



Article

Influence of Tool Geometry, Straightening Strategy and Tool Clearance in Thin Wire Punch-Bending

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Abstract

In punch-bending of thin stainless steel components, the final product angle is significantly influenced by springback after process completion. In the present study, an attempt has been made to investigate the effect of wire straightening strategies and bending tool parameters on the springback behavior of cold-rolled EN 1.4310 flat wire (3.9 mm × 0.4 mm). The wire, supplied in coiled form with inherent residual stresses, was subjected to single-pass, two-pass, and four-pass three-roller straightening prior to bending. Tensile characterization was performed to examine changes in elastic-plastic flow stress behavior, and the experimentally obtained true stress–true plastic strain data were directly implemented in finite element simulations. A full factorial parametric study was conducted by varying the bending angle (66–90°), bending radius (1.33 mm–2.93 mm), and die-punch clearance conditions. Experimental investigations on a subset process parameters were performed to assess the simulation outcomes. It was observed that the straightening history modifies the springback magnitude. Among the parameters considered, the bending radius was found to be the dominant factor governing springback sensitivity. An increase in the clearance gap between the die and punch produces systematic and monotonic shifts in the final product angle due to an increase in the effective bending radius.

Keywords: punch bending; thin wire; wire straightening strategies; springback behavior; finite element simulation

1. Introduction

In recent years, data-driven approaches have gained increasing attention for modeling and prediction in metal forming processes. The rising cost and time associated with extensive experimental studies, together with advancements in computational and data analysis techniques, have motivated the development of predictive models based on available experimental and simulation datasets. Several studies have proposed statistical and machine learning-based methods to establish relationships between process parameters and forming responses [1–4]. Punch-bending is one such forming operation where data-driven modeling can be effectively applied. In the precision punch-bending of thin sheet, springback, which is a change in the shape of a formed component after unloading, is one of the major challenges [5]. The change in dimensions is due to springback occurring via the release of elastic strains stored during elastic-plastic deformation that leads to a deviation between the final intended geometry and the deformed geometry [6]. As this process has large-scale application in the aerospace, automotive, and high-performance



Academic Editor: Andrea Ghiotti

Received: 9 March 2026

Revised: 2 April 2026

Accepted: 13 April 2026

Published: 27 April 2026

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mechanical applications, overcoming this challenge becomes a necessity rather than an option [7,8]. Panthi et al. [7] have observed that accurate prediction or control of springback is therefore essential to achieve dimensional accuracy, as it reduces the rework required due to failed parts from dimensional inaccuracy.

Analytical models developed for simple bending configurations have identified the influence of geometric and material parameters such as the bending radius, punch radius, sheet thickness, and elastic modulus on springback [9–11]. These simplified approaches are often inadequate for high-strength materials, cold-worked material and materials with a varying distribution of residual stresses [12–14]. Carrera et al. [15] observed that most of the models are inadequate to precisely predict the springback or final angle and gave recommendations to improve the models. Greze et al. [16], Oliveira et al. [17] and Xu et al. [18] observed that the presence of residual stresses, strain hardening, anisotropy, and microstructural evolution can affect elastic recovery. However, these effects are not precisely inherited into the simplified approaches used for modeling bending processes. Such pre-existing conditions, which are difficult to model in a simplified approach, influence local yielding behavior and alter the springback magnitude in real experiment [19,20]. Thus, this leads to a variation between the experimentally obtained data and the estimated data from the models.

Austenitic stainless steels such as EN 1.4310 are widely used in precision components due to their high strength, corrosion resistance, and good fatigue performance [21,22]. These materials are generally supplied in cold-rolled and coiled conditions, introducing heterogeneous residual stress distributions [23,24]. In addition, as reported by Seemann et al. [25], strain-induced martensitic transformation and metastable microstructures can further modify the mechanical response during subsequent forming. Rostek and Homberg [23] and Daehn et al. [24] demonstrated innovative straightening operations that can be employed to remove curvature present in the as-received thin coil wire. Straightening using a roller mechanism reduces geometric curvature but simultaneously redistributes internal stresses [26,27]. Reverse loading during multiple straightening passes may introduce the Bauschinger effect, resulting in reduced yield strength in the reverse loading direction. Nastran and Kuzman [28] reported that the straightening history can significantly influence the elastic-plastic response of the material after the process completion that can affect the subsequent forming processes. Yu [29] observed that the elastic modulus varies with plastic strain and can influence the springback during the forming processes.

Experimental studies have shown that springback is dependent on the bending angle, bending radius, tool wear, material history and residual stress distribution [30–32]. Lajarin et al. [33], Shi et al. [34] and Shi et al. [35] observed that tooling geometric parameters such as die-punch clearance, bending radius, and contact conditions affect the stress distribution during loading and unloading, thereby influencing elastic recovery [33]. Changes in these parameters can significantly affect the final product dimensions. Several approaches have been developed to analyze the effect of different parameters and have a precise prediction [19,36,37]. However, the studies are material-specific and dependent on the process design and tools. These effects are more pronounced in high-strength materials, where the elastic strain fraction is comparatively large.

In recent decades, finite element (FE) modelling has been increasingly used for simulating the bending process to predict the desired deformation and the obtained springback [38–40]. This process is widely enhanced to compensate by incorporating elastic-plastic constitutive laws with isotropic, kinematic, or combined hardening behavior [41–43]. Jamli and Farid [44] observed the various existing finite element methods for sheet metal forming processes and further developed an updated method with a neural network within finite element analysis to obtain improved prediction of the springback. However, the

predictions from finite element still vary from real data due to sensitivity to residual stress representation and material history, which cannot be totally incorporated in the developed models [45].

From the literature, it can be observed that despite these investigations, limited studies have systematically examined the combined effect of the straightening strategy and tooling clearance on springback behavior in thin, high-strength flat wire geometries. In the present study, an attempt has been made to investigate the influence of straightening history and tooling parameters on the springback behavior of EN 1.4310 stainless steel flat wire. Experimental tensile characterization was performed to capture the material response, and the measured data were implemented directly in FE simulations. A systematic parametric study covering different bending angles, radii, and die-punch clearance conditions was conducted. Representative experiments were carried out to validate simulation trends. The study provides quantitative insight into the relative influence of geometric, material and tooling parameters.

2. Materials and Methods

2.1. Work Piece Material

The material used in this study for the investigation is EN 1.4310 stainless steel, supplied in the form of a cold-rolled flat wire having a width of 3.9 mm and a sub-millimetre thickness of 0.4 mm. Due to manufacturing and logistical requirements, the flat wire is supplied in coiled form. The coiling process and storage condition induce a permanent transverse curvature associated with a non-uniform residual stress distribution through the thickness. This curved wire can be described as a circular segment having a segment height for a given circular segment span, as shown in Figure 1. In this study, the coiled form wire was used in the supplied form without any subsequent heat treatment to avoid property alteration. The curvature of the wire has been estimated with the BVS002R camera from Balluff (Neuhausen a.d.F., Germany) using BVS Cockpit 2.6 as analysis software. In this, the wire is placed and Balluff BVS002R camera is used to take an optical image. Further, for curvature measurement, multiple points are extracted along the wire profile and a geometric fit is applied to determine the curvature and the corresponding segment height. In the present wire, the curvature leads to a segment height of 11 mm for a wire spanning 300 mm, as shown in Figure 1. The outer surface of the coil is subjected predominantly to tensile residual stress, while the inner surface carries compressive residual stress. This pre-existing stress state influences subsequent forming operations through stress superposition effects. During bending, externally applied stresses are added to the internal residual stress field, potentially accelerating or delaying local yielding depending on the orientation.

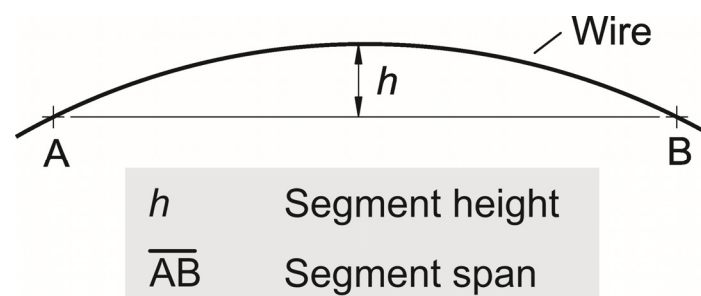


Figure 1. Curved wire described as circular segment.

The inherent curvature in the coiled form can impact the precision of the subsequent forming processes. To remove the curvature before performing the bending process, various straightening strategies were developed. The straightening was performed at room

temperature using a three-roller straightening setup. The description of the straightening setup has been provided in Table 1. The schematic representation of the three-roller straightening process is shown in Figure 2. The wire with curvature is fed into the three-roller system and a wire with the required segment height is obtained. The straightening process introduces additional plastic deformation, altering the distribution of the residual stress in the material [46]. This can thereby modify the residual stress state and can alter the strain-hardening behavior and the overall mechanical response of the material. To investigate this effect, three different straightening routines were applied by using single-pass, two-pass and four-pass straightening.

Table 1. Description of straightening machine setup.

Parameter	Dimension	Units
Roll Diameter	21.6	mm
Roll Thickness	4.1	mm
Roll distance	26	mm
Roll feed range	−4 to 4	mm
Wire feed rate	100	mm/min

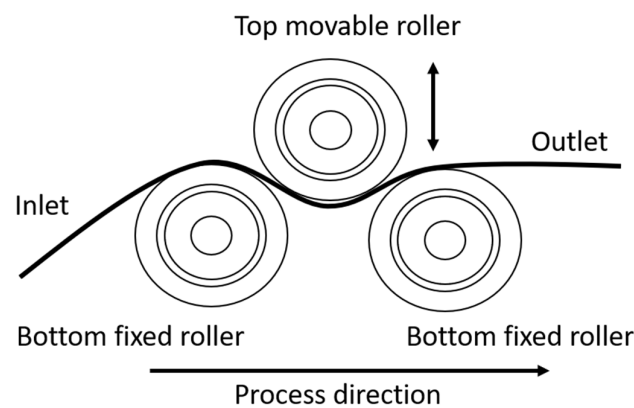


Figure 2. Schematic representation of the straightening process.

These straightening processes were done with different roller feeds to obtain different changes in curvature. In the single-pass method, the wire was passed once to directly obtain a straight wire, removing the segment height to get a straight wire that is represented by a segment height of 0 mm. In the two-pass and four-pass methods, the wires were introduced with positive and negative curvatures and finally a straight wire was obtained. Negative curvature implies having a curvature in the opposite direction to the initial curvature direction. The process parameters and pass sequences are summarized in Table 2. The strategies were developed to obtain a positive or negative segment height and finally a straightened wire was obtained. The varying segment heights were measured for a wire span of 300 mm. Each straightening strategy results in a distinct deformation history.

Table 2. Description of straightening strategies used in the study.

Strategy	Nomenclature	Strategy with Varying Segment Height
Original wire	1.4310_ORG	No straightening (11 mm Segment height)
Single-pass	1.4310_STR1	11 mm → 0 mm
Two-pass	1.4310_STR2	11 mm → −11 mm → 0 mm
Four-pass	1.4310_STR3	11 mm → −22 mm → 11 mm → −5.5 mm → 0 mm

After the straightening processes, mechanical characterization of the straightened wire is required to analyze the impact on the mechanical properties. To characterize the

responses, uniaxial tensile tests were conducted in accordance with standardized tensile testing procedures. Five tests were performed for each wire produced with different strategies and were averaged to get a mean value that can be used in further analyses. Tests were performed under the displacement-controlled conditions at room temperature. The experimentally obtained stress–strain data were subsequently implemented as material input for the FE simulations.

2.2. Finite Element Simulation Method

Finite Element Analyses (FEM) were performed to assess the effect of different parameters of the bending process. These analyses were conducted using the commercial software SIMULIA Abaqus Version 2022. The bending operation was modeled using a dynamic formulation with geometric nonlinearity enabled in order to account for rotations, finite elastic and plastic strains, and evolving contact conditions during loading and unloading. The approach was designed to have robustness in handling complex contact interactions to avoid convergence difficulties during the initiation and separation of contact between the workpiece and tools. The flat wire specimen ($3.9 \text{ mm} \times 0.4 \text{ mm}$ cross-section) was discretized using eight-node linear brick elements with reduced integration (C3D8R). This element formulation was used to achieve a balance between computational efficiency and accuracy for elasto-plastic deformation. The wire was designed with five elements along the thickness to capture the distribution of different parameters along the thickness of the wire. The punch, die, and blank holder were defined as rigid bodies and controlled through reference nodes, thereby reducing the number of degrees of freedom and computational time while maintaining the geometric rigidity and contour of the tooling surfaces. A typical tool setup used during the Abaqus simulations is shown in Figure 3. Figure 3 shows the initial position of the tools and wire. Figure 3 shows the maximum displacement of the punch tool that leads to maximum bending position, providing the initial bend angle of the wire. Figure 3 shows the tool position after the unloading step leading to elastic recovery-led springback and final position of the wire, referred to as the product angle.

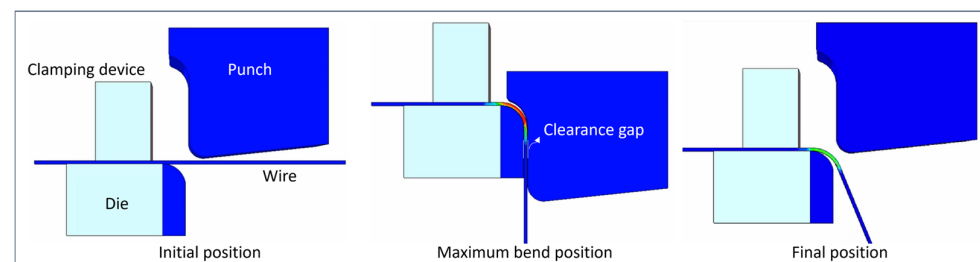


Figure 3. Representation of tool setup for the simulation in Abaqus FE simulation.

Simulations were performed using the Abaqus/Explicit solver under quasi-static conditions, achieved by applying sufficiently low punch displacement rates to minimize inertial effects. The ratio of kinetic to internal energy remained negligible throughout the simulation, confirming quasi-static behavior. The explicit time increment was governed by the stability criterion, and no significant mass scaling effects were introduced. A surface-to-surface contact formulation with finite sliding was employed. The mesh size and element discretization were selected based on a mesh sensitivity study to ensure accurate stress representation. A mesh sensitivity study was conducted to evaluate the influence of element discretization through the wire thickness. Simulations were initially performed with 9, 7, 6, and 5 elements across the thickness. It was observed that the stress distribution and resulting springback predictions were sufficiently captured with 5 elements using the chosen element formulation, with no significant change in results compared to finer meshes. Therefore, 5 elements were selected as a suitable balance between accuracy and

computational efficiency. Boundary conditions were applied to prevent rigid body motion while allowing deformation of the wire.

Material behavior was described using linear elasticity combined with isotropic hardening plasticity. The elastic properties were used as obtained from the uniaxial tensile testing. The plastic response from the tensile tests was implemented directly via tabulated true stress–true plastic strain data. No analytical hardening law was fitted to the experimental data to avoid additional fitting uncertainty and also to ensure the experimentally observed nonlinear response was preserved in the numerical model. Contact between the wire and tooling components was modeled using a surface-to-surface formulation. Normal interaction was defined using hard contact, while tangential interaction followed a Coulomb friction model with a friction coefficient of 0.35. The coefficient is as reported for dry steel-to-tool step interaction by various authors [47]. The same contact properties were applied to all interacting surfaces. There is no direct tool-to-tool contact at any point and all contact interactions are between either of the tools and the workpiece.

The bending processes were simulated within a single dynamic step. Punch motion was defined through a displacement boundary condition applied to the corresponding rigid reference node of the punch tool. The die was constrained fixed at a position without any rotational or transverse degrees of freedom to eliminate rigid body motion. After reaching the target punch displacement associated with the prescribed bending angle, as shown in Figure 3, unloading was performed within the same step to allow for elastic recovery and springback. The springback and final product angle were evaluated by measuring the final product angle after complete unloading and comparing it to the initial bend angle at the maximum bending position.

Using the Abaqus simulations, a parametric investigation was carried out to examine the influence of tool geometry, uncertainty variables and the straightening strategy on the final product angle. The tool geometry was varied from 66° to 90° in increments of 2° leading to 13 different angles, while the bending radius ranged from 1.33 mm to 2.93 mm in increments of 0.1 mm, leading to 17 different radii. The resulting full factorial design comprised 221 parameter combinations. In addition, to account for possible uncertainty effects and deviations in tool positioning due to wear or assembly tolerances, three tool gap configurations were introduced with an initial nominal tool gap to accommodate the wire between the tools and further configurations were defined by applying horizontal offsets of 0.2 mm and 0.4 mm. In total, 663 simulations were performed for the 1.4310_STR1 material. To evaluate the effect of the straightening strategy in the given parametric range, the simulation set of 221 simulations with nominal tool gap was performed for the 1.4310_STR2 and 1.4310_STR3 materials. To compare the results with the original wire (1.4310_ORG), the same set of 221 simulations was performed with unstraightened wire properties without the curvature. Simulations were also performed for a reference with material properties obtained for the initial wire before straightening, without the curvature, for the given 221 combinations. This systematic procedure enables a sensitivity assessment of the tool geometric parameters, tooling uncertainties and straightening strategies on the final product angle of the wire.

2.3. Experimental Method

A total of 663 tool configurations were investigated numerically in the finite element study for the material 1.4310_STR1. However, manufacturing and experimentally testing all corresponding tool setups would not be economically feasible. Therefore, a representative subset of configurations was selected for comparative analysis between the experimental and simulation datasets. All experiments were conducted using the nominal (initial) tool gap condition, within the parameter range of the finite element simulations. Figure 4 shows

the tool setup used for the experiments. This setup was developed for punch-bending partially in collaboration with Bihler. The optical sensors, force sensors and used motors are industrially available standard parts. The curvature of the wire was measured using an optical system that measures the curvature along a given length. The wire can also be fed directly to the bending setup to obtain bending in any desired initial or pre-straightened wire. To ensure representative coverage of the simulated parameter space, three bending angles (66° , 78° , and 90°) and three bending radii (1.33 mm, 2.13 mm, and 2.93 mm) were selected. These values represent the lower, intermediate, and upper bounds of the investigated ranges for both geometric parameters. The full factorial combination of these levels resulted in nine distinct tool configurations. In addition, one intermediate configuration consisting of a 72° bending angle combined with a bending radius of 2.13 mm was examined. This additional test case was introduced to further evaluate the interpolation capability of the finite element model and to assess its predictive accuracy within the parameter space, rather than only at its boundaries. The bending experiments were performed under controlled laboratory conditions. After forming and complete unloading, the final product bending angle was measured using an industrial camera and Cognex In-Sight Explorer as the optical measurement system. The product angle was compared with the initial bending angle to determine the springback.

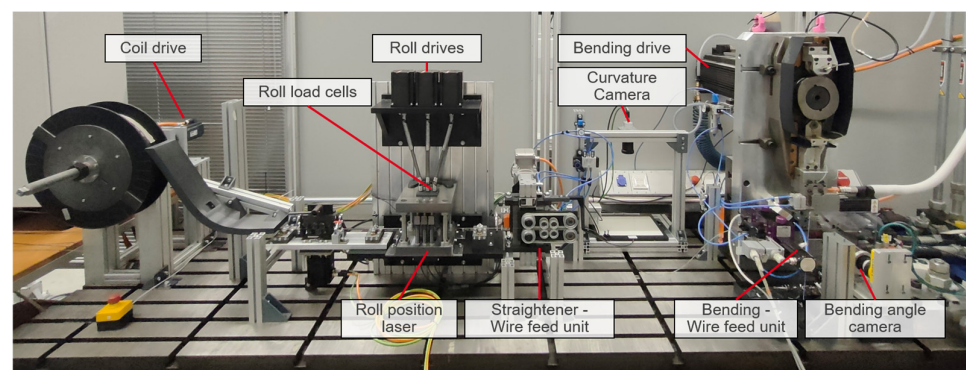


Figure 4. Experimental setup for performing straightening and punch-bending of wire [4].

3. Results

3.1. Mechanical Characterization of Wire Before and After Straightening

Engineering stress–strain flow curves obtained for specimens subjected to different straightening routines are shown in Figure 5. Table 3 shows the mechanical properties such as Young’s modulus, yield strength, ultimate tensile strength and total elongation at fracture for various wires. The tensile results indicate that the applied straightening strategies induce measurable, although moderate, modifications in the mechanical response of EN 1.4310 flat wire, as observed in Figure 5 and Table 3. The tensile behavior of the as-received material reflects its cold-rolled origin. The engineering stress–strain curves display a well-defined linear elastic region followed by continuous yielding without a pronounced yield plateau. Such behavior is typical of strain-hardened austenitic stainless steels, where prior deformation suppresses Lüders band formation and promotes smooth plastic flow [48,49].

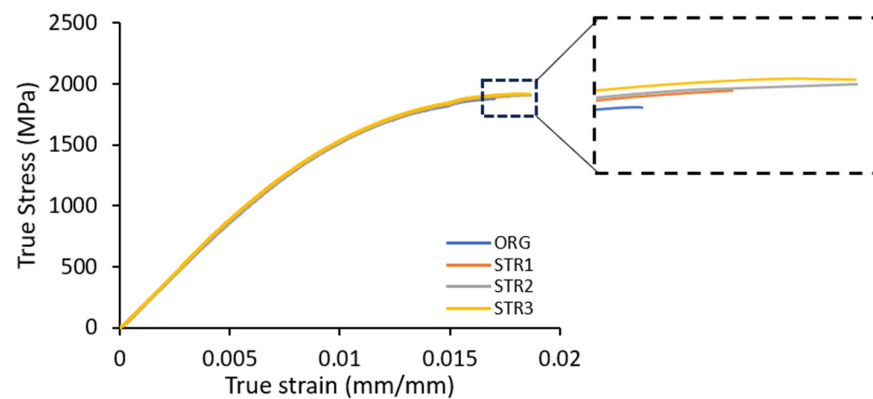


Figure 5. Tensile true stress-true strain properties obtained for different wires. A magnified view of the area in the small dashed rectangular box is shown in the larger dashed box.

Table 3. The average value of the mechanical properties observed for the wires.

Strategy	E (GPa)	Rp0.2 (MPa)	RM (MPa)	At (%)
1.4310_ORG	192.31	1644.69	1946.17	1.73
1.4310_STR1	190.26	1651.30	1959.66	1.76
1.4310_STR2	190.66	1641.93	1972.38	1.86
1.4310_STR3	187.79	1611.61	1924.66	1.86

Straightening is often regarded as a geometric correction step which induces additional mechanical deformation into the wire. Dahms and Homberg [26] observed that the material undergoes alternating bending in the roller system. This process induces additional plastic deformation in the surface regions and redistributes internal stresses. From Table 3, it is observed that a slight variation in Young's modulus, remaining below approximately 5%, is observed after the introduction of plastic deformation during straightening. While the elastic modulus is fundamentally governed by interatomic bonding forces and is generally considered insensitive to prior plastic strain, small deviations in the apparent macroscopic modulus can arise from changes in the internal microstructural state [29]. The variation in the state of dislocation-density generated during reverse bending, together with the formation of internal stress fields and micro-cracks, can contribute to additional reversible strain during tensile tests, thereby slightly altering the measured stiffness.

Variations in yield strength and ultimate tensile strength are also observed across the investigated straightening conditions. Although the magnitude of change remains below 10%, it is systematic and therefore mechanically relevant. The alternating tensile and compressive loading imposed during straightening modifies the dislocation structure and redistributes residual stresses, influencing the onset of plastic yielding and subsequent hardening behavior [27,46]. These changes reflect a change in the material's internal stress state.

Interestingly, the total elongation at fracture shows a slight increase following straightening. This behavior may be attributed to the introduction of compressive residual stresses in surface regions during reverse bending, which can delay crack initiation under subsequent tensile loading and stabilize deformation [50,51]. Similar trends have been reported for mechanically pre-strained stainless steels, where controlled reverse loading leads to partial stress redistribution and improved ductility [51]. Overall, the results suggest that straightening primarily affects the internal stress state and microstructural configuration, with only limited influence on the bulk tensile properties. In further analysis, we check the effect of these changes in properties on subsequent forming operations.

3.2. Analysis of Effect of Tool Geometric on Product Angle

To examine the influence of bending geometry on the final product angle, linear response surface models were generated by Response Surface Regression fitted using least-squares estimation using the commercial software MATLAB version online to the finite element-based and experimental-based datasets. The adopted model's mathematical form is:

$$\theta_{\text{prod}} = \beta_0 + \beta_1 A + \beta_2 R \quad (1)$$

where A represents the bending angle (deg ($^{\circ}$)) and R represents the bending radius (mm). The coefficients β_0 , β_1 , and β_2 in Equation (1) are the regression coefficients corresponding to the intercept, bending angle, and bending radius, respectively. For the experimental sets, the standard deviations have been in the range of $0.05\text{--}0.08^{\circ}$ for different experimental set. For the simulation sets, the finite element model is deterministic; thus, for a given parameter set, it produces a single consistent value without statistical variation.

The experimental data yielded:

$$\theta_{\text{prod_exp}} = -9.866 + 0.924A - 5.606R, \quad (2)$$

with $R^2 = 0.995$, the RMSE (Root Mean Square Error) = 0.676° .

For the simulation data, the resulting model is:

$$\theta_{\text{prod_sim_STR1_N}} = -5.983 + 1.046A - 7.971R, \quad (3)$$

$$R^2 = 0.965, \text{ RMSE} = 1.516^{\circ}$$

The models were used to predict product angles in the studied range of parameters generated by regression-based response surface modelling. Figure 6 shows the distribution of product angles and the predicted models for the dataset with the nominal tool gap. In Figure 6, dots are the experimentally obtained data points or predicted datapoint by the simulation model. Further, the continuous 3-D surfaces show the projected model. It can be observed that the linear model is effectively modeling the observed data set for both the simulation and experimental data. These values indicate that a first-order model captures the dominant behavior of the product angle with high accuracy over the investigated parameter range. The relatively small error metrics further suggest that the linear approximation is able to describe the observed trends for analyzing the effect of different parameters. Inspection of the fitted coefficients provides insight into parameter sensitivity. In the models, the coefficient associated with the bending angle is positive, confirming that increasing the imposed angle leads to a proportional increase in the final product angle. The coefficient associated with radius is negative, indicating that larger radii reduce the final product angle due to increased elastic recovery. The magnitude of the radius coefficient exceeds that of the angle coefficient when considered relative to their respective parameter ranges, demonstrating that the radius has a stronger influence on the final geometry.

When comparing the simulation and experimental models, the overall effect of the parameters and the ranking of their effects remain consistent. Although the difference in the numerical values of the coefficients differ, the sign of each term remains similar. The simulation predicts a stronger angular influence ($\beta_1 = 1.0465$) compared to the experimental model ($\beta_1 = 0.9240$). This indicates that the finite element model slightly overestimates the sensitivity of product angle to changes in the bending angle. Similarly, both models show a negative coefficient for the radius, confirming that an increasing radius reduces the final product angle due to a proportionally higher elastic recovery. The magnitude of the radius coefficient is larger in the simulation model ($\beta_2 = -7.9716$) than in the experimental

model ($\beta_2 = -5.6066$). This suggests that the simulation predicts a stronger reduction in the product angle with an increasing radius, effectively overestimating the geometric sensitivity associated with curvature. However, both models estimate that the effect of change in radii is higher than the effect of a change in the bending angle.

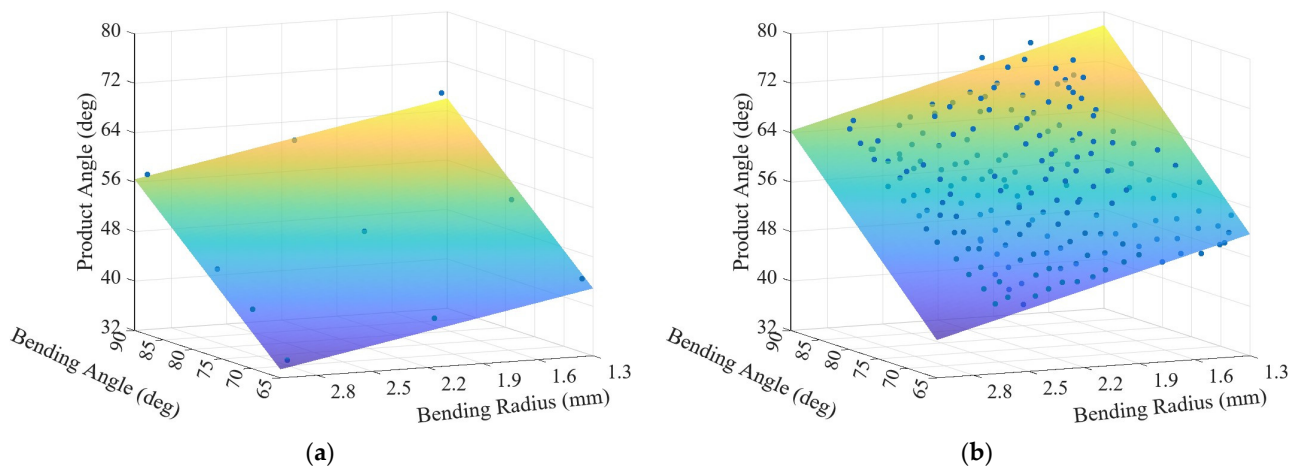


Figure 6. Distribution of product angle and predicted model for (a) experimental dataset and (b) Simulation dataset with nominal tool gap. The dots show the obtained data points from experiment or simulation. The continuous 3-D surface shows the projected model.

From a mechanical perspective, the observed behavior is consistent with the known tendency of finite element models to slightly overestimate the influence of process parameters [38,45]. In the present simulations, the material behavior is represented using an isotropic hardening model, which can lead to an overprediction of elastic recovery during unloading. As a result, the sensitivity of the product angle to the geometric parameters appears more significant in the numerical results than in the experimental observations. Nevertheless, the overall trends and the relative importance of the parameters remain consistent between the simulation and the experiment. This agreement indicates that the numerical model captures the primary deformation mechanisms governing the bending process, even though it slightly amplifies the geometric dependence.

From a physical standpoint, the strong influence of the bending radius can be attributed to the reduced curvature associated with larger radii. Under these conditions, the amount of plastic strain accumulated during bending is lower, and a greater portion of the deformation remains elastic. Consequently, a larger elastic recovery occurs during unloading, leading to a smaller final product angle. The high values of the coefficient of determination (R^2), together with the low prediction errors obtained for both datasets, further indicate that the models provide a reliable representation of the parametric trends.

The observed differences in coefficient magnitude between the simulation and experimental models can be attributed to several physical factors that are not fully captured within the idealized numerical formulation. The finite element model did not capture the effects of residual stresses in the wire, dislocation density, and the microstructural state resulting from prior cold rolling and straightening. In particular, the distribution of residual stresses through the thickness, which arises from coiling and subsequent plastic deformation, can influence the effective elastic recovery during unloading after the bending step. Additionally, localized microstructural heterogeneity and potential strain-induced martensitic transformation in EN 1.4310 may alter the stiffness and hardening behavior under bending, effects that are not explicitly represented in the FE-based simulation model. These factors can lead to deviations of the predictions from the real values. Nevertheless, the simulation successfully reproduces the correct directional trends and parameter hi-

erarchy observed experimentally, indicating that it captures the dominant deformation mechanisms. As such, the numerical model provides a reliable framework for assessing parametric influence and conducting preliminary process evaluations.

3.3. Effect of Tool Gap Variation on Springback

The effect of die-punch clearance on the bending behavior was examined by comparing the product angles obtained for the nominal gap, nominal +0.2 mm, and nominal +0.4 mm configurations over the complete set of 221 angle–radius combinations. The represented simulation data and the fitted models are shown in Figure 7. The mathematical models for the nominal gap, nominal +0.2 mm, and nominal +0.4 mm are shown in Equation (3), Equation (4) and Equation (5), respectively. Figure 7 shows the distribution of the product angle and the predicted models for datasets with nominal gap + 0.2 mm and nominal gap + 0.4 mm. The clearance between the die and punch can directly influence contact constraints, curvature development, and the through-thickness stress distribution during loading. The results indicate a systematic increase in springback with increasing tool gap. Across all radii and angles, the +0.2 mm gap condition produces higher springback than the nominal configuration, and the +0.4 mm gap leads to a further increase in the final product angle:

$$\theta_{\text{prod_sim_STR1_N+0.2}} = -5.138 + 0.971 A - 7.580 R \quad (4)$$

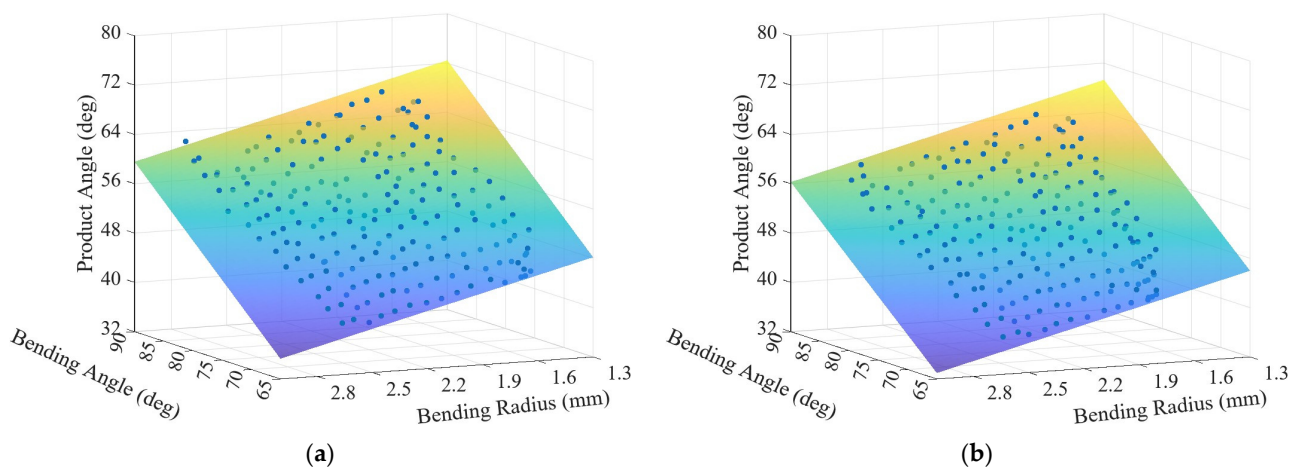


Figure 7. Distribution of product angle and predicted model for dataset with (a) nominal tool gap + 0.2 mm and (b) nominal tool gap + 0.4 mm. The dots show the data points obtained from the simulation model. The continuous 3-D surface shows the projected model.

$$R^2 = 0.985, \text{RMSE} = 0.925^\circ$$

$$\theta_{\text{prod_sim_STR1_N+0.4}} = -4.657 + 0.932 A - 7.653 R \quad (5)$$

$$R^2 = 0.990, \text{RMSE} = 0.721^\circ$$

The changes in the bending angle and bending radius were observed with the change in tool clearance. This phenomenon can have an impact on the final product angle observed after unloading. At the maximum bending position, the angle and radius describe the deformation state prior to unloading. Comparative analyses between the bending angle for different die clearances show that increasing clearance produces only a marginal reduction in the achieved bending angle. This is due to the fact that a marginal increase of 0.2 mm does not have a large impact on the tool position to have a significant increase in the bend angle. However, the bending radius exhibits a higher sensitivity to clearance. As the gap increases from nominal to +0.4 mm, the effective initial radius increases consistently

across all parameter combinations. This indicates that the workpiece wire does not fully conform to the die curvature when the clearance is increased giving a higher effective bend radius. The increase in the effective radius directly lowers the curvature and, consequently, the plastic strain. It was observed in Section 3.2. that a change in the radius can have a significant impact on the final product angle.

A larger tool gap also reduces the compressive contact pressure exerted by the tools (die and punch). Reduced confinement lowers the magnitude of plastic strain accumulated through the thickness. As plastic deformation decreases, the elastic component of deformation represents a larger fraction of the total strain, resulting in increased elastic recovery during unloading. The sensitivity to gap variation is not uniform across all geometric conditions [52]. This observation aligns with the earlier finding that larger radii produce more elastic-dominated deformation states. Under such conditions, even small reductions in plastic strain due to reduced constraint can significantly affect angular recovery.

It was observed in the previous section that the product angle is highly sensitive to the bend radius. The effect becomes more pronounced at larger nominal radii, where bending is already less constrained and the contact conditions play a greater role in defining curvature. The product angle decreases progressively with increasing gap, while springback increases accordingly. The magnitude of change in the product angle between the nominal and +0.4 mm clearances is noticeably larger than the corresponding change in initial angle, demonstrating that clearance predominantly affects elastic recovery rather than the imposed bending geometry. The parameter hierarchy remains unchanged; that is, the bending radius continues to exert the strongest influence on the product angle. In practical terms, this means that tooling tolerances can produce measurable deviations in the final geometry, particularly in large-radius bending operations. These findings highlight the importance of maintaining tight control over tool assembly and wear. Incremental increases in the gap due to wear or misalignment may lead to measurable dimensional deviations, particularly when forming components with larger bending radii. The relationship observed between gap increase and springback suggests that compensation strategies could be developed.

3.4. Effect of Straightening Strategy on Product Angle

The influence of the straightening strategy on the subsequent bending response was evaluated by comparing the complete parametric datasets for the original (as-received), STR1 (single-pass), STR2 (two-pass), and STR3 (four-pass) conditions for bending with a nominal gap and a given set of 13 bending angles and 17 bending radii, giving a total 221 simulations for each. The comparison was performed on the final product angle distributions across the entire parameter space. The predicted models can be given for the original wire by Equation (6), for STR1 by Equation (3), for STR2 by Equation (7), and for STR3 by Equation (8). The following are the observed R^2 and RMSE values for the fitted models:

$$\theta_{\text{prod_sim_ORG_N}} = -6.024 + 1.046 A - 7.759 R, \quad (6)$$

$$R^2 = 0.966, \text{RMSE} = 1.498^\circ$$

$$\theta_{\text{prod_sim_STR2_N}} = -3.842 + 0.993 A - 7.315 R, \quad (7)$$

$$R^2 = 0.961, \text{RMSE} = 1.411^\circ$$

$$\theta_{\text{prod_sim_STR3_N}} = -3.733 + 0.991 A - 7.460 R, \quad (8)$$

$$R^2 = 0.967, \text{RMSE} = 1.43^\circ$$

Figure 8 shows the distribution of the product angle and the predicted models for the datasets with 14310_ORG, 14310_STR2 and 14310_STR3. In all cases, the product angle

exhibited a strong linear dependence on the initial angle (coefficient ≈ 1.0) and a negative dependence on the initial radius (coefficient between -7.3 and -8.0 deg/mm), with a high goodness of fit ($R^2 \approx 0.97$). However, systematic differences in the radius sensitivity coefficient reveal the effect of straightening on the bending response.

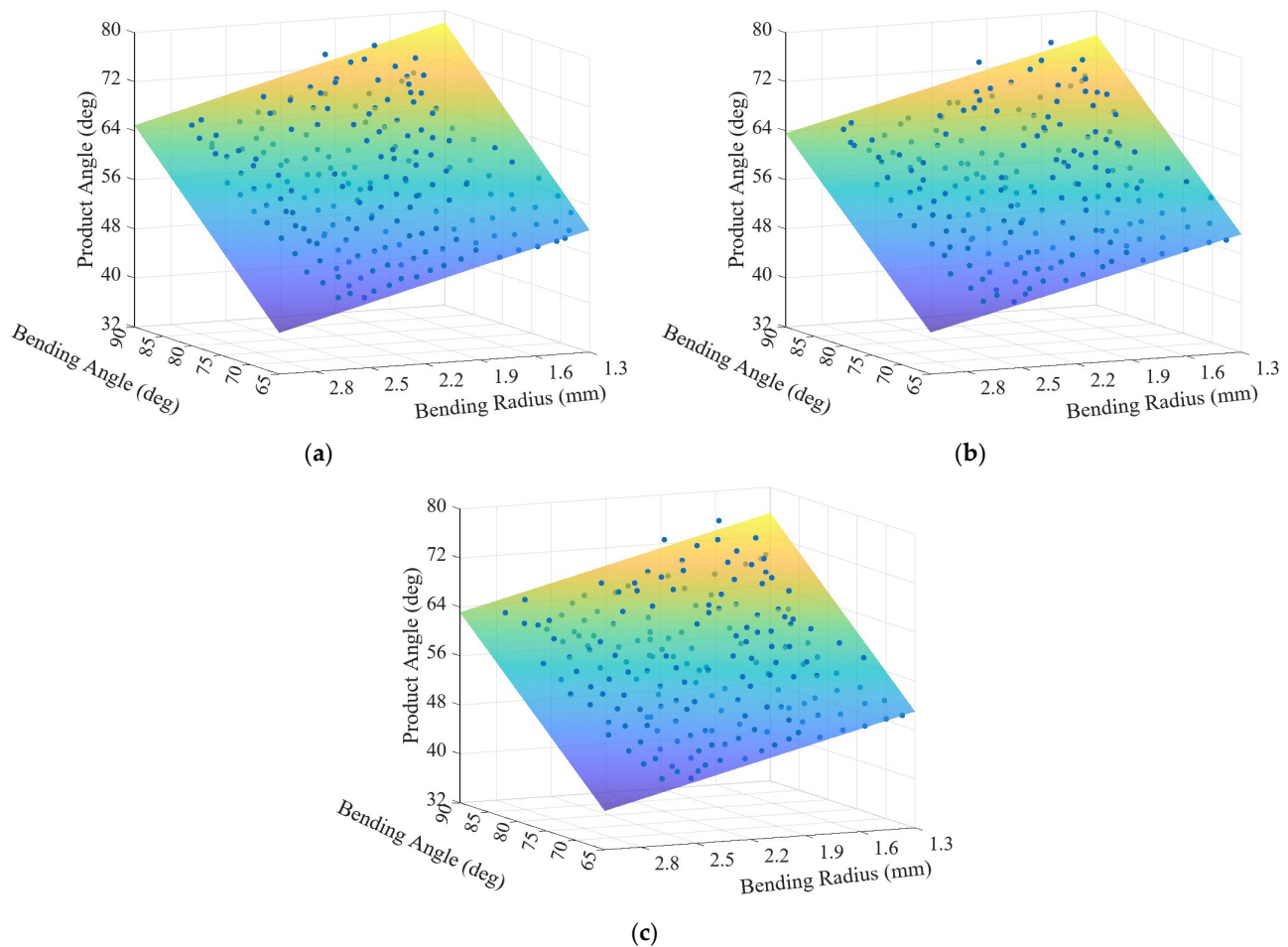


Figure 8. Distribution of product angle and predicted model for dataset with (a) 14310_ORG (b) 14310_STR2 and (c) 14310_STR3. The dots show the data points obtained from the simulation model. The continuous 3-D surface shows the projected model.

Relative to the as-received (radius coefficient ≈ -7.76 deg/mm), the one-pass straightening strategy (STR1) increased the magnitude of radius sensitivity to approximately -7.97 deg/mm, corresponding to an increase of about 2.7%. This indicates that, for a 1 mm increase in radius, the reduction in the product angle becomes approximately 0.21° larger compared to the original wire. In contrast, two-pass straightening (STR2) reduced the magnitude of the radius coefficient to approximately -7.32 deg/mm, representing a decrease of about 5.7% relative to STR1. This corresponds to an increase in the product angle of approximately 0.44° per millimeter of radius compared to the unstraightened condition. The four-pass strategy (STR3) yielded a radius coefficient of approximately -7.46 deg/mm, a 3.9% reduction relative to STR1, indicating partial stabilization but no additional substantial improvement beyond the two-pass condition.

The change in product angle response with increasing straightening passes, therefore, follows a non-monotonic trend: an initial increase in radius sensitivity after one pass, followed by a significant reduction after two passes and only marginal additional change at four passes. Quantitatively, transitioning from STR1 to STR2 reduces radius sensitivity by approximately 0.65 deg/mm ($\sim 8\%$ change), representing the largest incremental im-

provement among the strategies. Across the investigated bending domain of the present dataset (ORG–STR3), the influence of straightening strategy on the final product angle is systematic and curvature-dependent.

For identical bending angles and small radii, the deviation in the product angle between strategies remains limited (typically below $\sim 0.5\text{--}1^\circ$), indicating that under high-curvature conditions, the response is dominated by plastic deformation and material history plays a secondary role. In contrast, at larger bending radii the separation between strategies increases markedly, with maximum differences approaching approximately $3\text{--}4^\circ$ within the studied parameter space. This confirms that the influence of straightening becomes progressively more pronounced as elastic recovery constitutes a larger fraction of the total deformation.

These differences arise from the redistribution of tensile–compressive residual stress gradients introduced during successive straightening passes. The as-received wire (ORG) retains a residual stress state associated with prior coiling. A single pass (STR1) partially redistributes this profile, increasing the effective bending stiffness during unloading and thereby reducing springback. Further passes (STR2 and STR3) modify this internal stress balance again, producing a stabilized but not linearly progressive response. Consequently, the straightening strategy acts as a secondary but measurable modifier of the product angle, with its influence becoming increasingly significant in low-curvature bending regimes where elastic recovery dominates the final geometry.

4. Conclusions

Analyses were conducted to assess the effects of straightening history, bending geometry, and die-punch clearance on the final product angle behavior of EN 1.4310 cold-rolled flat wire. Although tensile tests showed only moderate variations in Young's modulus, yield strength, and ultimate tensile strength after straightening, bending simulations demonstrated that these small changes, along with the redistribution of residual stresses, lead to noticeable differences in the final product geometry. Under identical bending conditions, the final product angle differed by up to approximately 4° between the as-received and straightened states, a deviation that is significant for precision wire components. The results indicate that straightening primarily modifies the through-thickness residual stress distribution, which interacts with applied bending stresses and influences elastic recovery during unloading. Among the geometric parameters, the bending radius emerged as the dominant factor governing springback, exerting a much stronger influence on the product angle than the bending angle, thereby confirming that curvature and the associated strain gradient control the elastic recovery behavior. Additionally, variations in die-punch clearance within the investigated range from nominal to $+0.4\text{ mm}$ produced predictable changes in the product angle, with larger clearances increasing springback, especially at larger bending radii, highlighting the importance of tooling tolerances and assembly accuracy in high-precision bending operations.

This study systematically investigated the influence of the straightening strategy, bending geometry, and die-punch clearance on the springback behavior of thin EN 1.4310 flat wires using a combined experimental and numerical approach. The primary objective was to understand the coupled effects of prior deformation (straightening) and process parameters on the final product geometry. The results confirm that the bending radius is the dominant factor influencing springback; however, straightening strategy and tool clearance introduce significant secondary effects. In particular, the two-pass straightening strategy (STR2) was found to provide optimal springback reduction, while additional passes (STR3) did not yield further improvement. The linear regression model demonstrated a high level

of accuracy ($R^2 \approx 0.96$ and $RMSE \approx 1.5^\circ$), indicating that the dominant trends are well captured within the investigated parameter range.

This work provides a systematic evaluation of the combined influence of straightening history, tool geometry, and clearance, which are typically studied independently in the literature. The findings highlight that process history plays a critical role in modifying material response and must be considered in precision forming applications involving thin wires. The results provide practical guidance for improving dimensional accuracy by optimizing straightening conditions and tool parameters, thereby reducing trial and error in process setup. Future work will focus on incorporating advanced material models (e.g., kinematic or combined hardening), detailed residual stress characterization, and the application of machine learning approaches to further improve prediction accuracy and capture nonlinear process interactions.

Author Contributions: Conceptualization: W.H., A.K.P. and T.R.; Methodology: A.K.P., T.R. and W.H.; Software: A.K.P. and H.P.; Validation: A.K.P.; Formal analysis: A.K.P. and H.P.; Investigation: A.K.P.; Resources: W.H.; Data curation: A.K.P. and H.P.; Writing—original draft preparation: A.K.P.; Writing—review and editing: A.K.P., W.H., H.P. and T.R.; Supervision: W.H.; Visualization: A.K.P. and W.H.; Project administration: W.H. and T.R.; Funding acquisition: W.H. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) for the project “Data-Driven Modelling of Metal Bending Processes” (project no. 520459685), funded in the frame of the DFG priority program 2422 “Data-driven process modelling in metal forming technology” (500936349).

Data Availability Statement: The complete data set is available at <https://doi.org/10.5281/zenodo.18304940> (accessed on 12 April 2026.)

Conflicts 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.

Abbreviations

The following abbreviations are used in this manuscript:

FE	Finite Element
R^2	R Square
RMSE	Root Mean Square Error
1.4310_ORG	Original wire without straightening
1.4310_STR1	Wire produced with one pass straightening
1.4310_STR2	Wire produced with two pass straightening
1.4310_STR3	Wire produced with four pass straightening

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