuable tool for predictive design and optimization of sheet metal forming processes, especially in applications where multi-layered or hybrid materials are employed and springback control is critical for ensuring dimensional accuracy.

Future work will extend this analysis to include temperature effects, strain rate sensitivity, and interface behavior between layered materials, further enhancing the predictive accuracy of springback in complex forming scenarios.

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