NELINEARNA SIMULACIJA FORMIRANJA UNUTRAŠNJEG RADIJUSA TOKOM ZRAČNOG SAVIJANJA TANKIH LIMOVA

NONLINEAR SIMULATION OF INSIDE RADIUS FORMING DURING AIR BENDING OF THIN SHEETS

Stručni rad

Arnel Jašarević
Edin Begović
Ibrahim Plančić

University of Zenica
Faculty of Mechanical Engineering,
Fakultetska 1, Zenica, B&H

Ključne riječi:
Zračno savijanje,
Nelinearne simulacije,
Solidworks simulacije

Keywords:
Air bending,
Non-linear simulations,
Solidworks simulations

Paper received:
13.06.2025.
Paper accepted:
25.09.2025.

REZIME
Ovo istraživanje analizira formiranje unutrašnjeg radijusa prilikom savijanja tankih limova koristeći nelinearne simulacije u SolidWorks-u. Analizirane su različite V-matrice kako bi se procijenio njihov utjecaj na proces savijanja. Rezultati simulacija su upoređeni sa stvarno savijenim dijelovima i postojećim podacima iz literature kako bi se ocijenila tačnost modela. Nalazi pokazuju snažnu korelaciju između simuliranih i stvarnih rezultata, potvrđujući pouzdanost nelinearnih simulacija u SolidWorks-u za predviđanje ponašanja materijala tokom zračnog savijanja. Ovi uvidi doprinose optimizaciji procesa i izboru alata, poboljšavajući preciznost savijanja u proizvodnim aplikacijama.

Professional paper

SUMMARY
This study investigates the forming of the inside radius in thin sheet bending using nonlinear simulations in SolidWorks. Various V-die sizes were analyzed to evaluate their influence on the bending process. Simulation results were compared with actual bent components and existing data from literature to assess accuracy and reliability. The findings demonstrate a strong correlation between simulated and real-world results, confirming the validity of SolidWorks' nonlinear simulation capabilities in predicting material behavior during air bending. These insights contribute to improved die selection and process optimization, ensuring enhanced bending accuracy for manufacturing applications.

1. INTRODUCTION

Air bending is one of the most widely used manufacturing processes in the production of various structural components across multiple industrial sectors. Traditionally, the design of precise bending technology involved conducting trial bends on test strips or components, measuring the resulting geometry, and analyzing key parameters such as K-factor values, developed lengths, and inside radii. These factors are largely dependent on the material quality, thickness, and primary processing method. Additionally, tooling plays a crucial role in determining the final geometry.

In this study, the nonlinear simulation module within the SolidWorks Simulation package was utilized to model the plastic deformation occurring during air bending. Nonlinear simulations enable the analysis of stress and strain distribution throughout the bending process, as well as the determination of total bending force requirements. However, the primary focus of this research was on the final geometry obtained from the simulation, aiming to validate its accuracy against experimental data and existing literature.

Figure 1 shows a typical set-up for air bending consisting of a upper tool called punch and a bottom tool called V-die.

The shown set-up clearly shows the basic characteristic that separates air bending from bending in moulds, which is that the sheet, being bent, never touches the bottom of the bottom tool but bending takes place in air with three-point contact with the tools.
It is also interesting that the radius on the upper tool does not play a decisive role in the formation of the inner radius on the part. The width of V-die is the main parameter which determines the final inner radius on the part.

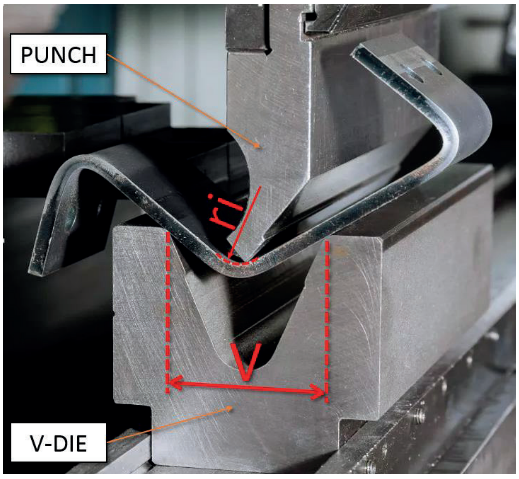

Figure 1. *Air bending set-up*

Based on empirical data, the inner radius can be expressed as a percentage of the width of V-die in the following way:
ri = 15-17% V: structural steels Rm < 410 MPa
ri = 20-22% V: stainless steels Cr=18% Ni=10%
ri = 13-15% V: aluminum group H (1)

This information must be taken into account when calculating the developed shape of the bending position, in such a way that if the actual radius differs from the one given on the drawing of the finished piece, the necessary geometry corrections are made before the K-factor calculation.
The correlation between the inner radius and the opening of the V-die also means that for a certain sheet thickness there is a minimum width of the prism that can be used.
Namely, for any material being bent, there is a certain minimum internal radius below which if the piece is bent, the piece will inevitably crack, It is recommended that for structural steels, the inner radius should not be less than the thickness of the sheet being bent. most often along the outer contour, as shown in Figure 2.
Materials that have better plastic properties such as certain types of aluminum and cold forming steel can have an inner radius smaller than the sheet thickness.

Figure 2. *Cracks during air bending*

On the other hand, steels showing increased stiffness can start to crack even with radii equal to 2x the sheet thickness.
Figure 4 shows recommendations of the manufacturer of bending machines and tools: "Amada Tools", for the selection of the appropriate bottom tool, i.e. the width of the opening on it: "V", as well as the required bending forces expressed in tons/meter. The presented table clearly indicates that the bending force is a function of the thickness of the material and the width of the prism opening.

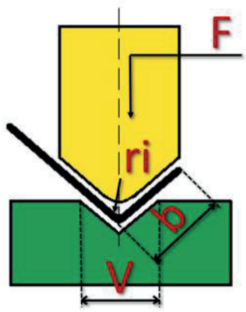

Figure 3. *Ilustration of important parameters for air bending*

s mm	4	6	7	8	10	12	14	16	18	20	25	32	40	50	63	80	100	125	160	200	250	V
	2.8	4	5	5.5	7	8.5	10	11	13.5	14	17.5	22	28	35	45	55	71	89	113	140	175	b
	0.7	1	1.1	1.3	1.6	2	2.3	2.6	3	3.3	4	5	6.5	8	10	13	16	20	26	33	41	ri
0.5	4	3																				
0.6	6	4	4	4																		
0.8		7	7	5	4																	
1		11	10	8	7	6																
1.2			14	12	10	8	7	6														
1.4				15	13	11	10	9	8													
1.6					17	15	13	11	10	9												
2						22	19	17	15	13	11											
2.3							25	23	19	17	15	12										
2.6								28	25	22	18	14										
3									34	30	24	19	15									
3.2										34	27	22	17	14								
3.5											33	26	20	16	13							
4											43	34	27	21	17							F
4.5												44	34	27	21							
5												52	42	33	26	21						
6													60	48	38	30	24					
7															52	41	33	26				
9																67	54	43				
10																85	67	53	42			
12																	96	78	60	55		
16																		136	107	86		
19																			150	125	100	
22																				160	130	
25																				210	170	
30																					240	

s=4 mm
V=63 mm
ri=10 mm
F=17 ton/m

s Sheet thickness (Rm 45-50 kg/mm)
F Bending force (ton/m)
ri Inside radius
b Minimal leg length
V V-die opening width

Figure 4. *Recommendations for selection of V-die and bending force from AMADA-TOOLS (2)*

2. BENDING OF SAMPLES

To ensure accurate data for comparison with the simulation, three test strips were bent under controlled conditions. All strips were made from S235JR (low-carbon structural steel with a thickness of 6 mm and a yield strength of 235 MPa). The test specimens were cut from the same metal sheet using a CO_2 laser, ensuring consistency in material properties and edge quality.

Bending operations were performed using a 200-ton press brake, maintaining uniform bending parameters for all trials. A single upper tool (punch) was used throughout the experiments, while the lower tooling (V-die) was varied to assess the effect of different die openings on inside radius formation. The selected V-die openings were 63 mm, 80 mm, and 125 mm, all within the manufacturer's recommended specifications for the press brake.

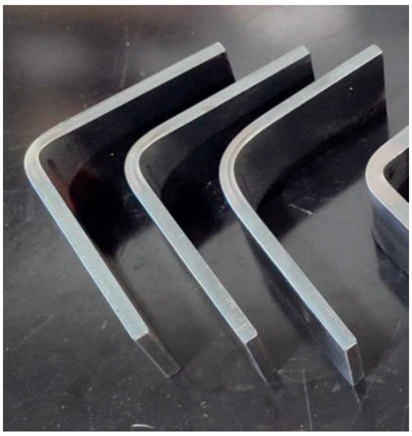

Figure 5. *Bent samples*

The bent specimens obtained from these trials are illustrated in Figure 5, showing variations in final geometry based on die selection.

After bending, the specimens were meticulously measured by scanning the contour of the bent profiles and transferring the data into a CAD format. This allowed for the extraction of critical parameters, such as the internal radius. It is important to note that the bending process does not yield a perfectly circular radius; instead, it results in a curve that closely resembles a parabolic shape. Therefore, an approximation method must be applied to adjust the contour to a form that more accurately corresponds to a radius. The CAD representation of one of the scanned bent profiles is shown in Figure 6, while the final measured radii after bending are provided in Table 1.

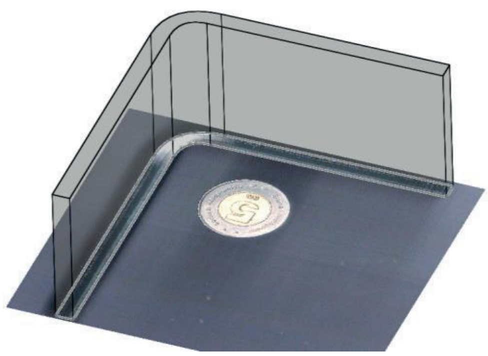

Figure 6. *Conversion of a 2d scan to a parametric model*

Table 1. *Actual inner radius values*

Sheet s(mm)	Die V(mm)	ri (mm)	ri/V *100%
6	63	9,7	15,5%
6	80	13,5	16,9%
6	125	23,8	19,0%

A more detailed analysis of the obtained results reveals that the actual internal radius for the openings of V-dies 63 and 80 falls within the 15–17% range, as cited in literature sources. However, for the V-die opening of 125, the measured radius slightly exceeds this range.

2. MATERIAL PROPERTIES FOR NONLINEAR SIMULATION

The simulations were conducted using the SolidWorks Premium Simulation package. Within the material database in SolidWorks, the steel grade S235JR is available; however, its material properties in the database are incomplete for accurately simulating the material's behavior in the plastic flow region. To achieve a precise simulation of plastic deformation, an appropriate stress-strain curve must be defined for this material.

To define an appropriate stress-strain curve, data from the DNV-RP-C208 norm was used. Section 4 of this standard provides detailed information on both the engineering stress-strain curve and the true stress-strain curve for S235JR steel. These curves are essential for accurately modeling the material's behavior under plastic deformation, ensuring reliable simulation results.
True sress strain curve measured values for significant points are shown in Table 2, and a visual representation of the sress strain curve is shown in Figure 7.

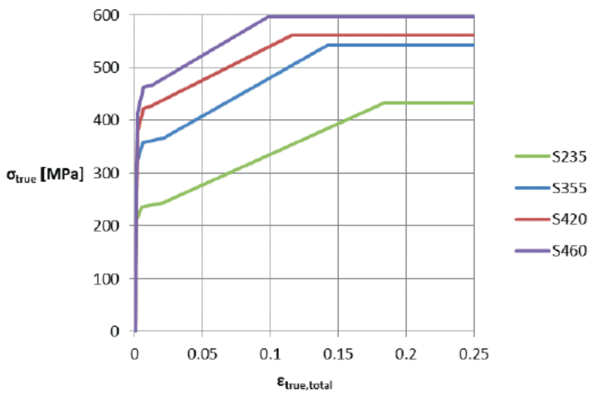

Figure 7. *Material curves according to Table 2 (t< 16 mm)*

The plasticity model used in the simulation was: „Plasticity-von misses“, which requires along with the correct stress-strain curve also a defines hardening factor.
The hardening factor is typically derived from the stress-strain curve using the strain-hardening exponent (n-value), which quantifies how a material strengthens as it undergoes plastic deformation.
Using these stress-strain points, we can estimate the strain-hardening exponent (n-value) based on the Hollomon equation [5]

$$\sigma = K\epsilon^n$$

We get a value of 0,26 which fals within the range which is within the expected range for mild structural steels like S235JR.

For bending tools (punch and V-die) a tool steel with linear elastic model was defined with a Tensile strength of 1900 MPa.

Table 2. *Proposed non-linear properties for S235 steels (True stress strain)* DNV-RP-C208

Thickness [mm]	t ≤ 16	16< t ≤ 40	40 < t ≤ 63
E [MPa]	210000	210000	210000
s_{prop} [MPa]	211.7	202.7	193.7
s_{yield1} [MPa]	236.2	226.1	216.1
s_{yield2} [MPa]	243.4	233.2	223.0
s_{ult} [MPa]	432.6	432.6	432.6
e_{p_y1}	0.0040	0.0040	0.0040
e_{p_y2}	0.0198	0.0198	0.0198
e_{p_ult}	0.1817	0.1817	0.1817

4. NONLINEAR SIMULATION AND ANALYSIS OF RESULTS

To conduct the bending simulation, 3D models of the upper and lower tooling were created using technical documentation in the Amada press brake tooling catalogue[(2)], along with a model for the 6 mm thick plate to be bent. The lower die was designed in three different configurations, corresponding to varying die opening widths of V = 63 mm, 80 mm, and 125 mm.

A 2D simplified simulation was implemented, as the setup maintained a uniform structure along its length. The core simulation concept assumed a fixed lower die, while the upper tool moved downward by a predefined displacement until a 90-degree bending angle was achieved.

Since three different simulations were conducted for the three distinct lower die openings, the displacement of the upper tool had to be individually adjusted for each case. This was done through iterative simulation runs, continuously refining the displacement until the bending angle fell within the tolerance range of 90° ± 1°.

The basic setup is shown in Figure 8.

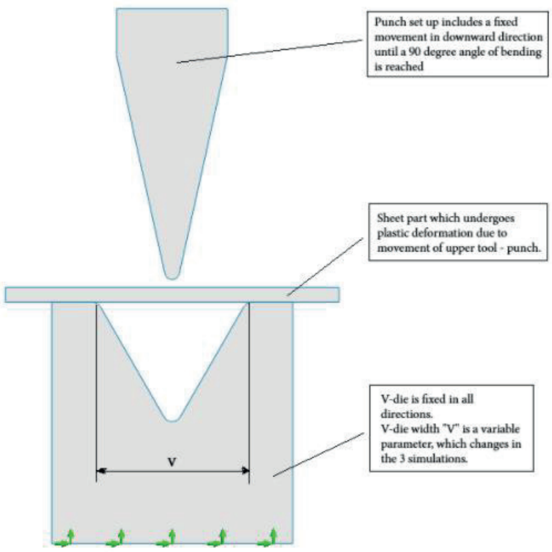

Figure 8. *Simulation set-up*

The contact sets were defined for the following interaction surfaces:

- The tip of the upper tool in contact with the top surface of the bent plate
- The tip of the lower die and the radius sections along which the plate slides during bending, interacting with the bottom surface of the plate.

This ensures accurate representation of tool-plate interactions, particularly for force distribution, friction effects, and material deformation within the simulation.

The finite element mesh used in this study was generated using SolidWorks Simulation with the following parameters:

Mesh type: Planar 2D mesh

Mesher used: Blended curvature-based meshing algorithm

Mesh control: Locally defined mesh control applied to critical regions

Element size:

- Maximum: 3.20354 mm
- Minimum: 3.20354 mm

Mesh quality: High

Mesh statistics:

- Total nodes: 15,602
- Total elements: 7,487

After completing the simulation, the deformed contours were exported into a 2D format, allowing for the extraction of internal radius values.

These deformed resuls along with inner radius values are shown in Figures 9.1 to 9.3.

A strain plot for bending simulation on V=125 mm die is shown in Figure 10.

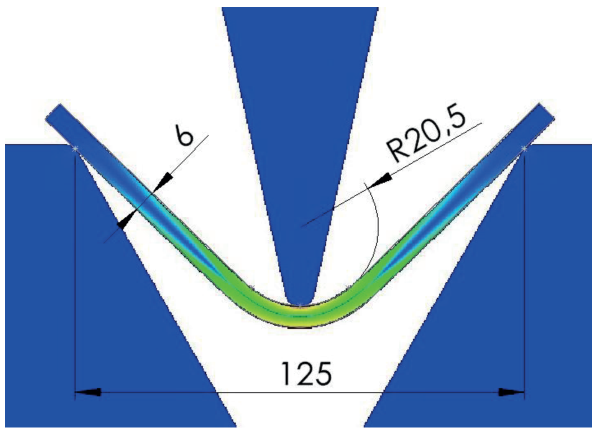

Figure 9.1 *Deformed results for V=125mm*

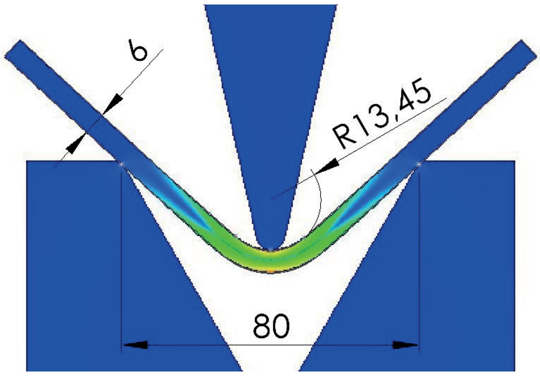

Figure 9.1 *Deformed results for V=80mm*

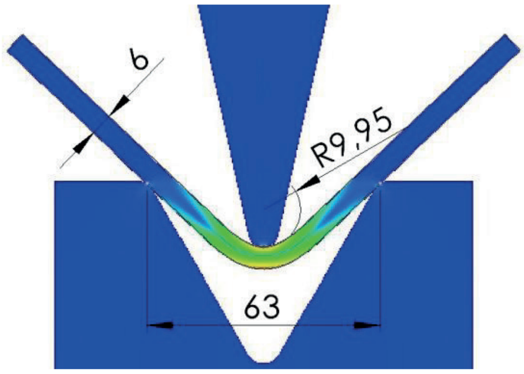

Figure 9.1 *Deformed results for V=63mm*

Figure 10. *Strain plot for bending simulation on V-die width V=125mm*

5. CONCLUSION

By comparing the nonlinear simulation results for inner radius values with the actual measurements presented in Table 1, it can be concluded that the simulated values for components bent using V-die openings of V = 63 mm and V = 80 mm closely correspond to the real-world measurements. However, in the case of the V = 125 mm opening, a certain deviation is observed.

Nevertheless, when the simulation results are compared with empirical data—which indicate that the inner radius typically falls within 15–17% of the V-die opening width—it is evident that the simulated values align within this range across all three simulations. This can be clearly seen in Table 3.***Table 3.***

V-die width (mm)	ri(mm) (simulation)	ri/V *100%	ri(mm) (actual part)	ri/V *100%
63	9.95	15.8%	9,7	15,5%
80	13.45	16.8%	13,5	16,9%
125	20.50	16.4%	23,8	19,0%

This validation supports the reliability of the numerical approach for predicting bending behavior, while also highlighting the need for further refinement in cases involving larger die openings.

It should be noted, however, that SolidWorks Simulation is not ideally suited for advanced nonlinear analyses, particularly those involving complex material behavior or large deformations. The observed deviations, especially in the case of the 125 mm die, may reflect limitations in the solver's ability to capture nonlinear effects with high fidelity.

While SolidWorks Simulation provides accessible nonlinear analysis capabilities, several studies have highlighted its limitations in handling complex material behavior, contact interactions, and convergence stability. For instance, Shi (2021)(6) demonstrates that SolidWorks struggles with large deformation problems and lacks the solver robustness found in Abaqus, particularly for plasticity and contact-dominated scenarios. Similarly, Schlitt (2023)(7) notes that SolidWorks is best suited for linear or mildly nonlinear

problems, recommending Abaqus for high-fidelity simulations involving creep, hyperelasticity, or dynamic loading. These findings suggest that while SolidWorks can offer reasonable approximations, further validation using specialized tools such as Abaqus or ANSYS is advisable for critical nonlinear studies.

REFERENCES

[1] Steve Benson. “Air forming and bending basics”. *The Fabricator* (October 27, 2022) https://www.thefabricator.com/thefabricator

[2] Amada tools. “Amada press brake tooling catalogue“. https://www.amada.eu/uk-en/products/tooling/

[3] Binko Musafija. Obrada metala plastičnom deformacijom Sarajevo, 1997.

[4] DNV-RP-C208 norm

[5] Daniel Schaefler. “Metal Properties: Strain-Hardening Exponent (n-Value)”. *MetalForming Magazine* (January 20, 2023) https://www.metalformingmagazine.com/

[6] Shi, B. (2021). “Abaqus vs SolidWorks: Dawn of FEA“. ResearchGate: https://www.researchgate.net/publication/352059057_Abaqus_vs_SolidWorks_Dawn_of_FEA

[7] Schlitt, T. (2023). “SOLIDWORKS Simulation vs Abaqus: When Should You Upgrade? “ GoEngineer: https://www.goengineer.com/blog/solidworks-simulation-vs-abaqus

Corresponding author:
Arnel Jašarević
University of Zenica
Faculty of Mechanical Engineering
Fakultetska 1, Zenica
Email: arnel.jasarevic@unze.ba