

Process-Integrated Springback Identification in Swivel Bending Using Distributed Machine Deformation Measurements

Springback compensation in swivel bending commonly relies on empirical correction values, material databases, or iterative workpiece measurements. This study investigates whether process-induced upper-beam deformation can instead serve as an in-process information source for determining the required overbending angle. Distributed linear potentiometers recorded the upper-beam response during bending tests on 3 mm DC01 sheets with three different lengths. A reproducible change in slope was identified in the Z-direction deformation response and defined as an effective process transition point of the coupled workpiece–tool–machine system. The corresponding transition angle was used as an additional bending-beam rotation for springback compensation and validated by final workpiece measurements after unloading. In a second validation series, specimens loaded only up to the identified transition angle exhibited only minor residual deformation. Within the investigated configuration, the results demonstrate that machine deformation can provide a process-integrated signal for estimating the springback-related correction without requiring explicit prior knowledge of individual material parameters or predefined springback correction values.

Keywords: *swivel bending, sheet-metal forming, springback compensation, machine deformation, process monitoring*

Introduction

Swivel bending is a sheet-metal forming process used for the production of bent components by clamping the workpiece and subsequently forming the free sheet section through a rotational movement of the bending beam (DIN 8586 2025; Heller et al. 2015). Despite modern computer numerical control, the final bending angle can deviate from the target value due to the elastic recovery of the sheet and the elastic deformation of the machine–tool system (Heller et al. 2015; Singh et al. 2004; Coelho et al. 2005). In industrial practice, springback-related angular deviations are commonly compensated by overbending (Heller et al. 2015). The required correction angle, however, depends on material properties, workpiece geometry, tooling conditions and machine compliance and is therefore frequently determined using empirical data, bending databases or iterative adjustment procedures (Buang et al. 2014; Gardiner 1957; SCHRÖDER Group 2024; Ma et al. 2019).

Existing compensation approaches predominantly derive the required correction from known material and process information or from direct measurements of the workpiece during or after bending (TRUMPF 2024; Molitor et al. 2024; Ma et al. 2019). In contrast, the deformation of the machine structure itself has received comparatively little attention as a direct source of information for identifying the springback-related correction required during swivel bending. Previous work introduced machine-deformation-based process

correction using an optical laser–camera measurement concept and considered both springback- and crowning-related correction mechanisms (Donhauser et al. 2026). The underlying optical measurement concept and its application to springback-related process correction have also been documented in a recently published patent (Hans SCHRÖDER Maschinenbau GmbH 2026). The present study isolates the springback-related contribution and extends this approach through distributed displacement measurements, an automated transition-point identification procedure, and an additional unloading-based validation. Building on this previous work, the present study further develops the springback-identification methodology through distributed displacement measurements, an automated transition-point identification procedure, and an additional unloading-based validation, while specifically isolating springback-related compensation from crowning adjustments.

Parts of the nominal experimental dataset used in the present study were previously included in the broader process-optimization study reported by Donhauser et al. (2026). In contrast to the previous study, which investigated combined overbending and crowning adjustments, the present work focuses specifically on springback-related compensation without an additional crowning adjustment. Two additional experimental series were conducted to validate transition-based overbending independently of crowning and to investigate the physical interpretation of the identified effective process transition point.

The present study therefore investigates whether the process-induced upper-beam deformation can be used as an in-process information source for springback compensation. Instead of determining the required correction from the finished workpiece alone, the approach evaluates the deformation of the upper beam during the ongoing forming process. Distributed linear displacement sensors are used to capture the machine response at defined positions along the beam and as a function of the current bending angle.

The central research question is:

Can the effective springback during swivel bending be identified from the process-induced elastic deformation of the upper beam and used to determine the required overbending angle?

The working hypothesis is that the transition in the measured upper-beam deformation from an approximately linear to a nonlinear response represents an effective process transition of the coupled workpiece–tool–machine system. The corresponding transition angle is assumed to contain information about the effective elastic contribution relevant to springback and can therefore be used to estimate the overbending required to compensate for elastic recovery after unloading.

The remainder of this paper is organized as follows. The second section reviews springback, machine compliance and existing compensation strategies in bending. The third section describes the experimental setup, the distributed displacement measurement system and the method used to identify the effective process transition point. The fourth section presents the measured upper-beam deformation and the experimental validation of the derived overbending correction. The fifth section discusses the physical interpretation, applicability

and limitations of the proposed approach. The final section summarizes the principal conclusions and outlines directions for future work.

Literature Review

Springback in Sheet-Metal Bending

Springback is a widely observed phenomenon in sheet-metal forming and represents a major challenge for dimensional and angular accuracy not only in swivel bending, but also in numerous other bending processes (Heller et al. 2015; Spišák et al. 2025). Springback refers to the elastically induced change in shape of a previously formed component after unloading or removal of the process force. During bending, the total deformation consists of both elastic and plastic components. After removal of the external load, the elastic component is partially recovered, causing the resulting bending angle to differ from the angle reached under load during the forming process. Consequently, the final bending angle deviates from the intended target angle (Heller et al. 2015; Spišák et al. 2025). To compensate for springback, the sheet is therefore commonly bent beyond the target angle. The required overbending angle must be adapted to the expected elastic recovery of the workpiece (Heller et al. 2015; Gardiner 1957).

The magnitude of springback is influenced by a variety of material-dependent parameters. The most relevant factors include Young's modulus, yield stress, and the strain-hardening behavior of the material (Heller et al. 2015; Buang et al. 2014). A higher ratio of yield stress to Young's modulus generally results in a greater elastic recovery after unloading (Gardiner 1957; Buang et al. 2014). In addition, strain-hardening parameters such as the strain-hardening exponent and the strength coefficient affect the stress distribution developing during the bending process and, consequently, the resulting springback behavior (Buang et al. 2014; Şerban et al. 2013; Jung et al. 2017). The anisotropic behavior of sheet metals also has a relevant influence. The rolling process produces direction-dependent mechanical properties, which can lead to differences in forming and springback behavior depending on the orientation relative to the rolling direction (Daiezadeh et al. 2011; Jung et al. 2017).

In addition to material-related parameters, springback is also influenced by the geometry of the workpiece and the bending process (Heller et al. 2015; Gardiner 1957). A fundamental analytical relationship for describing springback in pure bending was developed by Gardiner (1957). In this approach, springback is expressed by the ratio between the radius of curvature r_1 under load and the radius of curvature r_2 after unloading (Eq. 1).

$$\frac{r_1}{r_2} = 4 \left(\frac{r_1 R_e}{E t} \right)^3 - 3 \left(\frac{r_1 R_e}{E t} \right) + 1 \quad (1)$$

where R_e denotes the material yield stress, E Young's modulus, and t the sheet thickness.

By rearranging the dimensionless expression, the governing term can be expressed as the product of a material-dependent ratio R_e/E and a geometry-dependent ratio r_1/t :

$$\frac{r_1}{r_2} = 4 \left(\frac{R_e}{E} \cdot \frac{r_1}{t} \right)^3 - 3 \left(\frac{R_e}{E} \cdot \frac{r_1}{t} \right) + 1 \quad (2)$$

The equation therefore demonstrates that springback is determined not only by the mechanical properties of the material, but also by the geometry of the bending process. In particular, the ratio of curvature radius to sheet thickness represents an important geometric parameter influencing springback (Gardiner 1957).

Machine Compliance in the Bending Process

Although these studies focus on other bending processes, elastic machine compliance is also relevant in swivel bending. Due to the clamping kinematics between the upper and lower beams and the rotational movement of the bending beam, several long machine and tool structures jointly contribute to the mechanical response of the process. Earlier investigations of swivel-bending machines have already shown that the upper beam undergoes measurable elastic deformation under load and that the magnitude of this deformation depends, among other factors, on the applied clamping force and clamping width (Warstat and Wehle 1992; Finus 2023). More recent investigations using digital image correlation with a GOM ARAMIS system have confirmed that both global and local upper-beam movements can be experimentally captured during the clamping process (Finus 2023). The elastic deformation of these machine structures can influence both the relative motion between tool and workpiece and the resulting angular distribution along the bending line (Donhauser et al. 2026).

The resulting position-dependent angular deviations are a known phenomenon in swivel bending and can be compensated by applying an appropriate crowning of the bending beam or tool arrangement (Hochstrate 1999; Hochstrate 2001). Corresponding design concepts, including dynamic crowning systems, demonstrate that machine deformation has long been considered a relevant source of process error in swivel bending.

Tool geometry and tool stiffness also influence the elastic system response of the bending process. Different tool shapes and dimensions can result in different elastic deformations under load and thereby alter the relative position between the tool and the workpiece. Singh et al. (2004) showed that elastic tool deformations can affect the effective tool penetration and, consequently, the accuracy of the resulting bending angle. Recent work on swivel bending has also addressed the prediction of bending radii and bending angles through process-specific kinematic and analytical models, illustrating the importance of accurately representing the underlying process geometry (Schiller et al. 2024).

Therefore, determination of the actually required overbending angle cannot be based solely on the elastic-plastic behavior of the sheet material. Instead, the real bending response must be considered as the result of the coupled mechanical

system consisting of the workpiece, tooling, and machine structure (Singh et al. 2004; Coelho et al. 2005). This leads to the question of whether the elastic machine deformation occurring during swivel bending can be used as a measurable process variable to identify the effective springback contribution and, on this basis, derive an appropriate overbending angle.

Existing Approaches for Bending-Angle Compensation

Existing strategies for compensating springback-related angular deviations can be distinguished primarily by the information source used and the stage at which the correction is determined. In industrial practice, required correction values are frequently derived from operator experience, empirical models, or stored material and process data (Tan et al. 1992; SCHRÖDER Group 2024). Corresponding database-based approaches are also implemented in commercial swivel-bending machines. For the PowerBend Professional, for example, the SCHRÖDER Group describes a material-database-based adjustment of the bending angle for springback compensation. However, the accuracy of predefined or model-based correction values depends on how accurately the actual material and process conditions are represented. Variations in material properties and sheet thickness can directly affect springback and therefore limit the reliability of corrections derived solely from predefined input data (D'Urso et al. 2007; Molitor et al. 2024).

Another approach is the direct measurement of the bending angle during the forming process. In press-brake and air-bending applications, optical or tactile measurement systems are used for this purpose. The ACB Laser system employed by TRUMPF, for example, measures the current bending angle without contact using a laser-camera system, enabling the machine motion to be adjusted during the ongoing bending process (TRUMPF 2024). Similar closed-loop concepts have also been investigated in scientific research. Molitor et al. (2004) combined camera-based measurement of the current bending angle with force signals recorded during forming and machine-learning methods to predict the loaded target angle required for springback compensation.

Iterative approaches represent another category, in which the bending result is evaluated after unloading and the resulting correction value is applied to a subsequent bending operation. Ma et al. (2019), for example, developed an iterative compensation algorithm in which the correction value is progressively adjusted on the basis of the measured springback until the resulting bending angle approaches the desired target value.

The described approaches therefore differ particularly with regard to the information source used for determining the correction. Database- and experience-based methods rely on previously available process knowledge, whereas direct measurement and closed-loop systems predominantly evaluate the current state of the workpiece or additional process variables. In contrast, the present study investigates the elastic response of the machine structure itself as a process-integrated source of information. For this purpose, the deformation of the upper beam occurring during swivel bending is recorded at distributed

positions and evaluated as a function of the current bending angle. The study investigates whether a characteristic effective process transition of the coupled workpiece–tool–machine system can be identified from this deformation response and subsequently used to determine an appropriate overbending angle for springback compensation.

Methodology and Materials

Swivel-Bending Machine and Experimental Setup

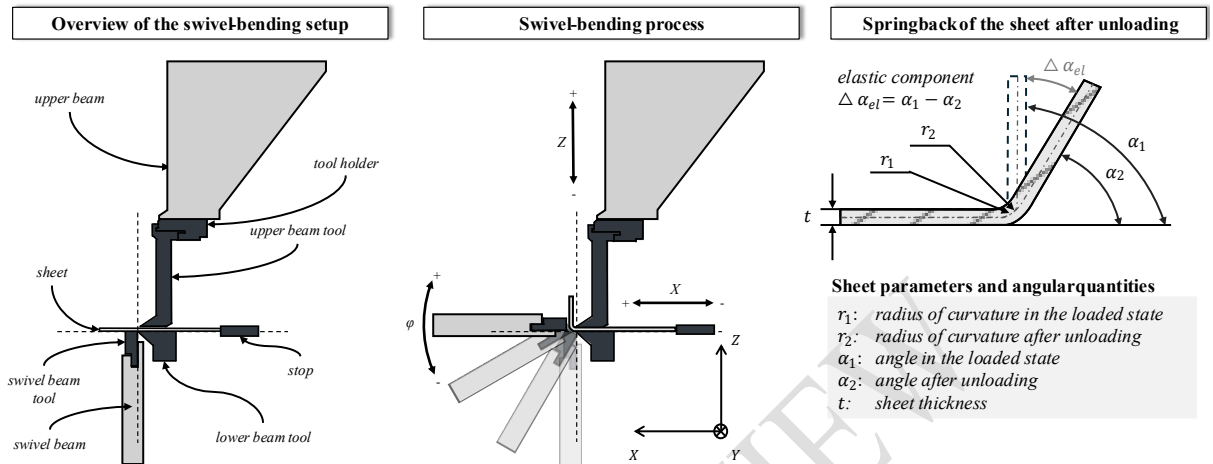
The experimental investigations were conducted on a PowerBend Professional swivel-bending machine manufactured by the SCHRÖDER Group. The machine configuration used in this study provides a working length of 3,240 mm and is designed for processing steel sheets with thicknesses of up to 3.0 mm at a tensile strength of 400 N/mm² (SCHRÖDER Group 2024). For all experimental series, a nominal bending angle of 90° was defined and kept constant in order to enable a consistent comparison of the influence of the deliberately varied test parameters on machine deformation and the resulting springback behavior.

DC01 steel with a constant sheet thickness of 3 mm was used as the test material. The specimen geometry was selected to generate a sufficiently high process load and, consequently, a clearly measurable deformation of the upper beam. The flange length was kept constant at 21 mm for all tests. This value corresponds to the selected minimum flange length for the investigated machine and tool configuration and simultaneously promotes a high mechanical load on the coupled tool–machine system.

To generate different loading conditions within the machine structure, sheet length was selected as the deliberately varied experimental parameter. Sheet lengths of 1,000 mm, 2,000 mm, and 3,000 mm were investigated. Increasing the sheet length increased the simultaneously loaded length along the bending line and therefore provided systematically different loading conditions for the coupled machine–tool system. All other geometric and process-related parameters were kept constant within the respective test series.

The fundamental swivel-bending process and the angular quantities relevant to the present investigation are shown schematically in Figure 1. During the bending process, the sheet is clamped between the upper and lower beams and formed by the rotational movement of the bending beam (DIN 8586 2025; Heller et al. 2015). To compensate for springback occurring after unloading, the workpiece must be bent beyond the nominal target angle. The difference between the bending state reached under load and the final angle after unloading forms the basis for determining the required overbending angle.

Figure 1. Overview of the swivel-bending setup, schematic representation of the swivel-bending process, and definition of the springback-related angular quantities after unloading



Source: Authors; springback-related parameters adapted from Heller et al. (2015, p. 152) and swivel-bending setup adapted from Heller et al. (2015, p. 199).

The principal workpiece, machine, and process parameters used in the experimental investigations are summarized in Table 1.

Table 1. Experimental Parameters

Parameter	Value
Machine	SCHRÖDER PowerBend Professional
Sheet material	DC01
Sheet thickness	3 mm
Sheet length	1,000 / 2,000 / 3,000 mm
Flange length	21 mm
Nominal bending angle	90°
Crowning setting	0 mm
Number of repetitions	10

Source: Authors.

Distributed Upper-Beam Deformation Measurement

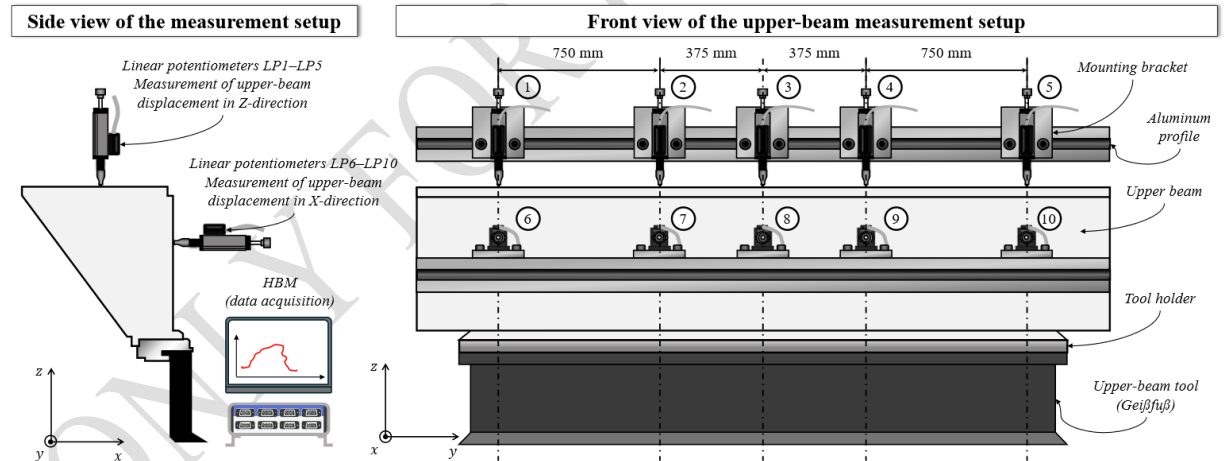
The deformation of the upper beam was measured using ten WayCon LRW3 linear potentiometers (WayCon Positionsmesstechnik GmbH, Germany) with a nominal measuring range of 10 mm (WayCon Positionsmesstechnik GmbH 2026). Five sensors (LP6–LP10) were oriented horizontally to record the displacement of the upper beam in the X-direction, while five additional sensors (LP1–LP5) were oriented vertically to measure the displacement in the Z-direction. The sensors were arranged at five corresponding measurement positions along the upper beam, allowing both orthogonal components of the process-induced deformation to be recorded simultaneously. The LRW3 sensors use a spring-loaded measuring rod with a roller tip and are specified by the manufacturer as potentiometric displacement sensors.

The central sensors LP3 and LP8 were positioned at the center of the machine, with LP3 measuring the Z-direction and LP8 the X-direction. The remaining sensors were arranged symmetrically with respect to the machine centerline in order to capture the spatial deformation distribution along the upper beam. All displacement signals were acquired using an HBM QuantumX MX840B data-acquisition system at a sampling frequency of 300 Hz.

The bending-beam rotation angle φ was recorded independently using two WayCon MH60 cable-extension sensors mounted on the left and right sides of the bending beam. The sensors were geometrically calibrated using a reference diameter of known dimensions, relating the measured cable displacement to the corresponding rotational angle through the circular-arc geometry. Since small deviations between the left- and right-side measurements can occur during bending, the arithmetic mean of both angular signals was used as the current bending-beam rotation angle φ . The angular signals were acquired synchronously with the displacement measurements using the same data-acquisition system.

The arrangement and orientation of the linear potentiometers are illustrated schematically in Figure 2.

Figure 2. Schematic representation of the distributed upper-beam measurement setup with linear potentiometers for recording the X- and Z-direction displacements at five positions along the machine



Source: Authors.

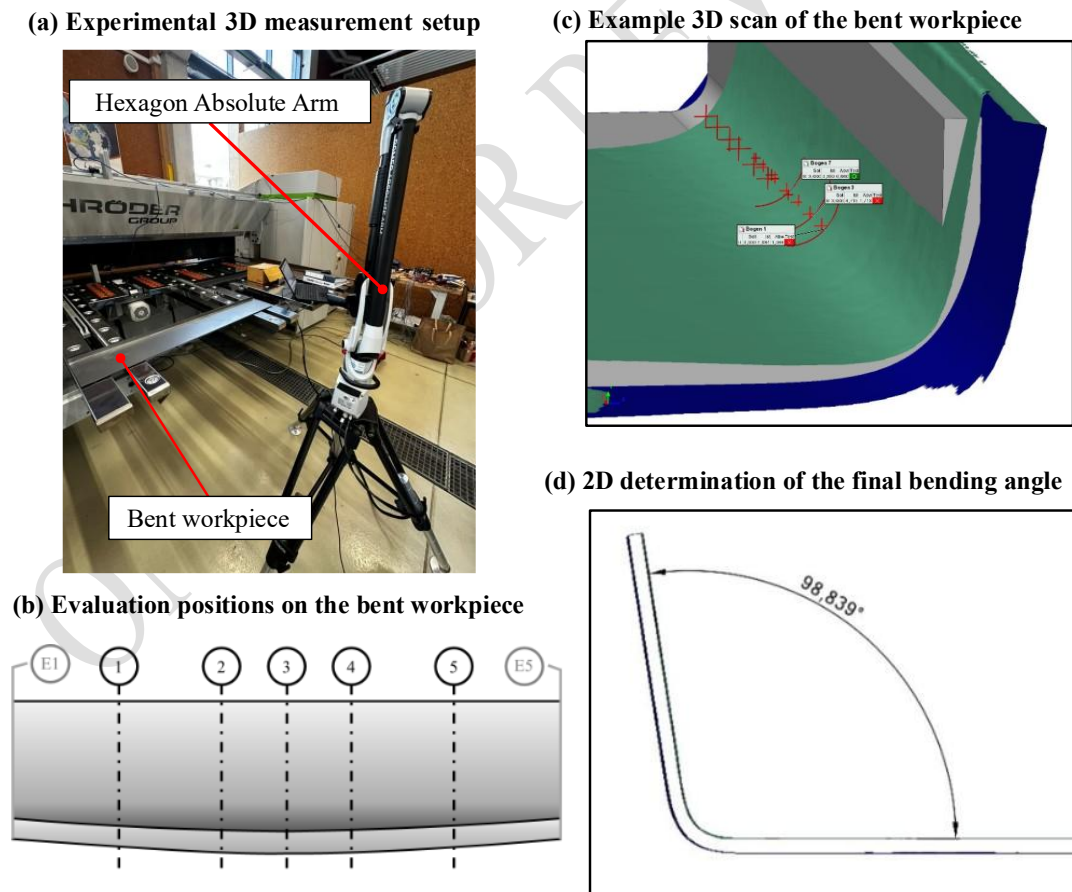
To relate the process-induced upper-beam deformation to the resulting workpiece geometry, the bent sheets were subsequently measured after unloading.

Workpiece Geometry and Bending-Angle Evaluation

After each bending test, the workpiece was unloaded and its final geometry was captured using a seven-axis Hexagon Absolute Arm equipped with a 3D scanning sensor. The scanned surface data were processed using PolyWorks. The bending angle was evaluated at defined positions along the bending line. For

the 3,000 mm specimens, five primary evaluation positions corresponding to the five linear-potentiometer measurement locations on the upper beam were used. For the shorter specimens (1,000 mm and 2,000 mm), three primary positions were evaluated due to the reduced sheet length. Two supplementary edge positions were additionally recorded for each sheet length to assess the bending-angle distribution after overbending. These edge positions were not used for the direct position-wise comparison with the upper-beam deformation measurements. At each evaluation position, two planes were fitted to the point-cloud data representing the two sheet surfaces adjacent to the bend. The resulting bending angle was determined from the angular relationship between these two fitted planes. The measurement principle and the evaluation positions for the 3,000 mm configuration are illustrated in Figure 3.

Figure 3. Workpiece measurement and evaluation procedure: (a) experimental 3D measurement setup using a Hexagon Absolute Arm, (b) five primary evaluation positions and two supplementary edge positions on the 3,000 mm workpiece, (c) example 3D scan of the bent workpiece, and (d) 2D determination of the final bending angle



Source: Authors.

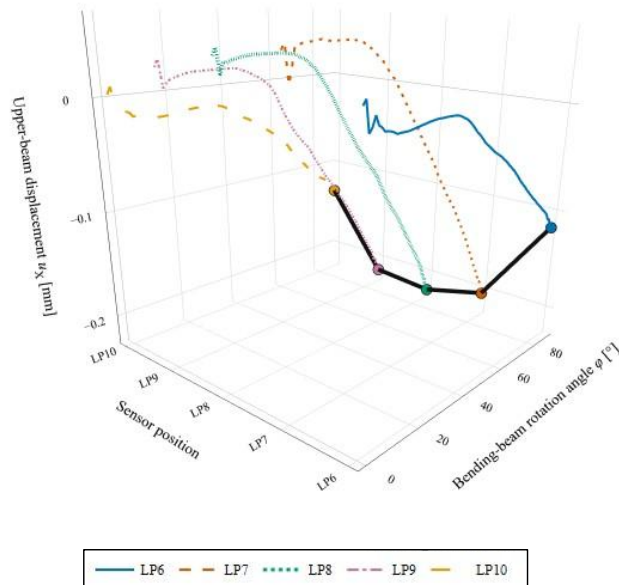
Results

Upper-Beam Deformation during Nominal Bending

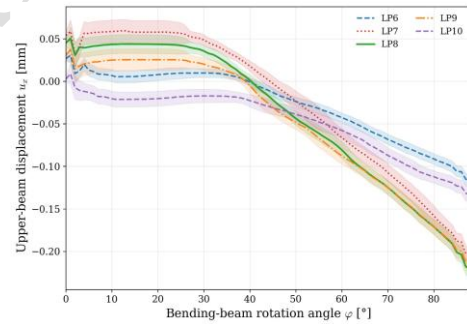
For each of the three investigated sheet lengths, ten bending tests were conducted under the experimental conditions summarized in Table 1. To characterize the deformation behavior of the upper beam in detail, the 3,000 mm sheet series is considered first, as this configuration produced the most pronounced machine response. The upper-beam displacement curves measured in the X-direction using LP6–LP10 are shown in Figure 4 as a function of the current bending angle. The corresponding displacement curves in the Z-direction, recorded using LP1–LP5, are presented in Figure 5. The results obtained for the shorter sheet lengths are subsequently considered for evaluating the transferability and validation of the proposed approach.

Figure 4. Upper-beam displacement in the X-direction for the 3,000 mm sheet series: (a) three-dimensional sensor curves as a function of bending-beam rotation angle φ and sensor position, (b) mean displacement curves of LP6–LP10, and (c) mean spatial displacement profile at $\varphi = 88^\circ$. Shaded regions in (b) and error bars in (c) indicate ± 1 SD ($n = 10$)

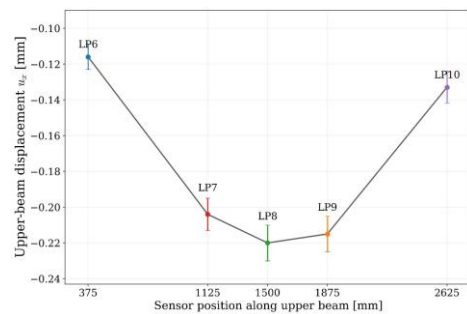
(a) Linear potentiometers LP6–LP10 — X-direction sensor curves



(b) 2D – sensor displacement curves



(c) 2D – spatial displacement profile $\varphi = 88^\circ$



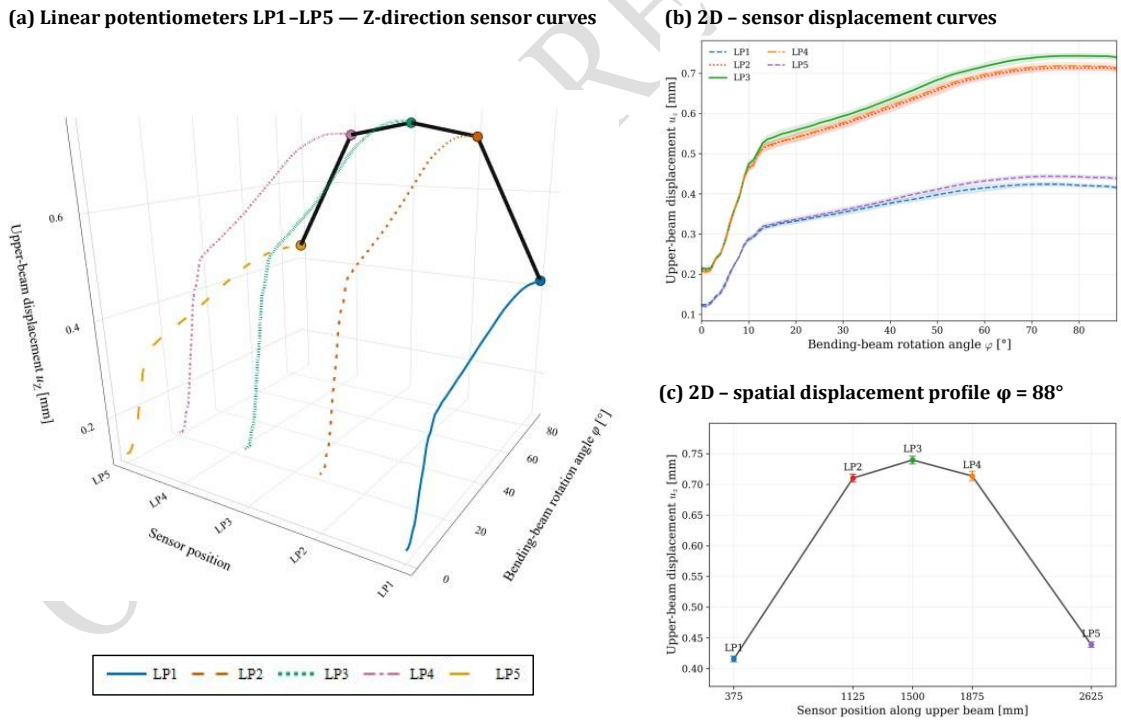
Source: Authors.

Considering the displacement curves recorded by the individual linear potentiometers for the 3,000 mm sheet series, the upper-beam displacement exhibits an approximately symmetric spatial distribution in the Z-direction, whereas the X-direction shows slight asymmetries between corresponding sensor positions on either side of the machine center. Nevertheless, the largest

displacement magnitudes occur in the central region of the machine. In the X-direction, the highest displacement magnitude is recorded at the centrally positioned sensor LP8, whereas in the Z-direction the corresponding maximum occurs at LP3.

The displacement responses in the X- and Z-directions exhibit distinctly different characteristic shapes. In the X-direction, the upper-beam displacement u_x initially remains at a comparatively small positive level before decreasing with increasing bending-beam rotation angle φ . During the subsequent process progression, the measured displacement changes sign at all measurement positions and becomes increasingly negative. This sign change indicates a reversal of the local X-direction displacement of the upper beam. At the end of the evaluated bending range, the largest displacement magnitude is again observed in the central region of the machine.

Figure 5. Upper-beam displacement in the Z-direction for the 3,000 mm sheet series: (a) three-dimensional sensor curves as a function of bending-beam rotation angle φ and sensor position, (b) mean displacement curves of LP1–LP5, and (c) mean spatial displacement profile at $\varphi = 88^\circ$. Shaded regions in (b) and error bars in (c) indicate ± 1 SD ($n = 10$)



Source: Authors.

The Z-direction displacement exhibits a characteristic response that can be divided into several successive regions. At the beginning of the bending process, the upper-beam displacement u_z initially follows a short nonlinear increase. This is followed by an approximately linear region in which the displacement increases with increasing bending-beam rotation angle φ . At a characteristic rotation angle, the curves exhibit a second pronounced change in curvature and

transition into a flatter, nonlinear response with a progressively decreasing slope. At bending-beam rotation angles of approximately 60° to 70° , particularly the central measurement positions approach an approximately constant displacement level.

It is also evident that the measured displacement curves do not start at zero at the onset of the bending-beam rotation. This is attributable to the preceding sheet-clamping operation, which is already included in the measurement sequence. The forces introduced during clamping therefore result in an initial displacement of the upper beam before the actual rotational bending motion begins. Consequently, the displacement values recorded at $\varphi = 0$ already contain a contribution resulting from the clamping operation.

The characteristic change in slope qualitatively resembles the transition from predominantly elastic to increasing plastic deformation observed in the stress–strain response of ductile materials (Gottstein and Korte-Kerzel 2025).

However, the measured upper-beam displacement does not represent a direct stress–strain relationship of the sheet material, but rather the coupled mechanical response of the workpiece, tooling, and machine structure. Based on the observed characteristic change in the deformation response, it is therefore hypothesized that the corresponding bending-beam rotation angle can be used as a process-related indicator of an effective transition within the coupled workpiece–tool–machine system. The following analysis investigates whether this effective process transition point can be used to identify the elastic contribution relevant to springback and, subsequently, to derive an appropriate overbending angle for springback compensation.

Identification of the Effective Process Transition Point

To quantify the transition identified in the preceding deformation analysis, the Z-direction displacement responses $u_z(\varphi)$ recorded by LP1–LP5 were evaluated independently. Here, $u_z(\varphi)$ denotes the measured vertical displacement of the upper beam in millimeters. Throughout the following procedure, φ exclusively denotes the bending-beam rotation angle of the machine, whereas α remains reserved for the workpiece bending angle. For each sensor, only the forward bending path up to the first occurrence of the maximum bending-beam rotation angle was considered. The ten repeated displacement curves were interpolated onto a common angular grid within their overlapping range. At each grid point, the arithmetic mean and sample standard deviation were calculated separately for each sensor. The resulting standard error of the mean was used in the subsequent weighted regression.

The two regression intervals required for the transition-point construction were not prescribed by fixed angular limits. Instead, they were identified automatically from a weighted piecewise-linear segmentation of the sensor-specific mean curve. For each candidate number K of independent linear segments, the segmentation minimizing the weighted residual sum of squares was determined, with at least four data points required per segment. The point-wise standard error of the mean displacement curve was used as the regression uncertainty; a small data-dependent lower bound was applied internally to

prevent numerical instabilities in regions of locally vanishing scatter. Following the general Bayesian information criterion (BIC) model-selection principle introduced by Schwarz (1978) and its application to segmented linear regression (Kim and Kim 2016), candidate models between $K = 2$ and $K = \min(10, \lfloor N/4 \rfloor)$ were compared using the criterion defined in Eq. (3):

$$\text{BIC}_K = \chi_K^2 + (3K - 1)\ln N, \quad \chi_K^2 = \sum_{k=1}^N \left(\frac{e_k}{\sigma_k} \right)^2 \quad (3)$$

where N is the number of points on the common angular grid, e_k denotes the residual of the corresponding piecewise-linear approximation, and $\sigma_k = s_k/\sqrt{n}$ is the point-wise regression uncertainty, with s_k denoting the sample standard deviation and $n = 10$ the number of repetitions. The term $3K - 1$ represents two regression parameters for each of the K independent line segments and $K - 1$ segment boundaries. The segmentation yielding the minimum BIC was retained.

After the segment boundaries had been determined, both coordinates of the complete mean curve were normalized to the interval $[0,1]$,

$$\tilde{\varphi} = \frac{\varphi - \varphi_{\min}}{\varphi_{\max} - \varphi_{\min}}, \quad \tilde{u}_Z = \frac{u_Z - u_{Z,\min}}{u_{Z,\max} - u_{Z,\min}} \quad (4)$$

so that the subsequent geometric construction is independent of the different physical units and axis scales of bending-beam rotation and upper-beam displacement. The BIC-defined segments were subsequently refitted by linear regression in the normalized coordinate system.

From the resulting segments, g_1 was defined as the segment with the largest positive normalized slope that ended no later than the maximum of the mean displacement curve. The subsequent segment g_2 was selected as the first later segment containing at least eight data points and exhibiting a positive but substantially lower normalized slope. The initial selection required the slope of g_2 to be no greater than 25% of the g_1 slope. If no segment fulfilled this condition, the limit was successively relaxed to 35% and finally 50%. These slope-ratio limits are algorithmic selection thresholds rather than material-specific parameters; their purpose is to prioritize a clearly flatter post-transition segment while retaining a deterministic fallback for curves with a less pronounced slope reduction. Intermediate BIC segments that did not satisfy the g_2 criterion were excluded from both regressions and were therefore treated as part of the transition region. The two selected regression lines are expressed as

$$g_i(\tilde{\varphi}) = m_i \tilde{\varphi} + b_i, \quad i \in \{1,2\} \quad (5)$$

where m_i and b_i denote the normalized slope and intercept, respectively. The automatically selected regression intervals are illustrated in Figure 6(a) using the representative mean Z-displacement curve of the centrally located sensor LP3. Their extrapolated intersection defines the auxiliary point $S = (\tilde{\varphi}_S, \tilde{u}_{Z,S})$,

$$\tilde{\varphi}_S = \frac{b_2 - b_1}{m_1 - m_2}, \quad \tilde{u}_{Z,S} = m_1 \tilde{\varphi}_S + b_1 \quad (6)$$

The geometric construction uses a specifically defined directed angle at S . The first ray follows g_2 from S toward decreasing $\tilde{\varphi}$, whereas the second ray follows g_1 from S toward increasing $\tilde{\varphi}$. The direction of the internal angle bisector is obtained by adding the normalized direction vectors of these two rays. Since only the slope of the bisector is required, the common normalization factor of the resulting vector cancels, yielding

$$m_B = \frac{\frac{m_1}{\sqrt{1+m_1^2}} - \frac{m_2}{\sqrt{1+m_2^2}}}{\frac{1}{\sqrt{1+m_1^2}} - \frac{1}{\sqrt{1+m_2^2}}} \quad (7)$$

Consequently, the selected angle bisector g_B passes through S and is given by

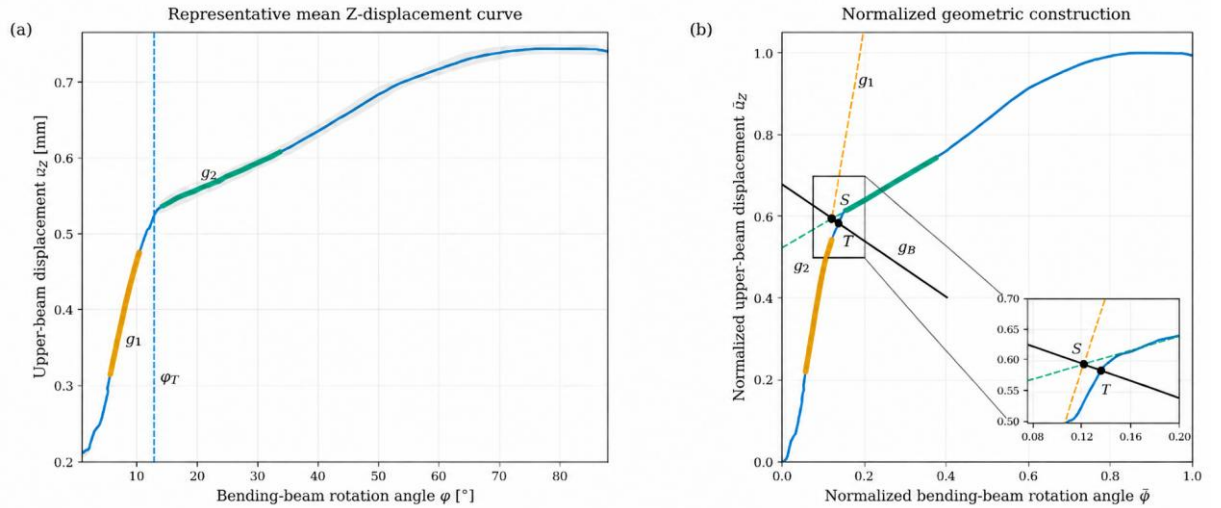
$$g_B(\tilde{\varphi}) = \tilde{u}_{Z,S} + m_B(\tilde{\varphi} - \tilde{\varphi}_S) \quad (8)$$

The effective process transition point T is defined as the intersection of g_B with the piecewise-linearly interpolated normalized displacement curve. Intersections within the interval between the end of g_1 and the beginning of g_2 are considered preferentially. If more than one intersection occurs, the intersection with the smallest angular distance from S is selected. If no intersection lies within this transition interval, the closest intersection to S over the complete curve is used. The corresponding physical bending-beam rotation angle is obtained from

$$T = (\tilde{\varphi}_T, \tilde{u}_{Z,T}) \in g_B \cap \tilde{u}_Z(\tilde{\varphi}), \quad \varphi_T = \varphi_{\min} + \tilde{\varphi}_T(\varphi_{\max} - \varphi_{\min}) \quad (9)$$

The complete geometric construction is illustrated in Figure 6(b), where the intersection of the angle bisector g_B with the normalized displacement curve defines the effective process transition point T , whose physical bending-beam rotation angle φ_T is obtained using Eq. (9).

Figure 6. Identification of the effective process transition point using a representative LP3 mean Z-displacement curve: (a) physical coordinates showing the automatically selected regression intervals g_1 and g_2 ; (b) geometric construction in normalized coordinates. The auxiliary point S is defined by the intersection of the extrapolated regression lines. The angle bisector g_B bisects the directed angle formed by g_2 before S and g_1 after S . Its intersection with the normalized displacement curve defines the effective process transition point T and the corresponding transition angle φ_T



Source: Authors.

For the evaluation of the repeated individual tests, the angular intervals of g_1 and g_2 were identified once from the corresponding sensor-specific mean curve and subsequently kept fixed. Each individual displacement curve was then normalized separately, the two regression lines were refitted within these fixed intervals, and the same geometric construction was applied to determine its individual transition angle. The complete procedure was performed independently for LP1-LP5. Consequently, this identification step provides sensor-specific transition angles without imposing a predefined combination or averaging rule across the five measurement positions.

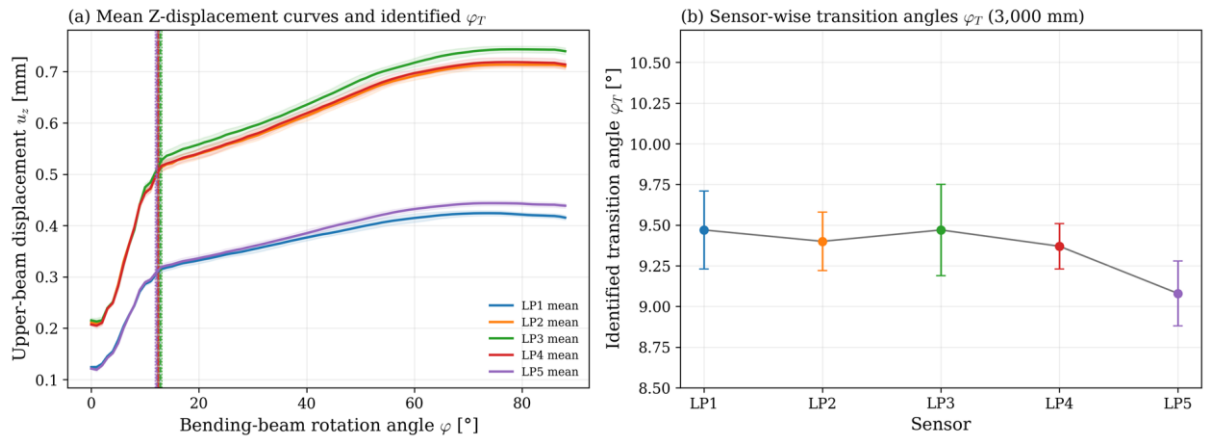
Validation Strategy

The validation procedure was divided into three experimental stages. First, the previously presented 3,000 mm nominal test series was complemented by nominal bending tests on 1,000 mm and 2,000 mm sheets. All nominal tests served to determine the effective process transition angles φ_T using the previously described automated evaluation procedure.

Although φ_T was determined independently at all five Z-direction sensor positions, the centrally located sensor LP3 was selected as the reference for the subsequent validation experiments. Under the investigated symmetric loading conditions, the largest Z-direction displacement of the upper beam occurs in the central region of the machine, resulting in the most pronounced deformation

response at LP3. For the 3,000 mm configuration, the mean transition angles identified from the individual trials ranged from 9.08° to 9.47° across LP1–LP5 (Figure 7), corresponding to a maximum sensor-wise difference of 0.39° . Since the overbending correction is applied as a single global rotation of the bending beam, LP3 was therefore used as the representative process reference, while the remaining sensors were retained to assess the spatial variation of the identified transition.

Figure 7. Effective process transition angles identified from the Z-direction upper-beam displacement signals for the 3,000 mm test series: (a) mean displacement curves with marked transition angles and (b) sensor-wise mean transition angles for LP1–LP5. Shaded regions and error bars indicate ± 1 SD ($n = 10$).



Source: Authors.

Based on the transition angles identified from the nominal test series, two independent validation experiments were subsequently performed. In the first validation series, the bending process was extended beyond the nominal machine setting by the corresponding transition angle φ_T . The identified transition angle therefore served as an additional overbending angle for compensating the elastic recovery occurring after unloading.

In the second validation series, ten specimens with a sheet length of 3,000 mm were bent only up to the corresponding mean transition angle φ_T and subsequently unloaded. The resulting workpiece geometry was measured after unloading to investigate whether the deformation accumulated up to the identified process transition point predominantly represents the effective elastic contribution of the coupled workpiece–tool–machine system.

For each investigated sheet length, ten nominal bending tests were evaluated at LP3. The arithmetic mean and sample standard deviation of the individually identified transition angles were calculated and are summarized in Table 2. Since the bending-beam rotation angle can be specified in increments of 0.1° on the investigated machine, the calculated mean values were rounded to the nearest 0.1° for implementation in the validation experiments. The resulting machine settings were 5.9° , 9.0° , and 9.5° for sheet lengths of 1,000 mm, 2,000 mm, and 3,000 mm, respectively. The three sheet-length-specific values were used as

additional overbending angles in the first validation series. The second validation series was conducted only for the 3,000 mm configuration using its corresponding mean transition angle of 9.5°.

Table 2. Effective process transition angles identified at LP3 from the nominal bending tests

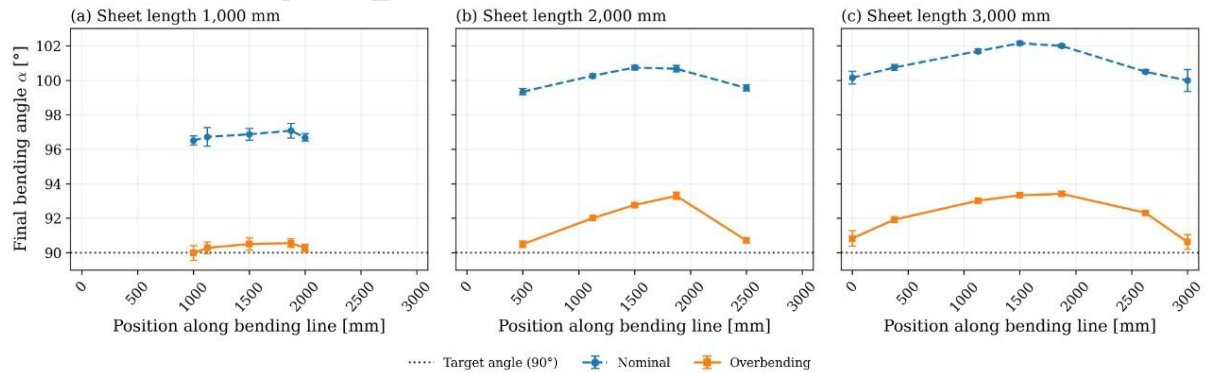
Sheet length [mm]	Mean transition angle $\bar{\varphi}_T$ [°]	Sample standard deviation [°]	Applied transition angle [°]	n [-]
1,000	5.86	0.29	5.9	10
2,000	9.04	0.26	9.0	10
3,000	9.47	0.28	9.5	10

Source: Authors.

Validation by Transition-Based Overbending

In the first validation series, springback was compensated by overbending using the previously identified transition angles. It should be noted that, for this validation series, no crowning adjustment was applied to the bending beam. The final bending angles determined after unloading at the available measurement positions are shown in Figure 8 for the investigated sheet lengths, with subfigures (a)–(c) corresponding to sheet lengths of 1,000 mm, 2,000 mm, and 3,000 mm, respectively.

Figure 8. Final bending angles after nominal bending and transition-based overbending without crowning for sheet lengths of (a) 1,000 mm, (b) 2,000 mm, and (c) 3,000 mm. Error bars indicate ± 1 SD ($n = 10$); the dotted line marks the 90° target angle



Source: Authors.

For the evaluation of the global springback correction, particular attention was given to the outer measurement positions, since the central region is additionally affected by the spatial deformation of the machine–tool system. At the outer positions, the transition-based overbending results in bending angles substantially closer to the target angle of 90° than those obtained from the nominal bending process. For the 1,000 mm specimens, bending angles close to

the target value are also obtained at the inner measurement positions, indicating that the spatial angular variation is comparatively small for this sheet length.

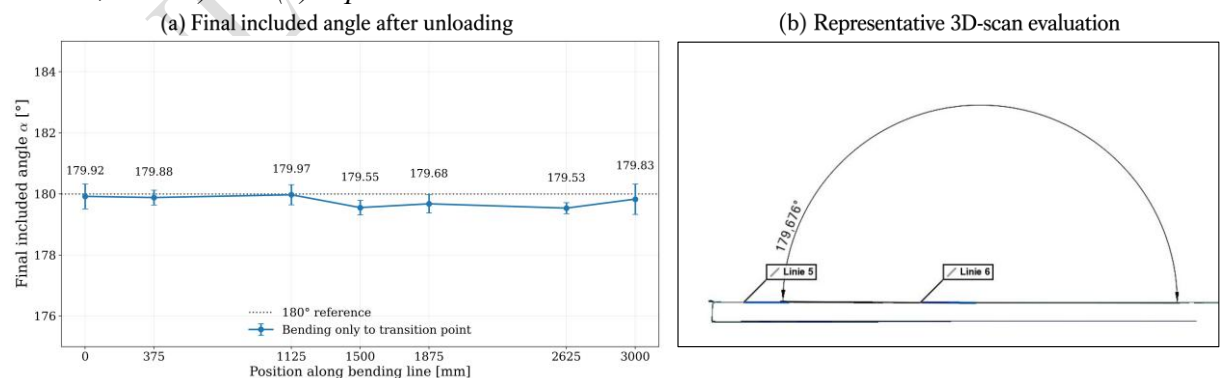
With increasing sheet length, a more pronounced position-dependent angular distribution remains after the transition-based correction, with the largest deviations occurring toward the central region of the machine. This distribution is consistent with the superimposed spatial deformation of the machine–tool system in the absence of crowning and should therefore be distinguished from the global springback contribution addressed by the proposed overbending approach. Consequently, the transition-based correction primarily addresses the global springback contribution, whereas the remaining angular distribution along the bending line requires a separate spatial compensation mechanism, such as an adapted crowning setting. The determination of such a crowning correction is outside the scope of the present study.

Validation by Bending Only to the Identified Transition Point

To further examine the physical interpretation of the identified effective process transition point, an additional validation series was conducted using the 3,000 mm sheet configuration. This configuration was selected because it exhibited the most pronounced upper-beam deformation and the strongest process response among the investigated sheet lengths. Ten specimens were bent only up to the previously determined mean transition angle φ_T and were subsequently fully unloaded.

The final workpiece geometry after unloading is shown in Figure 9. In the applied measurement convention, a completely flat sheet corresponds to an included angle of 180° ; consequently, deviations from 180° represent the residual bending deformation remaining after unloading.

Figure 9. Residual workpiece geometry after bending to the effective process transition angle φ_T (3,000 mm): (a) final included angles after unloading (mean ± 1 SD, $n = 10$) and (b) representative 3D-scan evaluation



Source: Authors.

The measured final angles remain close to the undeformed reference value of 180° at all investigated positions, indicating that only a very small permanent bending deformation remains after loading up to the identified transition angle.

Minor deviations from the undeformed geometry are observed at individual measurement positions. These deviations may result from the fact that a single mean transition angle obtained from the nominal test series was applied to all specimens. Material- and process-related scatter can therefore cause the effective transition angle of an individual specimen to deviate slightly from the applied mean value. Measurement uncertainty may additionally contribute to the small residual deviations. The limited permanent deformation observed after unloading supports the interpretation that deformation accumulated up to the identified transition angle is predominantly elastic. Accordingly, the effective process transition angle appears to mark a characteristic change from a predominantly recoverable system response toward increasing permanent workpiece deformation. Since the transition angle is derived from the deformation of the coupled workpiece–tool–machine system rather than from a direct material measurement, the result should not be interpreted as a material-specific yield point.

Together with the preceding overbending experiments, this second validation provides complementary evidence for the suitability of the identified effective process transition angle as a process-integrated indicator of the elastic contribution relevant to springback compensation.

Discussion

The results indicate that the identified effective process transition point represents a characteristic change in the mechanical response of the swivel-bending process. The measured upper-beam displacement is not governed solely by the material behavior of the sheet but reflects the coupled response of the workpiece, tooling, and machine structure. Consequently, the identified transition should not be interpreted as a material-specific yield point. Instead, it represents an effective process transition from a response predominantly governed by recoverable elastic deformation of the coupled system toward a regime in which permanent deformation of the workpiece increasingly contributes to the overall process response. Since springback originates from the elastic recovery occurring during unloading, the identified transition angle contains information about the effective elastic contribution relevant to the final angular recovery of the workpiece (Heller et al. 2015).

The physical interpretation of the transition point is supported by the two complementary validation approaches. In the transition-based overbending experiments, application of the identified transition angle as an additional bending-beam rotation moved the final workpiece angles substantially closer to the target angle at the outer measurement positions and, for the 1,000 mm sheets, also across large parts of the bending line. In the second validation experiment, the 3,000 mm specimens were loaded only up to the identified mean transition angle and subsequently unloaded. The very small residual deformation observed after unloading indicates that the deformation accumulated up to this point is predominantly recoverable. Taken together, these results support the interpretation

of φ_T as a process-related indicator of the effective elastic contribution relevant to springback compensation rather than as a conventional material yield criterion.

A further notable observation is the increase in the identified effective process transition angle with increasing sheet length. In the present experiments, the sheet material, thickness, flange geometry, bending radius, tooling, and nominal bending angle were kept constant, while the dimension along the bending line was varied. The classical pure-bending relationship proposed by Gardiner (1957) does not explicitly include the bend length as an independent parameter but relates springback primarily to material properties and the geometric relationship between curvature radius and sheet thickness. However, experimental studies on free and V-bending have shown that the component or blank dimension along the bending line can influence springback and that the magnitude and direction of this effect depend on the material and process conditions (Krinninger et al. 2016; Wasif et al. 2020). The length dependence observed in the present study should therefore not be attributed exclusively to machine compliance. It may result from a combination of three-dimensional workpiece effects and the increasing elastic response of the machine-tool system as a larger bending length is loaded simultaneously. This observation further supports the interpretation of φ_T as an effective transition of the coupled workpiece-tool-machine system rather than as a purely material-specific quantity.

At the same time, the overbending experiments demonstrate that the final angular error of a swivel-bent workpiece cannot be attributed exclusively to springback. Particularly for the longer sheets, a pronounced position-dependent angular distribution remains along the bending line. This behavior is consistent with the elastic spatial deformation of the machine-tool system, which changes the relative motion between the tool and workpiece along the machine length (Warstat and Wehle 1992; Finus 2023; Donhauser et al. 2026). Springback compensation and compensation of the spatial machine deformation therefore represent related but distinct correction tasks. The approach investigated in the present study primarily addresses the global springback-related contribution. Additional position-dependent compensation, for example by an adapted crowning setting, is required to further reduce the remaining spatial angular deviations but is outside the scope of the present study.

A central difference between the proposed approach and conventional springback-compensation strategies lies in the source of process information. Existing approaches frequently rely on empirical correction models, predefined material and process information, stored correction data, or direct measurement of the workpiece during or after bending (Tan et al. 1992; Ma et al. 2019; Molitor et al. 2024). In contrast, the present approach uses the process-induced deformation of the machine structure itself as an information source. Explicit prior knowledge of individual material parameters such as Young's modulus, yield strength, or hardening parameters is therefore not required for the identification of the effective process transition within the investigated approach. Likewise, the individual contributions of the workpiece, tooling, and machine structure do not need to be modeled separately because their combined

mechanical response is inherently contained in the measured upper-beam deformation.

Machine deformation is therefore not considered solely as an undesirable source of geometric error but also as a process-integrated measurement signal. Rather than predicting springback exclusively from predefined input parameters, the proposed methodology evaluates the system response that actually develops during the bending operation. This concept extends previous work on machine-deformation-based process monitoring in swivel bending (Donhauser et al. 2026) and provides a basis for future self-adaptive springback compensation in which the required correction could be derived from the current process state.

The present results are limited to the investigated combination of machine, tooling, DC01 sheet material, sheet thickness, and component geometry. Furthermore, the unloading validation performed by bending only up to φ_T was conducted for the 3,000 mm configuration. Transferability to other materials, sheet thicknesses, tooling configurations, and machine designs therefore remains to be evaluated. A further methodological limitation concerns the transition-point identification itself. Although the evaluation was automated, the present validation was based on transition angles obtained from previously recorded nominal test series and subsequently applied as mean correction values. For a fully self-adaptive implementation, it must therefore be demonstrated that the effective process transition angle can be identified robustly from the deformation signal of an individual workpiece during the ongoing bending operation and sufficiently early to update the final bending target within the same process cycle. In addition, the robustness of the automated segmentation and transition-point selection with respect to the applied algorithmic thresholds should be examined through a dedicated sensitivity analysis.

Conclusions

The present study investigated whether process-induced upper-beam deformation can be used to identify a characteristic transition within the swivel-bending process and to derive a corresponding springback correction. A reproducible change in the Z-direction deformation response was identified and interpreted as an effective process transition of the coupled workpiece–tool–machine system rather than as a material-specific yield point.

The validation experiments showed that the associated transition angle can be used as a process-related correction value. Applying the identified angle as an additional bending-beam rotation shifted the resulting workpiece angles toward the target angle, while specimens loaded only up to the transition angle exhibited only very small residual deformation after unloading. Within the investigated process configuration, the identified transition also varied systematically with sheet length, allowing length-specific correction values to be derived from the measured system response.

The results demonstrate that process-induced machine deformation can be used as a process-integrated information source for springback compensation

without requiring predefined springback correction values or explicit knowledge of individual material parameters. At the same time, the proposed correction addresses primarily the global springback-related contribution. Remaining position-dependent angular deviations along the bending line require a separate spatial compensation strategy, such as adapted crowning.

The findings are limited to the investigated machine, tooling, material, sheet thickness, and geometric configuration. Future work should therefore examine the transferability of the method to additional process conditions and, in particular, whether the effective process transition angle can be identified robustly from a single workpiece during the ongoing bending operation. This represents the key step toward a self-adaptive, process-integrated springback compensation strategy.

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