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Application of Abaqus Software to Simulate the Influence of Bending Angle and Sheet Thickness on The Inverse Elastic Parameters in the V-Bending Process of Sus 201 Material

Tran Thi Thu Thuy
Hanoi University of Mining and Geology, No 18 Vien, Duc Thang Ward, Bac Tu Liem District, Ha Noi City.

Abstract
Precision sheet metal bending is a widely utilized manufacturing process across numerous industries, including mechanical engineering, automotive production, electronics, medical devices, household appliances, and decorative applications. The dimensional accuracy of bent products is significantly influenced by the springback phenomenon - an elastic recovery behavior inherent in metal materials. Among the austenitic stainless steels, SUS 201 has gained widespread adoption due to its high strength under cold working conditions and cost-effectiveness, which results from partially replacing nickel with manganese and nitrogen.
This study investigates the influence of key parameters on the springback behavior during the V-bending process of SUS 201 sheet metal. The analysis is conducted using finite element simulations in ABAQUS, a powerful tool for modeling complex material deformation. The outcomes of this research not only provide practical insights for the sheet metal forming industry but also suggest a promising direction for applying computational methods in enhancing product quality and process efficiency.
Keywords:*ABAQUS, Bending angle,Spring-back Angle*

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I. Introduction

Spring-back phenomenon is one of the main challenges during the metal forming process. It occurs when the metal partially returns to its original shape after deformation (Figure 1).This phenomenon is affected by various factors such as the mechanical properties of the material, the bending radius, and the magnitude of the applied force, etc. The elastic spring-back of the metal during bending process can lead to inaccuracies in final products. This researchanalyzes the factors affecting spring-back behavior in the metal bending process, using simulation results to evaluate the impact of sheet thickness across various bending angles. Therefore, it provides specific data that can be used to control the spring-back angle in practical forming processes by adjusting the target bending angle – either adding or subtracting values obtained from experimental samples. Such an approach helps reduce material waste and optimize production time.

In the manufacturing industry, tool and die designers continuously strive to determine the appropriate die angle through calculations or empirical testing, in which both spring-back and spring-forward are taken into account to improve bending accuracy.

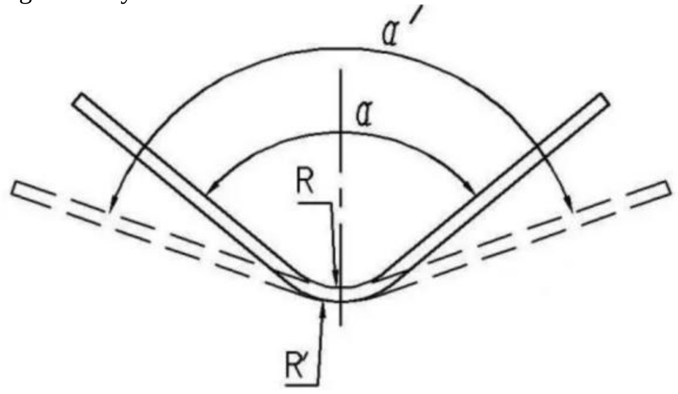


Figure 1. Spring-backAngle

II. Methodology

2.1. Research object

SUS 201,also calledInox, is currently one of over 200 types of the most common stainless steels.Mechanical properties of SUS 201 are shown below:

- Tensile strength: 515 - 735 Mpa.
- Yield strength: 275 - 380 Mpa.
- Hardness: 85 - 95 HRB.
- Elongation: 40% - 60%.
- Elastic modulus: 200 Gpa
- Simulation parameters:

In this research, the V-bending process is conducted on SUS 201 material with thicknesses of 1.0, 2.0, 2.5, 2.75 and 3.0 mm (which is widely used during bending process in the manufacturing industry), with the bending angles of45^{o}, 60^{o}, 90°, 100°, 120°, 130^{o} andpunch tip with 15 mm radius.

2.2. Theoretical basis

The calculations of spring-back angle during sheet metal bending process is related to determination the difference between initial bending angle and the bending angle after the material partially recovers its original shape due to elastic recovery. The magnitude of springback depends on various factors, including material properties, sheet thickness, bending angle, etc.

This study employs ABAQUS software to simulate different bending scenarios by varying parameters such as bending angle, sheet thickness, and punch radius. From the simulation models, the springback values are measured and analyzed. Based on these results, proposed solutions are suggested to help minimize springback in actual forming processes.

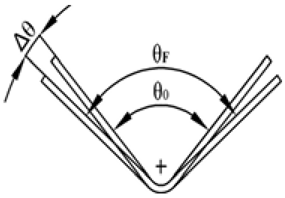


Figure 2. Elastic Angle

The main material parameters include:

- **Young's Modulus (E):**the elastic modulus of the material which is used to measure its stiffness
- **Yield Strength(σ_y):**the stress at which the material begins to undergo plastic deformation
- **Initial Bending Radius (R_b):** the radius of the bent portion formed by the punch before spring-back
- **Sheet Thickness (t):** the thickness of the metal sheet
- **Final Bending Angle(θ)**: the angle after spring-back has taken place

Spring-back is quantified by Spring-back coefficient (K_s), which is defined as the ratio of the final bending angle after the removal of force to the initial bending angle before unloading.

$$K_s = 1 - \frac{t}{R_b} \quad (1)$$

In this formula (1),K_s, t and R_b respectively represent thespring-back coefficient, the sheet thickness and the initial bending radius.

The spring-back angle can be calculated by multiplying the initial bending angle by the spring-back coefficient, according to the following relation:

$$\theta_f = \theta_0 \times K_s \quad (2)$$

Where:

- θ_f: Final bending angle before spring-back
- θ_0: Initial bending angle after spring-back
- K_s: Spring-back coefficient

To have a better detailed approach, especially while using high-durability materials, the elasticity can be calculated by the following equation:

$$\Delta\theta = \left(\frac{E}{2\sigma_y}\right)\left(\frac{t}{R_b}\right) \quad (3)$$

Where:

- Δθ: Spring-back angle after elastic recovery (measured in degrees)
- E: The material's elastic modulus
- σy: Yield stress
- t: Sheet thickness
- R_b: Initial bending radius

The final bending angle after spring-back can be calculated by the following formula:

$$\theta_f = \theta_0 - \Delta\theta \quad (4)$$

According to the predictive model for the spring-back behavior of metal sheets with varying thicknesses and materials [6], under specific sheet conditions, the curvature (K) is calculated using the formula bellow [6]:

$$k = \frac{1}{R_d + \frac{t}{2}} (1)$$

Where:

- K: the curvature of the metal sheet after spring-back
- R_d: die corner radius
- t: metal sheet thickness

According to the Von Mises yield criterion, the following relationship is derived[6]:

$$E' = \frac{E}{1-v^{e}};\ \sigma' = \frac{2\sigma}{\sqrt{3}};\ k' = \frac{2k}{\sqrt{3}}\ (2)$$

Where:

- E' : effective elastic modulus for plane strain
- E : elastic modulus of the material
- σ' : effective yield stress under plane strain conditions
- σ: yield stress of the material
- k′: effective strength coefficient for plane strain
- k: strength coefficient of the material
- v: Poision's ratio of the material

By applying Ramberg-Osgood relationship, we obtain the plastic deformation and moment of the material as follow [6]:

$$\sigma = K.\varepsilon^{n};\ My = \frac{2}{3} \cdot y' \cdot \left(\frac{t}{2}\right)^2 (3)$$

Where:

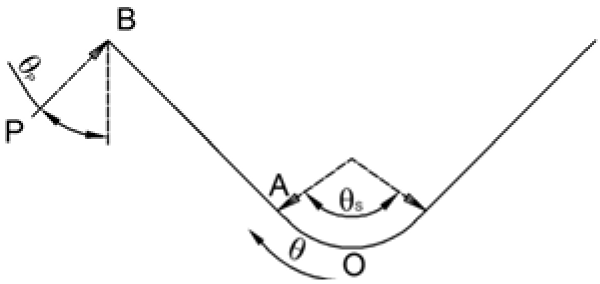
- σ: The material's yield stress
- K: Strength coefficient of the material
- n: Strain hardening exponent
- ε : Plastic strain

The force applied by the punch tool can be obtained using the formula below[6]:

$$P = \frac{1{,}2 \cdot C \cdot t^2 \cdot TS}{L} \quad (4)$$

Where:

- P: external force applied by the punch
- C: width of the metal sheet
- t: thickness of the sheet
- TS: tensile strength of the material
- L: width of the die



The bending moment at point O (the die corner) can be represented and derived by analyzing the pressure distribution along the bending zone S between points O and A [6]

$$M_0 = P.[l.\cos(\theta_b - \theta_p) + R.\sin(\theta_b - \theta_p)] \quad (5)$$

- θ_p: the angle formed by the die at point B which is oriented perpendicular to the surface plane of the metal sheet. Therefore, $\theta_p = 0$.

$$l = \sqrt{\frac{4.E'.t}{L.\sigma}} \text{ and approximately } l = \frac{L}{2},\ \theta_b = (\theta_p - \theta_l) \text{ and } S = R.\theta_b \quad (6)$$

To predict the spring-back angle, the following formulas can be used:[6]

$$\theta_l = \frac{1}{t}.\varepsilon.Y_b.l\ ;\ \theta_s = \frac{s}{t}\cdot\varepsilon\cdot R\cdot(1 + M') \quad (7)$$

- l: distance between the punch-force application point and the sheet support point
- θ_b: bending angle at the point B
- θ_p: punch action angle
- S: arc length of the bent region
- L: die opening length
- ε: plastic strain
- γ_b: bending radius
- M_o: bending moment at the bending corner
- M': correction factor
- $\Delta\theta$: spring-back angle
- θ_l: linear spring-back component
- θ_S: curved spring-back component

Therefore, the spring-back angle can be calculated as: $\Delta\theta = \theta_s + 2\theta_l$

The simulation depth is determined according to the following equation:

$$y = \frac{V}{2\cdot\tan\left(\frac{\alpha}{2}\right)} - (r_i + t)\cdot\frac{1-\sin\left(\frac{\alpha}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)} \quad (8)\ [8]$$

Where:

- r_i: inner radius of the bent sheet
- y: bending depth
- V: die width
- t : sheet thickness

Simulation Procedure in ABAQUS contains three steps:

- Step 1: Model creation and assembly of the sheet metal bending setup.
- Step 2: Input parameter assignment for the model.
- Step 3: Mesh generation and execution of the simulation.

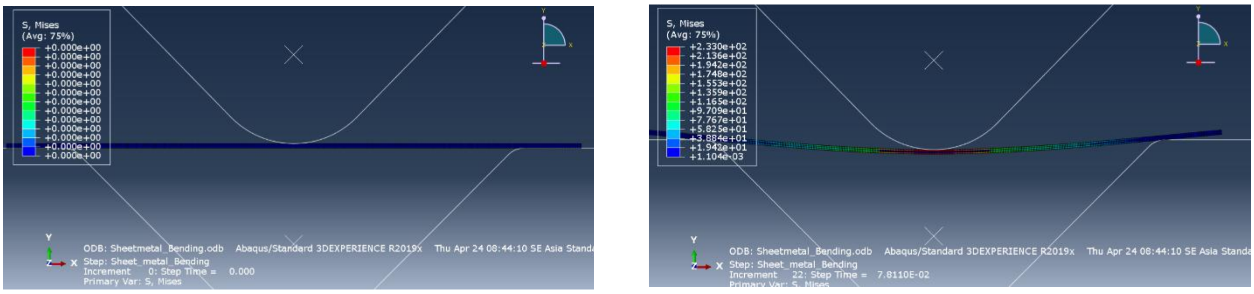


Figure 3. The initial stage of the sheet metal bending process

The initial stage (Figure 3) is the stage at which the metal sheet first comes into contact with the punch force, causing the workpiece to begin deforming and bending downward into the die cavity.

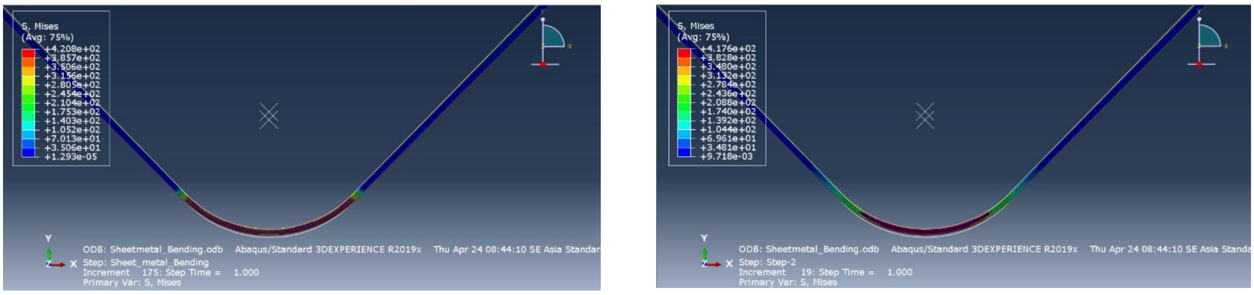


Figure 4 . The final stage of the sheet metal bending process

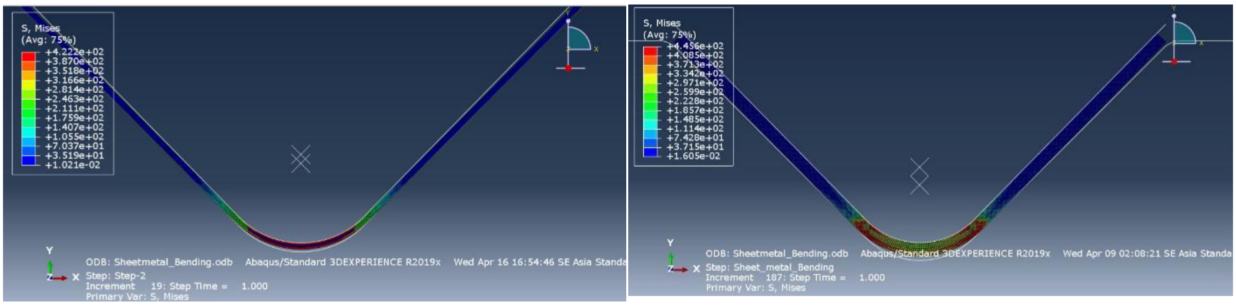
At thefinal stage (Figure 4), the workpiece has been fully formed by the interaction between the die and the punch. The punch then ceases to apply force to the metal sheet, allowing for the measurement of parameters necessary for further analysis and research.

In the bending zone, the maximum stress observed during the sheet metal bending process ranges from 401 to 422 MPa, which exceeds the material's yield strength (approximately 275–380 MPa). This level of stress causes plastic deformation in the bent region without inducing cracks or fractures. At the two ends of the sheet, the stress is significantly lower, resulting in elastic recovery with minimal permanent deformation.

After bending (unloading stage),once the applied load is removed, spring-back occurs, even during the unloading phase of the bending process. At this point, the stress in the central region – which may not have fully entered the plastic zone – begins to elastically recover, causing the sheet ends to spring inward or outward relative to the intended bending angle. This deviation is referred to as the spring-back angle of the sheet.

III. Resultsand discussion

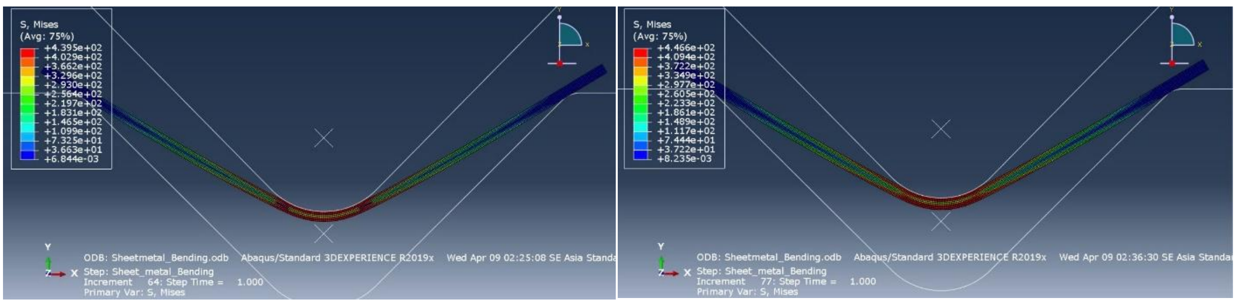
The investigation was conducted on samples with thicknesses of 1.0, 2.0, 2.5, 2.75, 3.0, and 3.5 mm, with the corresponding bending angles measured and presented in Table 3.1.



a, sheet with 1 mm thick *b, sheet with 2.5 mm thick*

Figure 5. Samples conducted at90^{o} bending angle

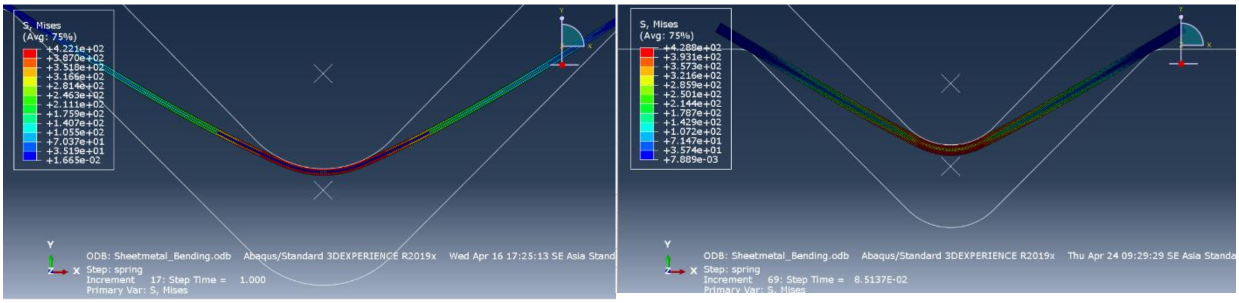
In thinner sheets, the high-stress region tends to spread more widely into the areas surrounding the bending angle. In contrast, for thicker sheets, the stress is more concentrated at the bend itself.In the other side, the stress distribution becomes more uneven as the sheet thickness increases (Figure 5).



a, sheet with 2 mm thick *b, sheet with 2.5 mm thick*

Figure 6. Samples conducted at 100^{o} bending angle

Thicker sheets exhibit a stronger spring-back tendency after bending, resulting in higher residual stresses at the bending zone (Figure 6).



a, sheet with 1 mm thick b, sheet with 2.5 mm thick

Figure 7. Samples conducted at 120^o bending angle

Figure 7a shows that the high-stress region extends further along the curved section, indicating a broader stress distribution. On contrary, Figure 7b demonstrates that the high-stress area is more concentrated near the bending angle.

This analysis highlights the influence of sheet thickness on stress distribution in the bent region. Thicker sheets exhibit significantly higher stress levels, which results in greater spring-back angles compared to thinner sheets. The higher stress values correspond to larger plastic deformation, thereby increasing the extent of spring-back.

Table 3.1. Research data

No.	Thickness (mm) \ Angle (°)	45	60	90	100	120	130
1	1	-0.36	-0.022	-0.54	0.57	0.42	0.05
2	2	-0.5	-0.424	0.233	0.293	1.246	0.37
3	2.5	-1.01	-0.719	0.316	0.156	0.237	0.38
4	2.75	-1.18	-0.898	-1.12	0.09	0.1	0.79
5	3	-1.98	-0.485	-0.14	0.28	0.53	0.39
6	3.5	-0.45	-0.484	-1.21	0.37	0.18	0.32

Based on the research data presented in Table 3.1, it can be observed that variations in the spring-back angle correspond to the changes in the investigated parameters, consistent with the earlier predictions. However, the differences between the individual samples are not as significant as initially expected.

Considering cases with negative spring-back angles, they indicate that the material sprang back inward toward the die cavity after unloading, whereas positive spring-back angles reflect outward spring-back behavior.

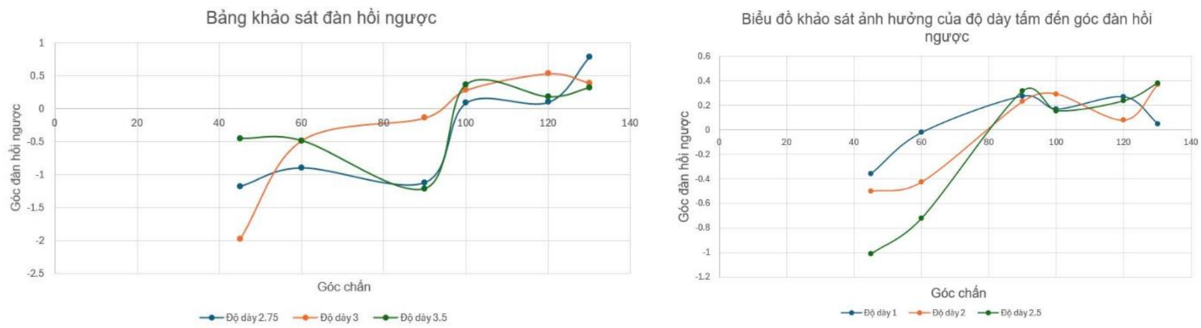


Figure8. Impact of sheet thicknesses on spring-back angles

From the Table 3.1, we can obtain the graphs which illustrates the change of spring-back angles according to the changing sheet thicknesses and bending angles.

With the high-thickness metal sheet, spring-back tends to be more significantat45^o, 60^o bending angles. However, at angles equal to or greater than 90^o, variations in spring-back became less stable and harder to predict.

The analysis results enable better control of the spring-back angle by adjusting the punch angle – either increasing or decreasing it by an amount equal to the expected spring-back – to achieve the desired final angle.For instance, for a 90° bend on a 1 mm sheet, the material springs back inward by approximately 0.54°. Therefore, in actual bending operations, the punch should form an angle of 90.54° to ensure that the final bend angle of the metal sheet is as close to 90° as possible.

In addition to spring-back, the study also considers the plastic strain of the metal sheet under different thickness conditions, highlighting how material thickness influences both elastic and plastic deformation during bending.

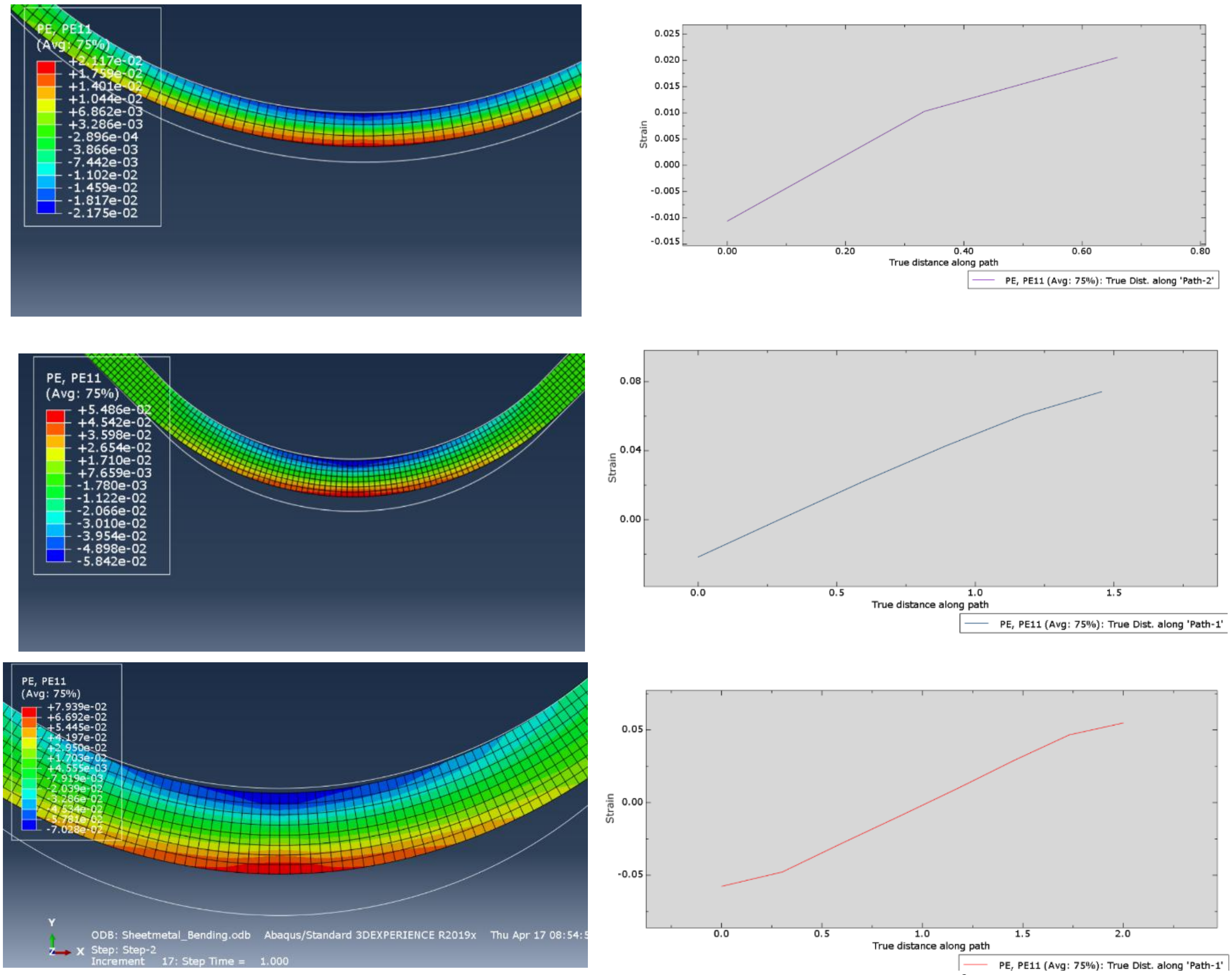


Figure9. Plastic strain in the bending zone of the sheet at the angle of 90°

According to Figure 9, the lower surface of the sheet tends to experience tensile elongation. As sheet thickness increases, the level of plastic strain also rises accordingly.

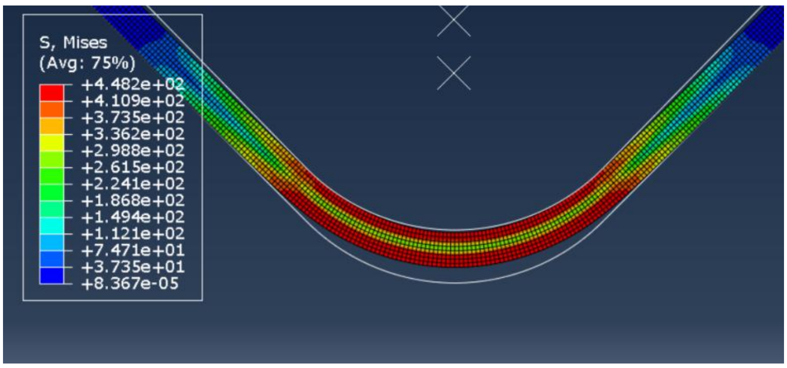


Figure10. Highest stress at the bending area

Cross-sectional analysis indicates that the bending region exhibits the highest stress concentration, Figure 10. The upper surface of the metal sheet undergoes compressive stress, whereas the lower surface experiences tensile stress. If the induced stress surpasses the material's allowable threshold, it may lead to defects such as cracking or surface scratches.

IV. Conclusion

The thickness of the bending plate has a significant effect on the springback angle;
The value of the springback angle is inversely proportional to the change of the bending angle;
Residual stress values are indicated on the stamped workpiece, which helps to predict the surface defect types of the stamped workpiece in practice;
By applying strategies such as over-bending, adjusting influencing parameters and using simulation tools, the producers can control the efficiency of the spring-back, therefore,enabling the production of components with high dimensional accuracy and high quality.

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