ANALIZA UTICAJA OTVORA V-MATRICE NA K-FAKTOR PRILIKOM ZRAČNOG SAVIJANJA TANKIH LIMOVA

ANALYSIS OF THE INFLUENCE OF V-DIE WIDTH ON K-FACTOR DURING AIR BENDING OF THIN SHEETS

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REZIME

Slobodno savijanje je jedan od najzastupljenijih postupaka oblikovanja pozicija iz limova. Široku upotrebu je našlo zbog jednostavnosti postupka i mogućnosti savijanja bilo kojeg ugla kontrolom hoda gornjeg dijela alata, odnosno noža. Ovim postupkom moguće je izraditi veoma složene oblike koji mogu imati i veliki broj savijanja.

Kako bi formirali razvijeni oblik na osnovu zadanog savijenog oblika moramo tačno odrediti K-faktor savijanja, koji je osnovni faktor koji definiše raspored linija savijana i dužinu komada u razvijenom obliku. Mnogo je parametara koji utiču na K-faktor, između ostalog vrsta i debljina materijala koji se savija. U ovom radu je analizirano da li i koliko izbor donjeg alata (prizme) utiče na K-faktor. U eksperimentalnom dijelu su probni komadi iste širine i dužine savijani na prizmama različitih širina, i nakon mjerenja i računanja K-faktora određen je tačno ovaj uticaj.

Professional paper

SUMMARY

Air bending is one of the most common methods of forming positions from sheet metal. It has found wide use due to the simplicity of the procedure and the possibility of bending any angle by controlling the movement of the upper tool (punch). With this procedure, it is possible to create very complex shapes that can have a large number of bends.

In order to form the developed form based on the given bent form, we must accurately determine the K-factor, which is the basic factor that defines the arrangement of the bent lines and the length of the piece in the developed form. There are many parameters that affect the K-factor, among others are the type and thickness of the material being bent. In this paper, it was analyzed whether, and to what extent, the choice of the bottom tool (V-die) affects the K-factor. In the experimental part, test pieces of the same width and length were bent on dies of different widths, and after required measurements and K-factor calculation, the magnitude of this influence was determined.

1. INTRODUCTION

Sheet metal is one of the key building blocks of modern industry. It offers greater flexibility in design and allows significant weight reduction compared to traditional designs, which are made of various profiles and tube shapes, while still achieving the required strength properties of the design. The global sheet metal market size is valued at USD 188.31 billion in 2023 and is projected to grow at a CAGR of 7.0% from 2024 to 2030 [4].

All this increasing demand and increasing requirements for precision place an emphasis on air bending as one of the main production operations of sheet metal parts. This paper will analyze the effects that different V-dies have on the resulting K-factor during bending, which is the main factor determining the bent part's final shape and size.

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

This 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.

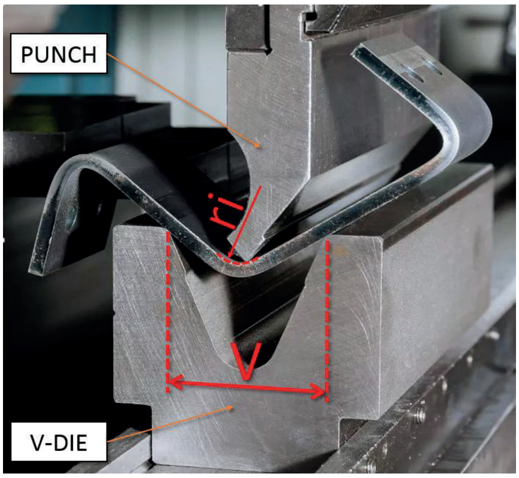


Figure 1. *Air bending set-up*

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 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.
Given that V-dies of different widths will be used during the experiment, and thus affect the actual inner radius, the geometry of the position will be corrected before calculating the K-factor. 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, most often along the outer contour, as shown in Figure 2. It is recommended that for structural steels, the inner radius should not be less than the thickness of the sheet being bent. 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 the bending force is a function of the thickness of the material and the width of the prism opening.

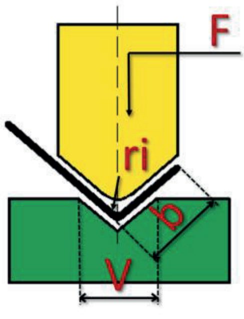


Figure 3. *Ilustration of important parameters for air bending*

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. BASICS OF K-FACTOR

In order to obtain the developed form based on the folded form, it is necessary to know the K-factor.

According to the theory, the K-factor represents the distance of the neutral line from the inner contour of the piece divided by the sheet thickness.

$$K = \frac{x}{s} \qquad \dots (1)$$

The neutral line represents the contour inside the piece that has not undergone any deformation, that is, its length is the same before and after bending, so its determination is crucial for us to determine the developed length of the position. These parameters are marked in Figure 5.

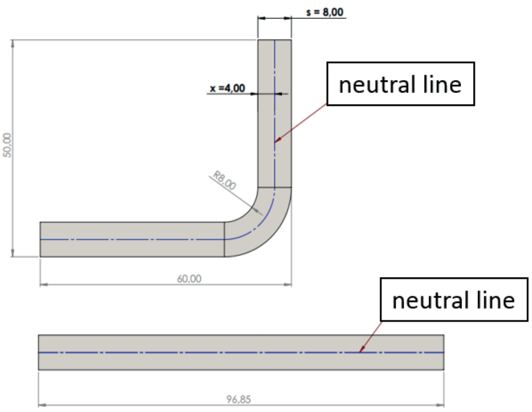


Figure 5. *Neutral line*

If we know the length of the position before bending and take the necessary measurements after bending, we can calculate the K-factor as follows:

$$L_n = (L_1 - r_i - s) + (L_2 - r_i - s) + \frac{(r_i + x)\cdot\pi}{2} \qquad \dots (2)$$

After sorting, the expression becomes:

$$K = \frac{x}{s} = \frac{2}{\pi s}\left(L_n - L_1 - L_2 + 2r_i + 2s - \frac{r_i\pi}{2}\right) \qquad \dots (3)$$

Where the parameters are:

- s – sheet thickness
- L_n – length of position before bending
- L_1 – length of the first arm
- L_2 – length of the second arm
- r_i – inner radius

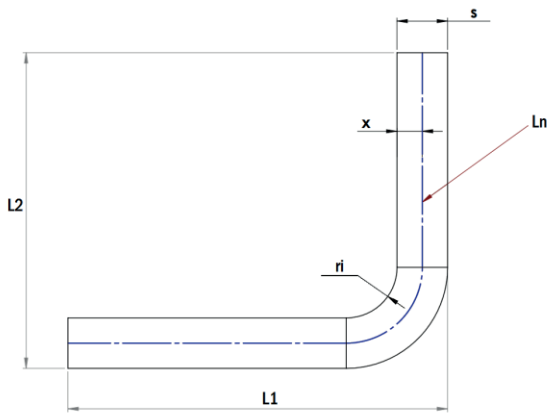


Figure 6. *K-factor parameters*

Using expression (3) it is possible to cut test pieces or test strips as they are often called, bend them and measure them, and based on the obtained data calculate the K-factor.
This is precisely the basic setting of the experiment that was performed and described in this paper.

3. EXPERIMENT PLAN

The basic set-up of the experiment consisted of the following 4 phases:
1. Cutting 9 test pieces on a CO2 laser, namely:
- 3 sheet samples: 6x190x50 (mm)
- 3 sheet samples: 8x190x50 (mm)
- 3 sheet samples: 10x190x50 (mm)

All 9 samples are from steel S235JR+N. During cutting, it was ensured that all 9 samples on the cutting plane were facing the same direction, considering that the material does not behave the same when bent vertically or parallel to the rolling direction of the sheet metal.
2. Milling the length of all samples on a CNC machine to the exact same length, in order to avoid measurement error because the laser-cut edge always has a certain bevel of the cut that could cause a measurement error.
3. Bending the samples on the press brake acording to the plan in Table 1.
The plan involves bending 6 mm sheet on die V = 125 and bending 10 mm sheet on die V = 63, which if we compare with the recommendations in the AMADA catalog (Figure 4) is not within the recommendations.
However, the rule that the inner radius (ri) is not smaller than the thickness of the sheet was not violated, so the piece could not break on the outer contour, therefore this is quite acceptable for the purposes of this experiment.
4. Measurement of positions after bending and calculation of K-factor. For most acurate measurements profiles of bent samples will be scanned and then the data can be procesed and used for calculations.

Table 1. *Plan for bending samples*

Sample thickness	Samples	Die V = 63	Die V = 80	Die V = 125
sheet s = 6 mm	1. sample	OK	/	/
	2. sample	/	OK	/
	3. sample	/	/	OK
sheet s = 8 mm	1. sample	OK	/	/
	2. sample	/	OK	/
	3. sample	/	/	OK
sheet t = 10 mm	1. sample	OK	/	/
	2. sample	/	OK	/
	3. sample	/	/	OK

4. PREPARATION OF SAMPLES

After laser cutting, the samples were cleaned of dirt and grease. After that, they were milled on a CNC milling machine to the exact same length. Figure 7 shows the procedure for measuring the length of the samples after milling using a measuring probe. All measured lengths were within ±0.02 mm.

Figure 7. *Length measurement of samples*

5. BENDING OF SAMPLES

The prepared samples were bent on a Durma press with rated pressure force of 200 tons.
The same bending line setting of 98 mm was used for all tests, and the automatic springback compensation features of this press were not used in order to obtain the most accurate results.
The appearance of the samples after bending is shown in Figure 8. It is clearly visible that samples after bending have different bend radiuses which is due to the use of different V-die opening widths. The difference in angle of bent positions is a consequence of the difference in springback action, hapening right after bending.

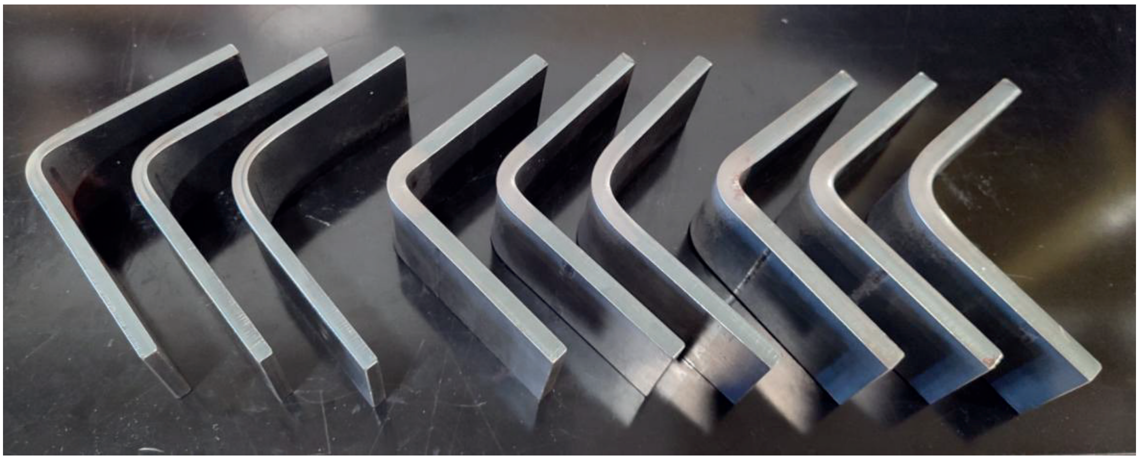


Figure 8. *Bent samples*

6. MEASUREMENTS AFTER BENDING

After bending, profiles of bent samples were 2D scanned. With 2D scanning, it is possible to analyze the actual outer and inner contours, radius and bending angle of every sample. In order to ensure the accuracy of the results for every sample, traditional measurements with height gauges of leg lengths were carried out, and then compared to scanned data. One scanned profile for the sample s = 8mm and prism opening V = 80mm is shown in Figure 9.

Figure 9. *Scanned profile of sample s = 8, V = 80mm*

7. ANALYSIS OF RESULTS

In order to analyze the scanned results, it is necessary to transfer data into a parametric model from which the necessary measurements of contour lengths, angles, and the like can be extracted.

For this purpose, a module in Solidworks for converting 2D scanned images into 2D sketches was used, shown in Figure 10.

Finaly, for every sample the most important geometric parameters were extracted from parametric models. They are shown in Table 3.

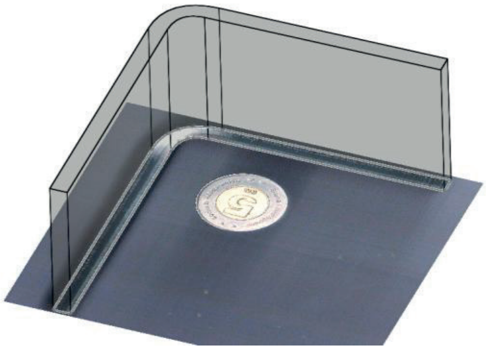


Figure 10. *Conversion of a 2D scan to a parametric model*

The bent contour does not follow an ideal radius, thus it can only be approximated. Approximating the outer contour with a radius gives less deviation from the actual contour than the inner contour. If the thickness of the sample is subtracted from the outer radius, we will get the value of the inner radius. If we arrange these values in a table, the results can be compared with the theoretical expression

ri = 15-17% V: for structural steels.

Table 2. *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%
8	63	8,9	14,2%
8	80	11,5	14,4%
8	125	21,6	17,3%
10	63	9,6	15,3%
10	80	12,1	15,1%
10	125	22,2	17,8%

Table 3. *Measured values of geometric factors after bending*

Sheet s (mm)	Die V (mm)	Outer contour length L_{VK} (mm)	Inner contour length L_{UK} (mm)	Angle (^{o})	Leg Lv1 (mm)	Leg Lv2 (mm)	Approximated outer radius Rv (mm)
6	63	193,82	185	90,24	96,05	104,51	15,74
6	80	193,99	184,96	90,23	96,84	105,46	19,48
6	125	193,73	184,56	92,51	97,4	108,22	29,8
8	63	195,48	183,82	91,27	97,76	104,94	16,92
8	80	196,04	184,23	91,7	98,03	106,23	19,51
8	125	195,37	183,69	93,09	98,55	108,6	29,60
10	63	197,16	182,66	89,83	99,00	106,68	19,64
10	80	197,6	182,84	89,82	99,87	107,2	22,08
10	125	197,33	182,38	90,37	100,87	110,2	32,22

In order to calculate the value of the actual K-factor on bent samples, the following expressions are arranged:

$$L_{VK} = L_{V1} + L_{V2} + \frac{R_V \cdot \pi \cdot (180° - \alpha)}{180°} \quad \dots (4)$$

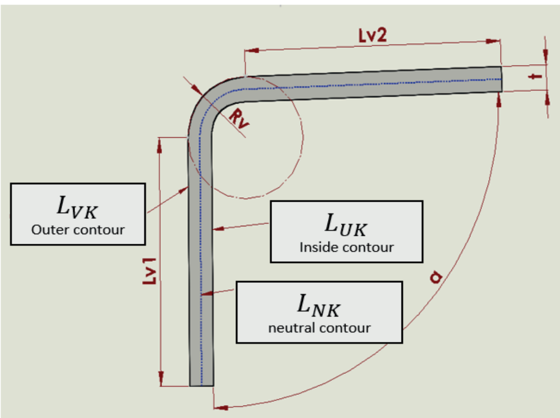
$$L_{NK} = L_{V1} + L_{V2} + \frac{R_N \cdot \pi \cdot (180° - \alpha)}{180°} \quad \dots (5)$$

$$R_V = R_N + x_2 \quad \dots (6)$$

$$t = x_1 + x_2 \quad \dots (7)$$

$$K = \frac{x1}{t} \quad \dots (8)$$

Parameters used in the equiations are shown in Figure 11.



L_{VK} : *Outer contour length*
L_{NK} : *Neutral contour length*
It is same for all samples (187,73)
R_V : *Outer radius*
R_N : *Neutral radius*
t : *Sheet thickness*
x_1 : *Distance from inside to neutral contour*
x_2 : *Distance from neutral to outside contour*
K : *K factor*

Figure 11. *Equation parameters*

By arranging the above expressions, the expression for the K-factor is as follows:

$$K = 1 - \frac{(L_{VK} - L_{NK}) \cdot 180°}{\pi \cdot t \cdot (180° - \alpha)} \quad \dots (9)$$

Using the values for the length of the outer contour, the thickness of the position and the angle after bending, the K-factor can be calculated for each of the samples.
The calculated K-factor values are given in Table 4.
As it can be seen from the data in Table 4 and the display in graphs in Figures 9 and 10, the value of the K-factor increases with the increase in thickness of the samples.
When analyzing the influence of the V-die opening (V), the situation is a bit more complex, because for all 3 analyzed samples, the K-factor minimal value is achieved using the V-die with V = 80mm, while for dies V = 63mm and V = 125mm it is larger and quite uniform.

Table 4. *K-factor values*

sheet t (mm)	Die V (mm)	Outer contour length L_{VK} (mm)	Angle (^{o})	**K factor**
6	63	193,82	90,24	0,35
6	80	193,99	90,23	0,33
6	125	193,73	92,51	0,35
8	63	195,48	91,27	0,37
8	80	196,04	91,7	0,33
8	125	195,37	93,09	0,37
10	63	197,16	89,83	0,40
10	80	197,6	89,82	0,37
10	125	197,33	90,37	0,39

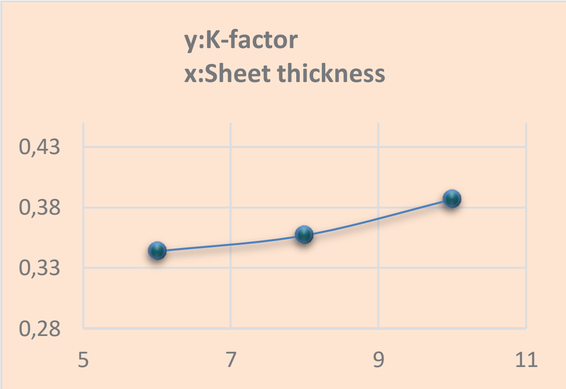


Figure 12. *Effect of thickness on K-factor*

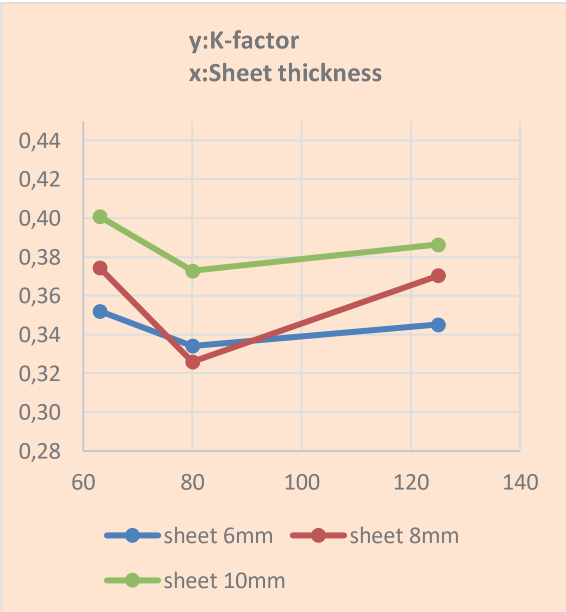


Figure 13. *Effect of V-die opening on K-factor*

8. CONCLUSION

The first conclusion that can be obtained from the results is that the V-die opening (bottom tool) definitely affects the K-factor during air bending. This means it would be advisable in the technological map of sheet metal part bent on press brakes to have exactly defined which V-die is to be used, in order to ensure the accuracy and repeatibility of the proces.

In industry, this is often not the case, this information is often ignored, i.e. considers less important.

It was to be expected that the opening of the V-die would affect the flow of the material during bending, if we take into account that changing the die also changes the value of the bending force (see Figure 4). Greater bending force also means greater friction during sliding of the position over the edges of the die, which directly results in moving the neutral line towards the inner edge, that is, reducing the K-factor. However, from the obtained results, it is clear that this is not the case if V-die is V = 63, because it has an increase in the value of the K-factor, compared to the larger opening V = 80.

There are several factors that could have potentially influenced this result, and which should be taken into account during a more detailed investigation:

1. Greater influence of the punch (upper tool) on the flow of material at smaller V-die openings

2. Wear of dies. If the edges of some dies are more worn than others, this could directly affect the coefficient of friction at the contact between the position and the tool.

3. Lateral flow of material during bending has a greater influence at positions of smaller widths, so it would be expedient to repeat the experiment with positions of larger widths.

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