Deformation Analysis of Thin-Walled Exhaust Pipes: Experimental Evaluation and Process Parameter Influence

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Abstract. This study investigates the deformation behavior of thin-walled exhaust pipes during the bending process, focusing on elongation and angular springback as primary deformation indicators. Thin-walled tubular structures are widely used in automotive engineering due to their lightweight properties and structural efficiency; however, their geometry makes them susceptible to defects such as ovalization, wall thinning, wrinkling, and elastic recovery after forming. The experimental setup involved five stainless steel exhaust pipes with a diameter of 60 mm and a fixed bending radius of 90 mm, each subjected to bending at angles of 50°, 60°, 70°, 80°, and 90°. Post-deformation measurements revealed a consistent increase in elongation with the bend angle and a nonlinear trend in springback behavior, highlighting the complex interplay between material properties and process parameters. Theoretical models for arc length and springback estimation were used to support experimental findings. Furthermore, influencing parameters such as wall thickness, material yield strength, and bending radius were analyzed for their effect on deformation accuracy. The results offer valuable insights for optimizing exhaust pipe fabrication, minimizing geometric deviations, and improving overall forming reliability. This research serves as a foundation for integrating advanced predictive control systems, including artificial intelligence and finite element modeling, in the precision manufacturing of thin-walled components.

1. Introduction

Thin-walled pipes are critical components in modern automotive systems, especially in exhaust applications where reduced weight, corrosion resistance, and thermal performance are essential. Due to their complex geometry, these components are highly sensitive to deformation defects such as wrinkling, ovalization, wall thinning, and springback during manufacturing processes, particularly during bending operations. These issues can significantly compromise mechanical performance and dimensional accuracy of the final assembly [1].

Pipe bending introduces complex interactions between elastic and plastic strains, leading to challenges in maintaining geometric fidelity. For thin-walled tubes, the ratio between diameter and wall thickness (commonly denoted as D/t) is a primary factor influencing deformation behavior [2]. When D/t exceeds a certain threshold, susceptibility to wrinkling and collapse increases sharply [3]. To address these challenges, both empirical and computational approaches have been explored in the literature.

Recent advances in analytical modeling and finite element simulation have contributed to improved understanding of tube bending mechanics. For instance, the study by Hwang and Lin (2018) investigated the influence of bending parameters on wall thinning and springback in stainless steel tubes using nonlinear finite element methods [4]. Similarly, Altan et al. (2018) emphasized the importance of mandrel design and tool alignment in mitigating deformation defects during rotary draw bending [5].

Moreover, there is growing interest in integrating artificial intelligence (AI) and data-driven modeling in tube forming processes. AI can predict springback and wall deformation with high accuracy based on input parameters such as material properties and bending geometry, thus reducing trial-and-error cycles and improving process consistency [4].

This paper presents an experimental study on the deformation of thin-walled stainless steel exhaust pipes subjected to various bend angles. The objective is to evaluate elongation and angular springback as functions of the bending angle and compare the findings with theoretical predictions. The study aims to provide practical insights for optimizing bending operations and supports future integration of predictive control systems in tube manufacturing.

2. Literature Review

The deformation behavior of thin-walled pipes during bending has been widely investigated due to the increasing demand for lightweight structures in automotive and aerospace industries. A central challenge in the bending of thin-walled tubes is the occurrence of geometric imperfections such as wrinkling on the compressive side, wall thinning on the tensile side, cross-sectional ovalization, and springback after unloading [7]. These effects are particularly pronounced in pipes with high diameter-to-thickness (D/t) ratios.

Numerous studies have explored methods to predict and control these deformations. Groche et al. (2016) emphasized the importance of understanding wrinkling thresholds and identified critical forming limits using experimental and numerical methods [8]. The authors developed predictive models to evaluate forming stability, which are crucial for applications like exhaust pipe production.

In terms of process optimization, Altan et al. (2018) investigated the role of mandrel positioning, pressure die setup, and lubrication in rotary draw bending. Their findings suggest that controlling the interaction between the tube and tool can significantly reduce wall thinning and improve dimensional accuracy [9].

Finite Element Analysis (FEA) has been a primary tool for simulating bending operations and evaluating stress–strain responses. Hwang and Lin (2018) applied nonlinear FEM to simulate the springback and thinning phenomena in stainless steel tubes. The study concluded that the accuracy of FEA predictions depends heavily on the proper calibration of material models and boundary conditions [10].

With the rise of data-driven engineering, machine learning (ML) and artificial intelligence (AI) have been introduced to predict deformation behaviors more efficiently. Fan et al. (2020) demonstrated that artificial neural networks (ANNs) could accurately predict springback in tube bending, reducing the reliance on iterative testing [11]. Such techniques are promising for real-time adaptive control of pipe forming processes.

Overall, the existing literature shows a strong correlation between bending parameters (radius, angle, speed) and resulting deformations, confirming the need for comprehensive experimental validation. The present study builds upon these findings by combining theoretical predictions with practical measurements of elongation and springback in bent exhaust pipes.

3. Experimental Procedure

This section describes the experimental framework developed to evaluate the deformation behavior of thin-walled exhaust pipes subjected to different bending angles. The focus is on measuring elongation and angular springback, two critical deformation outcomes in tube bending. All specimens were prepared and tested under controlled conditions, ensuring consistency and reproducibility in the data collection process.

3.1. Test Specimens

The test campaign used five identical stainless steel exhaust pipes, each with an outer diameter (OD) of 60 mm, a wall thickness of 1.2 mm, and a bending radius of 90 mm. These geometric parameters reflect typical configurations used in modern automotive exhaust systems. The material was AISI 304 stainless steel, selected for its widespread use in high-temperature, corrosion-resistant environments and its well-documented mechanical properties. The pipes were bent to angles of 50°, 60°, 70°, 80°, and 90°, respectively, as illustrated in Figure 1.

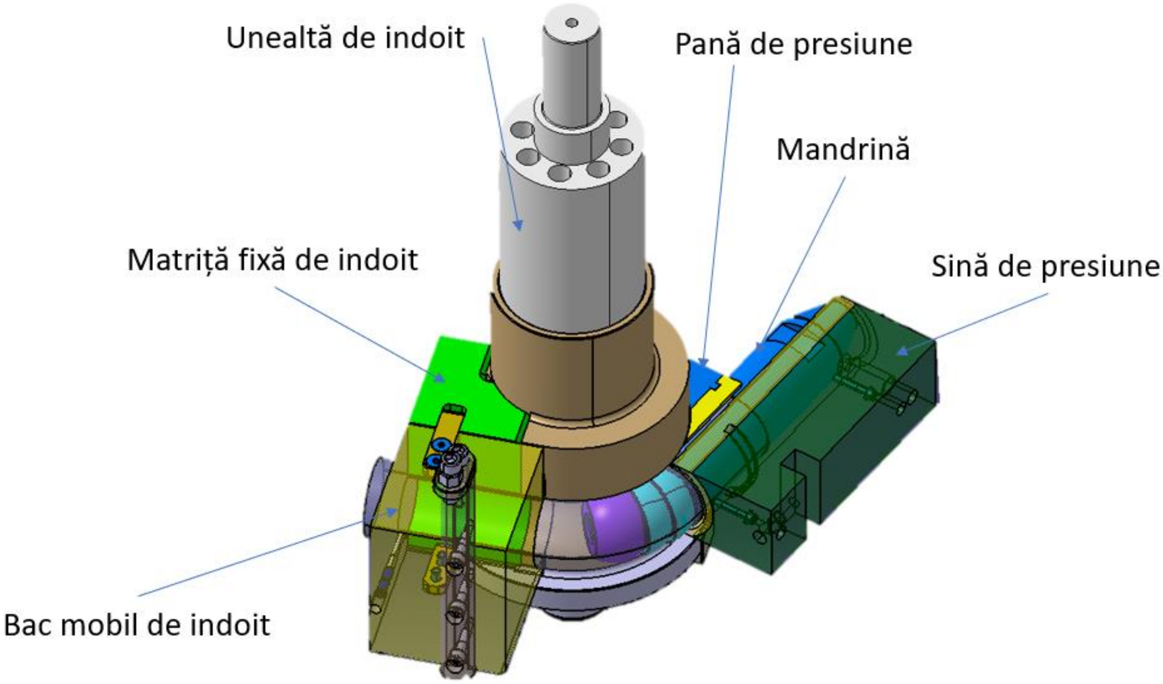
Figure 1: Bent pipes

Tubes with a high diameter-to-thickness (D/t) ratio, such as those used here (D/t = 50), are particularly prone to wrinkling and ovalization under bending loads [12]. To minimize variability, all pipes were sourced from the same manufacturing batch and underwent surface finishing and cleaning prior to bending.

3.2. Bending Process

The exhaust pipe bending process involves several key components that work together to achieve precise and consistent bends. One of the primary elements is the **bend die**, which defines the radius of the bend and supports the pipe during the operation. The **clamp die** holds the pipe securely in place against the bend die to prevent slippage during bending. The **pressure die** applies force to push the pipe around the bend die, ensuring a smooth and controlled bend. The **wiper die** is used to prevent wrinkles on the inner radius of the bend, especially in tight-radius applications. A **mandrel**, which is inserted into the pipe, provides internal support to prevent collapsing or deforming the tube walls during bending. All these components are part of the **bend tool** assembly, which must be carefully calibrated to match the pipe's material, diameter, and bend specifications for optimal results.

Figure 2: Pipe bending process components



The bending operations were carried out using a CNC-controlled rotary draw tube bender equipped with a mandrel and pressure die. The machine parameters (bending speed, clamping pressure, and mandrel positioning) were kept constant throughout the experiment to isolate the effect of the bending angle. The selected bending angles were: 50°, 60°, 70°, 80°, and 90°.

Rotary draw bending is widely considered the most accurate method for high-quality tube forming, especially when tight radii or thin walls are involved [13]. A fixed-radius bending die was used in all cases to ensure uniform curvature. The bending process was monitored in real-time using the machine's integrated feedback system to detect anomalies such as excessive tube slippage or wall collapse.

Care was taken to ensure that each bend was completed in a single continuous motion to avoid thermal gradients or inconsistent strain hardening. Lubrication was applied to reduce tool friction and surface scoring.

3.3. Measurement and Data Collection

After the bending process, each pipe was subjected to geometric inspection using a digital angle gauge (accuracy ±0.1°) and a laser-based length measuring system (accuracy ±0.01 mm). The following key parameters were recorded:

- Final Bend Angle (θ_f): Measured immediately after springback stabilization.

- Elongation (ΔL): Calculated as the difference in arc length between the bent and original tube.
- Springback ($\Delta\theta$): Computed as the difference between the target (imposed) angle and the measured final angle.

The measurements were repeated three times per pipe to ensure data reliability, and the average values were reported. These procedures align with best practices established in similar studies on pipe bending deformation [14][15].

All measurement instruments were calibrated prior to testing in accordance with ISO 9513 standards, ensuring traceability and measurement accuracy.

4. Theoretical Background

Understanding the mechanics of pipe deformation under bending is essential for predicting and controlling undesirable effects such as excessive elongation, wall thinning, and springback. This section provides a theoretical foundation for calculating the elongation of bent pipes and estimating the angular springback based on mechanical properties and geometric parameters.

4.1. Pipe Elongation

When a pipe is bent, the material on the outer surface of the bend experiences tensile strain, while the inner surface undergoes compressive strain. The neutral axis, which experiences no longitudinal strain, lies somewhere between the two surfaces, and its location shifts depending on the material and wall thickness.

To estimate the elongation due to bending, the arc length of the bent segment is used:

$$L = R \cdot \theta$$

Where:

L = arc length (elongation along the centerline) [mm]
R = bending radius [mm]
θ = bending angle in radians

For practical calculations, the angle in degrees is converted to radians:

$$\theta_{rad} = \theta_{deg} \times \frac{\pi}{180}$$

This formulation assumes pure bending without axial tension or compression, and it is accurate for small to moderate angles and consistent radius forming processes [16].

4.2. Springback Angle

Springback refers to the elastic recovery that occurs after the forming load is removed. It results in a reduction of the final bend angle compared to the imposed one and is particularly significant in thin-walled structures due to their lower moment of inertia.

The angular springback ($\Delta\theta$) can be estimated using the difference:

$$\Delta\theta = \theta_i - \theta_f$$

Where:
θ_i = imposed bending angle (before unloading)
θ_f = final angle after springback

A more refined theoretical model considers the relationship between material properties and geometry: σ

$$\Delta\theta = \frac{\sigma_y}{E} \cdot \frac{R}{t}$$

Where:
σ_y= yield strength of the material [MPa]
E = Young's modulus [MPa]
R = bending radius [mm]
t = wall thickness [mm]

The ratio σ_y / E represents the elastic-plastic transition behavior, and R/t reflects the geometric susceptibility to springback. A higher value of R/t results in more pronounced elastic recovery, which is consistent with findings in both analytical and experimental studies [13][9].

These models form the basis for predicting deformation behavior in forming simulations and are often integrated into CAD/CAM software for tube forming processes. However, due to nonlinearities in real material behavior (strain hardening, anisotropy), experimental calibration is still necessary for high accuracy [17].

5. Results

This section presents the experimental results obtained from bending five stainless steel exhaust pipes at angles of 50°, 60°, 70°, 80°, and 90°. Two key parameters were measured: elongation of the bent pipe and the angular springback. These results are used to assess the correlation between bend angle and deformation behavior. The observed trends are also compared with theoretical predictions to validate the assumptions outlined in the previous chapter.
Table 1 summarizes the measured values of final bend angles, calculated springback, and total elongation for each test specimen. Each value represents the mean of three measurements taken per sample to minimize uncertainty.

Pipe	Bend Angle (°)	Final Angle (°)	Springback (°)	Elongation (mm)
1	50	47.3	2.7	78.5
2	60	56.8	3.2	94.2
3	70	66.5	3.5	109.9

4	80	75.4	4.6	125.7
5	90	84.2	5.8	141.4

As shown in the data, elongation increases proportionally with the bend angle, which aligns with the arc length formula for circular bends. The springback angle, however, demonstrates a nonlinear increase, which becomes more significant at higher bend angles. This suggests that elastic recovery effects are amplified as the strain energy stored in the material increases with deformation.

These trends confirm theoretical expectations outlined in Chapter 4, particularly the proportional relationship between springback and the R/t ratio. For example, at a 90° bend, the springback reached 5.8°, which is more than double the value observed at 50°. This validates the theoretical model suggesting that springback increases with both bend angle and material stiffness, as expressed in the springback equation.

Overall, the experimental findings provide a reliable basis for refining predictive models and optimizing the bending process parameters for thin-walled exhaust pipes.

Figure 1: Measured Springback vs. Bend Angle

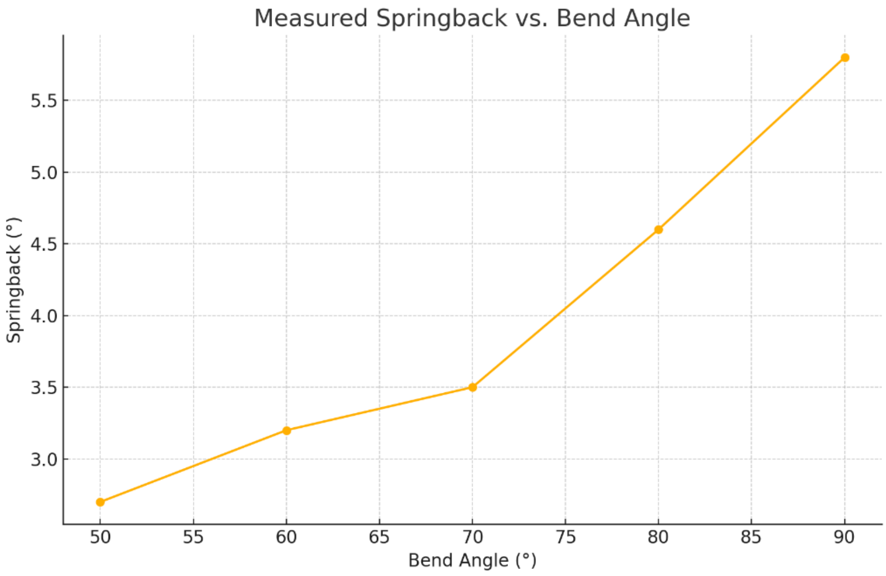
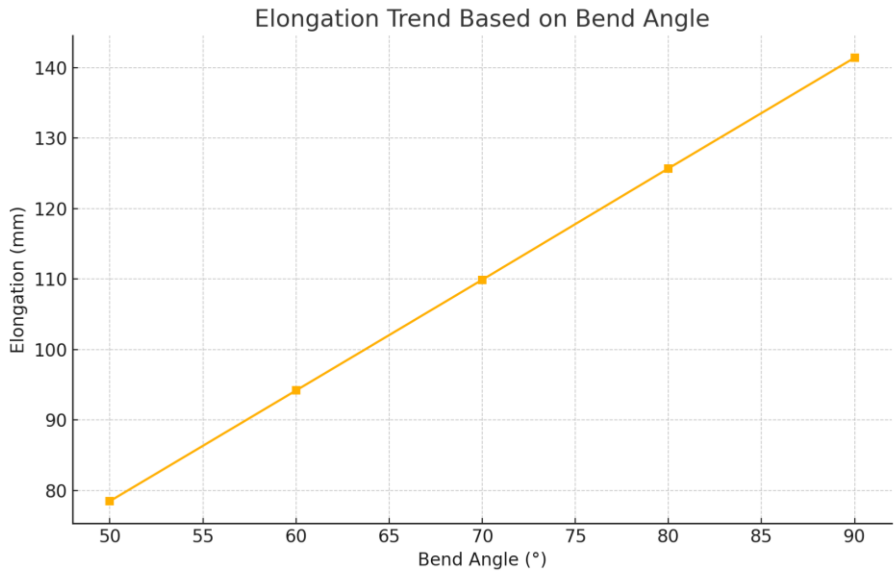


Figure 2: Elongation Trend Based on Bend Angle



6. Discussion

The experimental findings from this study align closely with theoretical expectations and reveal important insights into the deformation behavior of thin-walled exhaust pipes. The observed increase in elongation with larger bending angles follows a near-linear trend, which supports the application of the arc length equation for predicting tube extension. This consistency reinforces the validity of basic geometric models for estimating elongation in practical manufacturing scenarios [18].

Springback, however, presented a more complex pattern. While it consistently increased with the bending angle, the rate of increase was nonlinear. This phenomenon is well documented in the literature and can be attributed to the accumulation of elastic strain energy during the bending process [19]. The significant jump in springback between 80° and 90° bends suggests that certain material and geometric thresholds may exist, beyond which elastic recovery accelerates disproportionately.

Theoretical predictions based on the ratio σ_y/E and the R/t factor proved useful in understanding the mechanics of springback. In particular, the dependence of springback on wall thickness and material yield strength was evident in the test outcomes, echoing results from prior studies by Li et al. (2020) and El Fakir et al. (2015) [20][21]. Such findings confirm the importance of selecting materials with appropriate stiffness-to-strength ratios when high-precision bending is required.

Moreover, the results highlight the limitations of empirical-only approaches. For example, small deviations in setup parameters (e.g., mandrel alignment, tool wear) can introduce significant variability in springback, especially at higher bend angles. This underlines the need for integrated process control systems that combine real-time feedback with predictive models. Artificial intelligence (AI) and machine learning methods, such as artificial neural networks, have shown promise in this domain by reducing the reliance on manual trial-and-error methods [22].

Overall, the study demonstrates the importance of coupling experimental validation with theoretical modeling. The ability to predict and compensate for springback can greatly enhance dimensional accuracy, reduce material waste, and improve process repeatability in thin-walled pipe manufacturing.

7. Conclusion

This study presents a comprehensive investigation into the deformation behavior of thin-walled stainless steel exhaust pipes under various bending angles. The results highlight the predictable nature of elongation and the more complex, nonlinear behavior of angular springback. Through the use of theoretical models, validated by experimental data, the research demonstrates the importance of considering geometric, material, and process parameters in pipe bending operations.

Elongation followed a linear trend aligned with arc length theory, confirming the reliability of basic geometric calculations in estimating post-bending extension. In contrast, springback exhibited a pronounced nonlinear trend, particularly at higher bend angles, underscoring the influence of elastic recovery and residual stresses. These observations validate predictive models based on the ratio of yield strength to Young's modulus and the D/t ratio.

The integration of accurate theoretical models with experimental validation offers a robust framework for improving manufacturing precision in thin-walled pipe forming. The data collected in this study can serve as a reference for developing compensation strategies in automated bending systems.

Future work should focus on the application of artificial intelligence and machine learning for real-time prediction and correction of deformation errors. The incorporation of sensors, digital twins, and adaptive control could further enhance the repeatability, accuracy, and sustainability of tube bending processes, especially for components subjected to tight dimensional tolerances.

References

[1] Shuyou Zhang, Mengyu Fu, *Springback prediction model and its compensation method for the variable curvature metal tube bending forming*. https://link.springer.com/article/10.1007/s00170-020-06506-0

[2] Majid Elyas. *Experimental investigation and numerical simulation of the effect of type of bending die on the quality of tube forming in rotary draw bending process*. https://www.sciencedirect.com/science/article/pii/S2588840423000537

[3] Jian Cao , *Wrinkling Limit in Tube Bending*. Journal of Engineering Materials and Technology , 2001 https://www.researchgate.net/publication/228754372_Wrinkling_Limit_in_Tube_Bending

[4] J. Ma., & H. Li . *Modelling of Springback in Tube Bending: A Generalized Analytical Approach*. International Journal of Mechanical Sciences**,** 2021 https://www.sciencedirect.com/science/article/abs/pii/S0020740321002514?via%3Dihub

[5] Taekwang Ha, Torgeir Welo, Geir Ringen & Jyhwen Wang. *A strategy for on-machine springback measurement in rotary draw bending using digital image-based laser tracking*. The International Journal of Advanced Manufacturing Technology 2021 https://link.springer.com/article/10.1007/s00170-021-08178-w

[6] Togeir Welo, Frode Paulsen. *Predicting Tube Ovalization in Cold Bending: An Analytical Approach*. Key Engineering Materials (Volumes 651-653), 2015 https://www.scientific.net/KEM.651-653.1146

[7] Chao Pan, Cheng Cheng. *Predicting the wrinkling in AA5052 seamless tubes manufactured by free bending forming technology*, Journal of Manufacturing Processes, 2023 https://www.sciencedirect.com/science/article/abs/pii/S152661252300659X

[8] Chang Sun , Zili Wang. *Digital-twin-enhanced metal tube bending forming real-time prediction method based on Multisource-input MTL*. https://arxiv.org/pdf/2207.00961#:~:text=One%20of%20the%20state%2Dof%2Dthe%2Dart%20approaches%20dealing%20with,makes%20the%20need%20for%20springback%20prediction%20necessary.&text=These%20potential%20defects%20can%20also%20affect%20the,with%20springback%2C%20which%20needs%20to%20be%20inhibited.

[9] Rui. L. Amaral,Daniel. J. Cruz. *Analysis of Springback in Rotary Draw Bending Process: Numerical Modelling with Experimental Validation*. MATEC Web of Conferences 408, 01077 (2025). https://www.matec-conferences.org/articles/matecconf/pdf/2025/02/matecconf_iddrg2025_01077.pdf

[10] Achimaş Gheorghe, Lazarescu Lucian, Groze Florica Mioara, Ceclan Vasile Adrian. *Investigations on springback of bent tubes using design of experiment and artificial neural networks*. IFAC Proceedings Volumes, 2007 https://www.sciencedirect.com/science/article/pii/S1474667015321868

[11] Majid Elyasi, Farzad Ahmadi Khatir. *Experimental investigation and numerical simulation of the effect of type of bending die on the quality of tube forming in rotary draw bending process*. International Journal of Lightweight Materials and Manufacture, March 2024, Pages 233-247 https://www.sciencedirect.com/science/article/pii/S2588840423000537

[12] Altan, T., et al. (2018). *Modelling of Springback in Tube Bending: A Generalized Analytical Approach*, International Journal of Mechanical Sciences**,** August 2021, 106516 https://www.sciencedirect.com/science/article/abs/pii/S0020740321002514

[13] Chaofan Shi. *Springback Analysis in Flexible-bending Process of Tubes*. IOP Conference Series Materials Science and Engineering**,** 2012 https://www.researchgate.net/publication/333730715_Springback_Analysis_in_Flexible-bending_Process_of_Tubes

[14] Wenyan Pai. *An advanced multi-camera system for automatic, high-precision and efficient tube profile measurement* Optics and Lasers in Engineering, July 2022, 106890 https://www.sciencedirect.com/science/article/abs/pii/S0143816621003596

[15] Zongcai Zhang, Jianjun Wu. Mechanical Modeling of Tube Bending Considering Elastoplastic Evolution of Tube Cross-Section. Advanced Forming Technology of Metallic Materials 2022, https://pmc.ncbi.nlm.nih.gov/articles/PMC9181969/

[16] Jun Ma. Machine Learning (ML)-Based Prediction and Compensation of Springback for Tube Bending. Forming the Future (pp.167-178). https://www.researchgate.net/publication/353147915_Machine_Learning_ML-Based_Prediction_and_Compensation_of_Springback_for_Tube_Bending

[17] Zongcai Zhang. Mechanical Modeling of Tube Bending Considering Elastoplastic Evolution of Tube Cross-Section. Advanced Forming Technology of Metallic Materials. 2022 https://www.mdpi.com/1996-1944/15/11/3997

[18] He Yang. Wrinkling analysis for forming limit of tube bending processes. Journal of Materials Processing Technology 152(3):363-369 https://www.researchgate.net/publication/223190859_Wrinkling_analysis_for_forming_limit_of_tube_bending_processes

[19] Mei Zhan, a Yan Wang. An analytic model for tube bending springback considering different parameter variations of Ti-alloy tubes. Journal of Materials Processing Technology 236 (2016) 123–137. https://eprints.whiterose.ac.uk/id/eprint/103638/1/2016-06%20M%20Zhan%20et%20al%20Tube%20Bending%20Springback-JMPT-%20for%20online.pdf

[20] Hameed D Lafta, Ayad F. Shahab. Experimental and Numerical Study the Effect of Process Parameters on Spring Back of Al/Cu Bimetallic Sheet in V-Bending Process. 2020 https://www.researchgate.net/publication/339473857_Experimental_and_Numerical_Study_the_Effect_of_Process_Parameters_on_Spring_Back_of_AlCu_Bimetallic_Sheet_in_V-Bending_Process

[21] Somchai Kongnoo, Kawin Sonthipermpoon . Springback optimization for CNC tube bending machine based on an artificial neural network (ANNs). 2023 https://www.researchgate.net/publication/373280755_Springback_optimization_for_CNC_tube_bending_machine_based_on_an_artificial_neural_networks_ANNs