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Research Article

Determination of factors affect Spring-back in V-Bending operation with SUS304 material by simulation

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ABSTRACT

The V-bending process has become one of the most common and widely adopted techniques in sheet metal manufacturing. However, achieving precise and consistent bending angles remains a significant challenge in practice. Each material has unique mechanical characteristics, leading to a wide range of research opportunities and numerous cases that need to be studied. Among the most critical challenges is the spring-back effect, which is difficult to control uniformly but can still be estimated based on experimental conditions. Air V-bending is widely used in the industry due to its compatibility with numerical control systems, which facilitates easy adjustment of parameters and precise control over punch displacement to minimize the spring-back effect. This flexibility makes it particularly suitable for a broad range of industrial applications involving various material types and thicknesses. This research investigates the main parameters of the air V-bending process, namely die radius, material thickness, and bending angle, under the influence of spring-back effects. Two common die angles — 28° and 85° — were selected to represent a range of practical operating conditions. The study focuses on SUS304 stainless steel, a material widely used across various industrial applications due to its excellent corrosion resistance and mechanical properties. The virtual experiments conducted in this study use simulation methods, offering notable advantages in terms of cost reduction and ease of parameter adjustment, allowing for efficient exploration of a wide variety of cases. The design of experiments was carefully considered to ensure systematic and reliable evaluation of each parameter's influence. The results indicate that the spring-back of SUS304 in air V-bending is most significantly affected by the bending angle, followed by material thickness, with the die angle being the least influential factor among those examined. These findings offer valuable practical guidance for engineers aiming to improve dimensional accuracy in sheet metal forming operations.

Key words: Bending, Bending Angle, Die Radius, Simulation, SpringBack, SUS304

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INTRODUCTION

Recently, the application of CNC machines across various fields has become a key factor in advanced manufacturing processes. The V-bending process, widely utilized in industry, also requires precise parameters. Due to the elasticity of sheet metal, achieving the required machining parameters without modifications - based on analyzing the spring-back effect remains challenging. This area of study has attracted numerous experiments and research efforts aimed at achieving the most precise dimensions at minimal cost for manufacturers.

Firstly, the bottoming V-bending process, when applied with a new modified bending force formula, demonstrates higher accuracy compared to previous methods, which helps reduce errors in the applied load during the V-bending process[1]. Another study suggests that the spring-back/spring-forward phenomenon can occur when considering Dual-Phase steels (DP steels) used in the automotive industry[2]. An experiment reported in[3] investigates and predicts the spring-back in V-bending for high-tensile strength steels using MATLAB and factorial design methods. A new mathematical model to study the effects of different parameters on spring-back in the sheet metal formability process is presented in[4]. An experimental evaluation of spring-back in mild steel, validated using LS-DYNA software, is discussed in[5]. Research on the geometry involved in the V-bending process is covered in[6]. Knowledge about spring-back analysis calculations based on a modified Ludwik stress-strain relation is detailed in[7]. The bending force and spring-back in V-die bending of perforated sheet metal components are examined in[8]. Research into the spring-back of stainless-steel sheet metal in V-bending, which provides valuable insights for our report, is described in[9]. Finally, the finite element model (FEM) used to simulate the spring-back of the V-bending sheet metal forming process is noted in[10]. These articles provide valuable insights into understanding the spring-back effect in the sheet metal

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forming process. Most of them focus on sheet metal forming processes and die design [11], illustrating how to machine sheet metal, control parameters, and design punches and dies for the V-bending process. This research represents one of the first studies to address the spring-back effect specific to this sheet metal forming technique. It summarizes and prioritizes the factors affecting spring-back in sheet metal bending processes, including bending angle, workpiece thickness, punch radius, die lip radius, die width, and workpiece width.

This study builds on existing research to further investigate the spring-back effect in the V-bending process, particularly using the air-bend technique, which is widely employed in industry. The key factors for studying the effects of spring-back on metal sheets include the required bending angle, workpiece thickness, die radius, and punch displacement. Virtual experiments are designed using ANSYS software to explore these effects in the air-bend technique through simulation.

MATERIAL DEFORMATION AND BENDING OPERATION

The mechanical behavior of the material is hard to predict. To describe the mechanical behavior of the material, the stress-strain curve is used to determine the strength of that material [11] which is relative to tensile or compression and shown in Figure 1. The stress s(N/m^2) of the material is shown in Eq (1) with applied load F(N) and received force area (cross section) in m^2. The strain e of the material is the amount of dimensional deformation experienced by the body in the direction of force applied relative to the initial dimension of the body which is shown in Eq (2) with the measured length L (m) and initial length Lo (m).

$$\sigma = \frac{F}{A} \tag{1}$$

$$\varepsilon = \frac{L - L_0}{L_0} \tag{2}$$

The stress-strain curve of each material can be divided into regions named elastic region and inelastic region including plastic and fracture. In the elastic region OY, the relationship between stress and strain is proportional (also represented as part of Hooke's law). Point A is the largest strain that is still proportional to the stress. In the inelastic region YF, strain increases faster than stress. Point B is the elastic limit. In the BY region, the stress reduces as strain continues to increase. Point Y is the yield point. In the YM region, stress increases slower than strain and M is the ultimate stress point. This region also shows the plastic deformation of the material. In the MF region, this is a downward slope region that shows a decrease in stress as strain increases. As a result, F is a fracture point and the "neck" phenomenon appears on the material, and a part will be broken by passing the fracture point.

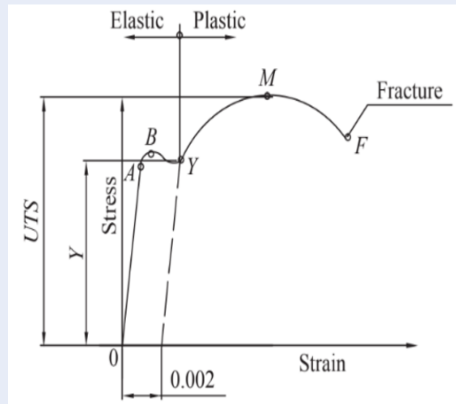

Figure 1: Illustration of the stress-strain curve of the material [11]

The modulus of elasticity (Young's modulus) $E\left(N/mm^2\right)$ is the ratio between stress and strain in the elastic region, which is also the measure of the stiffness of the material as shown in Eq. (3) with stress and strain.

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

Ramberg-Osgood constructed the stress-strain curve by software [12] and the Ramberg-Osgood coefficient n is calculated in equations from Eq. (4) to (5) with uniform strain at the end of uniform elongation region ε_{us}, ultimate stress $\sigma_{uts}\left(N/mm^2\right)$, yield stress$\sigma_y\left(N/mm^2\right)$, Ramberf-Osgood coefficient n, Young's modulus $E\left(N/mm^2\right)$.

$$\varepsilon_{us} = 100 \times \left(\varepsilon_r - \frac{\sigma_{uts}}{E}\right) \tag{4}$$

$$\rightarrow n = \frac{ln\left(\frac{\varepsilon_{us}}{0.2}\right)}{ln\left(\frac{\sigma_{uts}}{\sigma_y}\right)} \tag{5}$$

The equation for the engineering strain, true strain, and true stress are shown in equations from Eq. (6) to (8).

$$\varepsilon = \frac{\sigma}{E} + 0.002 \times \left(\frac{\sigma}{\sigma_{uts}}\right)^n \tag{6}$$

$$\varepsilon_{true} = ln\left(1+\varepsilon\right) \quad (7)$$

$$\sigma_{true} = \sigma\left(1+\varepsilon\right) \quad (8)$$

By constructing the stress-strain curve of the material based on the database for already researched material or calculating from the experiment, these parameters will be imported to the software for simulation purposes.

Bending is a cold metal forming process that has been used widely in industry, which can also improve the stiffness of sheet metal by increasing the moment of inertia. There are many shapes and sizes for sheet metal bending, such as L, U, and V-profile, which can also create more complex shapes with suitable machines and technology. Figure 2(a) shows the illustration of the bending operation principle with bend angle. The metal on the inside of the neutral (axis) plane is compressed, while the metal on the outside is stretched. The bending and bent angles in Figure 2(b) show the effect of spring-back in sheet metal bending with the material thickness T.

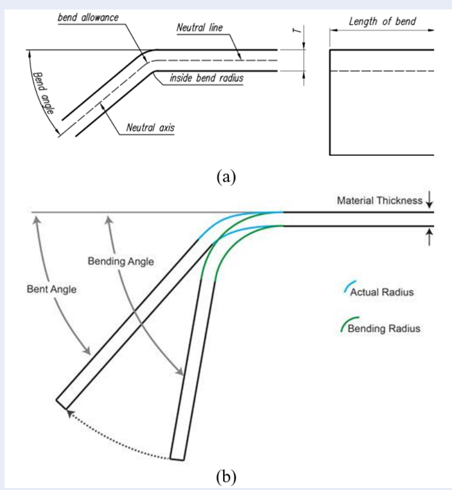

Figure 2: Illustration of bending operation principle [10]

Figure 3 shows the V-bending process where Figure 3(a) shows that the V-bending process still leaves the gap between the material and die, which is also called the air V-bending process, Figure 3(b) shows the fully material-contacted surface with the die, which is called bottoming, and Figure 3(c) shows the coining process. These figures show the difference between the bending force required to be applied for the die and punch to work and create the perfect bend angle of the workpiece. In this research, the air V-bending parameters are determined to study.

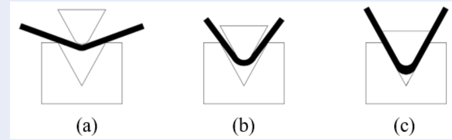

Figure 3: Illustration of the difference between (a) air V-bending, (b) air bottoming bending, and (c) the coining. [Source: Authors]

Bending force, which is bending force for air bending and bottoming, is shown in [11]. These spring-back values will be collected to analyze and modify.

The modified formula developed by Kongkiet's team [1] for a more precise calculation of total bending force is shown in Eq (9), where, b is width of the bend, T is material thickness, m is correction coefficient hardening of the material $(m = 1.6 \div 1.8)$, σ_{uts} is ultimate stress, σ_y is yield stress, l_k is die opening, R_{ud} is die radius, R_p is punch radius, φ is bend angle $(\varphi + \theta = 180°)$, and L_0 is the length of reversed bending allowance zone.

$$F = \frac{4m\sigma_{uts}\frac{bT^2}{4}cos^2\left(\frac{\varphi}{2}\right)}{l_k - 2\left(R_{ud}+R_p+T\right)sin\left(\frac{\varphi}{2}\right)} + 2\sigma_y L_0 bcos\left(\frac{\varphi}{2}\right) \quad (9)$$

The geometric parameters used in Eq. (9), including the bend angle and V-punch angle, are illustrated in Figure 4.

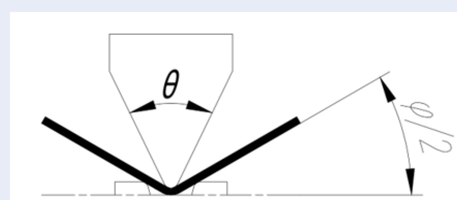

Figure 4: Illustration of bend angle and V-punch angle applied for the modified bending force formula [Source: Authors]

Spring-back is the difference between the received value (often bending angle, bend radius) and their theoretical value. The spring-back value calculated in the report will be presented in Eq (10). Whereas $\Delta\alpha$ is the spring-back value, α_{theo} is the bending angle (theoretical angle), $\alpha_{received}$ is the received angle (final angle).

$$\Delta\alpha = \alpha_{theo} - \alpha_{received} \quad (10)$$

The spring-back factor K_s is shown in Eq (11), where, φ_f is the received bend angle, φ_t is the theoretical bend angle R_f is the received bend radius, R_i is the theoretical bend radius, and T is material thickness.

$$K_s = \frac{\varphi_f}{\varphi_t} = \frac{R_f + \frac{T}{2}}{R_i + \frac{T}{2}} \quad (11)$$

METHODOLOGY

During the V-bending operation, factors that can affect the spring-back value include material thickness, punch radius, die radius, V-die opening, bending angle, length of the reverse bending allowance zone, workpiece width, workpiece material yield strength, and workpiece material ultimate tensile strength. In comparing the theoretical variables with the constructed ones, the die radius, bending angle, and material thickness are selected for investigation due to their significant potential effects on the spring-back in the air V-bending process.

Process Variables

To investigate the V-bending angle, the two most common bending angles are about 28^o and 85^o. These values are based on the available punch and die set in the experiment and used to produce the bending angle result of 30^o and 90^o. The die radius are 1.0 mm and 1.5 mm. The material thicknesses are 1.0 mm and 2.0 mm which are the popular thicknesses in the practice.

The illustration of the design of experiment cases (used for both die angle of 28°, 85°) are shown in Table 1, Table 2, respectively:

Table 1: Design of experiment parameter of 28° die angle

Parameter	Level 1	Level 2	Level 3
Bending angle (^{o})	28°	60°	92°
Thickness (mm)	1.0	2.0	N/A
Die radius (mm)	1.0	1.5	N/A

[Source: Authors]

In air V-bending, to control the bending angle of the part, punch displacement is controlled. The geometry characteristic of the suitable punch displacement is determined. Indirect punch displacement is also a factor that can be used to determine the spring-back of the V-bending operation in future studies.

Table 2: Design of experiment parameter of 85 die angle

Parameter	Level 1	Level 2	Level 3
Bending angle (^{o})	85°	120°	135°
Thickness (mm)	1.0	2.0	N/A
Die radius (mm)	1.0	1.5	N/A

[Source: Authors]

Simulation Setup

The SOLIDWORKS software and ANSYS WORKBENCH STUDENT VERSION are used to build the 3D models and simulations. The die and punch sets are modeled based on Bystronic's product code, which is available for the CAD model, which helps to reduce the system setup time as shown in Figure 5. The SUS 304 material data in the material library is imported from the stress-strain curve as in Figure 6. These were calculated based on the description of the stress-strain curve by three parameters [13]. Firstly, the Ramberg-Osgood coefficient was calculated using the Eq. (4) and Eq. (5). The parameters of the models are shown in Table 4.

In Figure 5, above of all the mentioned parameters, the V-die opening value is determined for each die set, which is $l_k = 10\,mm$ for the die set 28° and $l_k = 15\,mm$ for the die set of 85°. The determination of V-die opening is used for calculating punch displacement in the later works. Table 3 shows the parameter of the model materials.

In Table 4, two parameters about the strength of SS304 stainless steel can be found which are ultimate tensile strength $\sigma_{uts} = 505\ (MPa)$ and yield strength $\sigma_y = 215\ (MPa)$.

The boundary conditions applied for the simulations experiment included joint type general, punch displacement, and the magnitude as tabular data. The displacements are shown in Table 5 as punch travel parameters which are the functions of bending angle, die radius, and the workpiece's thickness.

Mesh Sensitivity Analysis

In the simulation, the mesh size is an important factor that affects the result. Since the mesh size is small, the result can be more precise, but the calculation time will be much longer. Therefore, by comparing the mesh size of 0.4 mm and 1.0 mm, the result difference in the spring-back angle was not too much. The smaller mesh size also showed the same result. However, to ensure the time for the experiment and the accuracy of the simulation test, a mesh size of 1.0 mm

Table 3: The parameter of the model

Workpiece	Thickness (mm)	Length (mm)	Width (mm)	Material
	1.0	40	10	SUS304
	2.0	40	10	SUS304
Punch	Punch radius (mm)	Punch angle (^{o})	Width (mm)	Material
	1.0	28	20	C45
	1.0	85	20	C45
Die	Die radius (mm)	Die angle (^{o})	Width (mm)	Material
	1.0	28	20	C45
	1.0	85	20	C45
	1.5	28	20	C45
	1.5	85	20	C45

[Source: Authors]

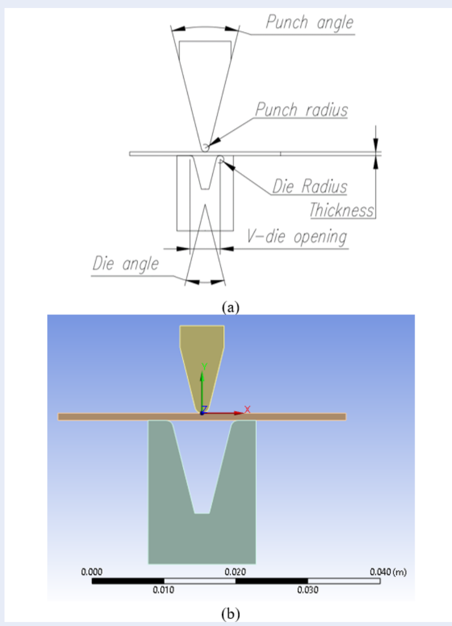

Figure 5: Illustration of 2D bending model with the parameters of experimental system (a) and the coordinate setting (b) [Source: Authors]

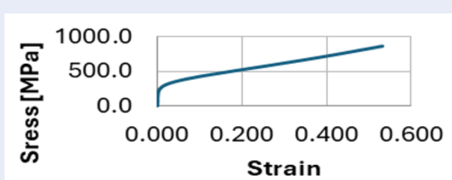

Figure 6: Illustration of the stress-strain curve of SUS304 [13]

Table 4: Mechanical properties of sus 304 material [13]

PROPERTIES	METRIC UNIT
Brinell hardness	123
Knoop hardness	138
Rockwell hardness	70
Vickers hardness	129
Ultimate tensile strength	505 (MPa)
Yield tensile strength	215 (MPa)
Elongation at break	70%
Modulus of Elasticity	193-200 (GPa)
Poisson's ratio	0.29
Charpy Impact	325 (J)
Shear modulus	86 (GPa)

will be used for all the simulation experiment, as illustrated in Figure 7(a) and (b).

The experiment simulations are conducted for all the cases and recorded the data by drawing the profile coordinate in the CAD system. The profiles from simulation are measured by using dimensional command in ANSYS software as shown in Figure 8 and Figure 9. These two figures use the data from the experiment of bending angle α =28°, die radius R_{ud}=1mm, and workpiece's thickness T=1.0 mm. The results are recorded at the end of the simulation process, as all coordinates were collected in the middle of the section face of the model.

In Figure 10, α_{1up} is the angle of the upper plane at the end of the workpiece; α_{1down} is the angle of the lower

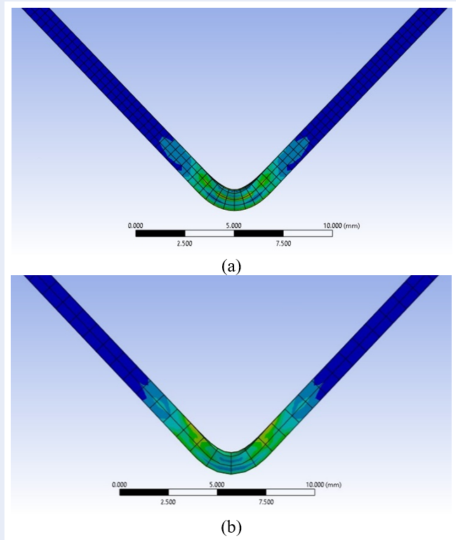

Figure 7: Illustration of comparing the mesh size of 0.4 mm (a) and 1.0 mm (b) [Source: Authors]

plane at the end of the workpiece; α_{11up} is the angle of the upper plane at the reverse bending zone; and α_{11down} is the angle of the lower plane at the reverse bending zone.

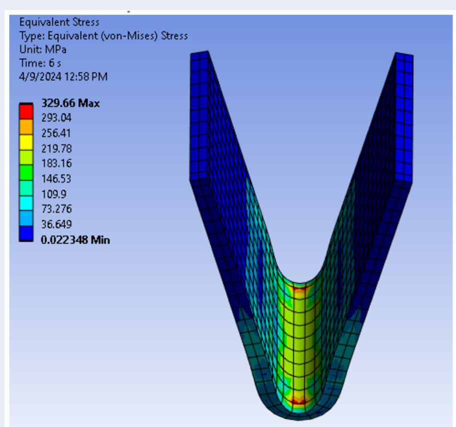

Figure 8: Illustration of Equivalent stress at the end of the process according to bending angle α=28°, die radius R_{ud} =1mm, and workpiece's thickness T=1.0mm [Source: Authors]

RESULTS

The spring-back value will be the difference between α_1, α_{11}, and the bending angle, which is the spring-back and the end of the workpiece and spring-back at the reverse bending zone, respectively.

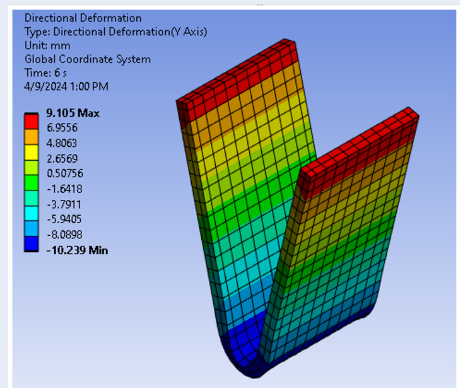

Figure 9: Illustration of directional deformation at the end of the process according to bending angleα =28°, die radius R_{ud} =1mm, and workpiece's thickness T=1.0mm [Source: Authors]

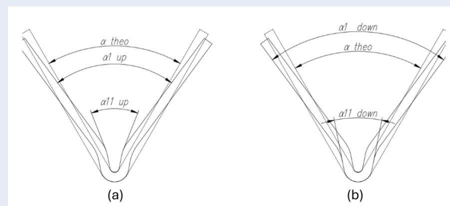

Figure 10: The illustration of the angle measured for upper plane (a) and lower plane (b)after simulation process [Source: Authors]

These value are chosen from the maximum between $(\alpha_{1up}, \alpha_{1down})$ and $(\alpha_{11up}, \alpha_{11down})$. Using the Eq. (10), the simulation-measured values are recorded in Table 5 and Table 6 respecting spring-back values of 28^o and 85^o angle of V-dies.

DISCUSSION

From the results presented, both spring-back and spring-forward phenomena occur with two different die sets and two different workpiece thicknesses, as reported by UMUR[2]. To facilitate comparison of the general effects of spring-back between both die sets, the average spring-back for each die set is chosen. The average spring-back values at the end of the workpiece and in the reverse bending region are smaller for the 28° die set compared to the 85° die set, with values of 4.01° and 7.63°, respectively, compared to 5.68° and 8.29°. For a larger required bending angle, the spring-back value is higher, which is consistent with the findings of G.M. Sayeed Ahmed[5] and Ozgur Takaslan[9]. The 1.0 mm die radius results in a higher spring-back value compared to the 1.5 mm

Table 5: Springback value of 28 degree die (die-opening $l_k = 10mm$)

Bending angle (^{o})	Die radius (mm)	Thick-ness T (*)	Punch travel (mm)	$\Delta\alpha_I$	$\Delta\alpha_{II}$
28	1.0	1.0	10.2	1.33	3.88
60	1.0	1.0	5.66	4.40	0.14
92	1.0	1.0	3.66	4.24	3.07
28	1.0	2.0	7.20	-0.40	-1.45
60	1.0	2.0	3.57	-22.04	-29.79
92	1.0	2.0	2.27	-23.27	-27.32
28	1.5	1.0	12.8	1.44	2.02
60	1.5	1.0	6.88	5.47	-2.21
92	1.5	1.0	4.42	4.99	2.72
28	1.5	2.0	9.60	2.02	-4.67
60	1.5	2.0	4.88	-10.42	-14.15
92	1.5	2.0	3.03	-15.83	-23.74
Average value				-4.01	-7.63
(*)T: thickness of workpiece (mm)					

[Source: Authors]

Table 6: Springback value of 85 degree die (die-opening $l_k = 12mm$)

Bending angle (^{o})	Die radius (mm)	T(*)	Punch travel (mm)	$\Delta\alpha_I$	$\Delta\alpha_{II}$
85	1.0	1.0	4.4	-5.67	-6.83
85	1.5	1.0	4.3	-4.32	-5.18
85	1.0	2.0	4.2	-0.91	-4.02
85	1.5	2.0	4.3	4.88	2.85
120	1.0	1.0	3	4.04	0.89
120	1.0	2.0	1.85	-18.14	-22.76
135	1.0	1.0	2.24	3.45	1.24
135	1.0	2.0	1.16	-19.44	-22.01
120	1.5	1.0	2.92	4.23	1.06
120	1.5	2.0	1.77	-18.86	-22.8
135	1.5	1.0	2.2	3.22	1.03
135	1.5	2.0	1.11	-20.62	-22.96
Average value				-5.68	-8.29
(*)T: thickness of workpiece (mm)					

[Source: Authors]

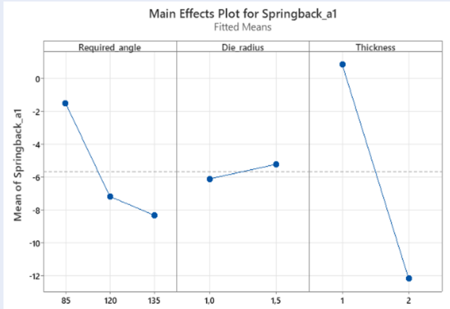

Figure 12: Illustration of spring-back a1 in the 85^{o}die relationship [Source: Authors]

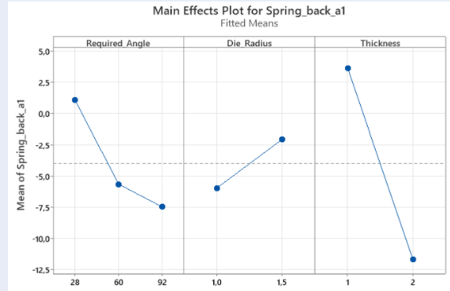

Figure 11: Illustration of spring-back a1 in the 28^{o} die relationship [Source: Authors]

die radius. Additionally, workpieces with a thickness of 2 mm exhibit significantly larger spring-back values compared to 1 mm thick workpieces. This finding aligns with the research of Muhamad Wasif[3], Sanjay Kumar Patel[7], and Ozgur Takaslan[9], but contrasts with the studies by Mastafa Ozdemir[4], G.M. Sayeed Ahmed[5], and Mohammad Ali Farsi[8].

When manufacturing at different bending angles, the 28° die set is more prone to causing a spring-forward phenomenon for lower-thickness workpieces than the 85° die set, which tends to result in spring-forward for higher-thickness workpieces. The spring-back value is higher at the reverse bending zone compared to the end of the workpiece for both die sets. For better analysis, Minitab software was used, with results shown in Figure 11 and Figure 12, where a1 denotes the spring-back angle at the end of the workpiece. The results of the Minitab DOE analysis indicate that the required bending angle has the greatest impact on the spring-back value. As the bending angle increases, the spring-back value also increases. The thickness of the workpiece has the second most significant impact on spring-back; as thickness increases, the spring-back value also rises. The die radius has the least impact on spring-back; as the die radius increases, the spring-back value decreases. However, the interaction plot between the required bending angle and thickness reveals different trends. As the bending angle increases, the spring-back value decreases with increasing thickness, but the value increases when the bending angle exceeds 60°. Conversely, for a 2 mm thickness, the spring-back value increases rapidly with the bending angle, but the rate of increase slows down afterward.

CONCLUSION

Spring-back increases significantly as the bending angle becomes larger, which suggests that using a die set with a larger angle may help mitigate this effect on one side of the workpiece. Additionally, spring-back is exacerbated by the thickness of the workpiece. Therefore, when bending thick materials, it is crucial to consider adjusting the bending angle to achieve an optimal spring-back value. For each set of die angles, a smaller die radius results in a greater spring-back value. Adjusting the dwell time of the process can also help reduce the spring-back value. The research findings indicate that, for SUS304 V-bending, the bending angle has the greatest impact on spring-back, followed by material thickness. The die angle of the die set has the least effect on spring-back. Future work will focus on refining the spring-back values based on real experimental results. Regression analysis will be used to construct a model that predicts the optimal punch travel distance required to achieve the desired bending angle. This approach is not limited to the angles studied in this research and aims to minimize the spring-back value with sufficient reliability.

CONFLICTS OF INTEREST

The author group confirms that there are no conflicts of interest related to the research work.

AUTHOR CONTRIBUTION

Authors Lynh Huyen Duong and Nam Hai Tran are accountable for the conceptualization, model selection, computational methodology, data analysis, manuscript refinement, and finalization. Students Hung Hong Tran, Vinh Nhat Doan and Nguyen Khoi Dang contributed to computational tasks, and data analysis.

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Bài nghiên cứu

Xác định các yếu tố ảnh hưởng đến hiệu ứng đàn hồi ngược trong quy trình chấn chữ V với vật liệu SUS304 bằng phương pháp mô phỏng

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TÓM TẮT
Quá trình chấn chữ V đã trở thành một trong những kỹ thuật phổ biến và được ứng dụng rộng rãi nhất trong sản xuất kim loại tấm. Tuy nhiên, việc đạt được góc uốn chính xác và ổn định vẫn là một thách thức lớn trong thực tế. Mỗi loại vật liệu có những đặc tính cơ học riêng, dẫn đến nhu cầu nghiên cứu đa dạng và nhiều trường hợp cần được khảo sát. Một trong những thách thức quan trọng nhất là hiệu ứng đàn hồi ngược (spring-back), vốn khó kiểm soát đồng đều nhưng vẫn có thể ước tính dựa trên các điều kiện thực nghiệm. Chấn chữ V tự do được sử dụng rộng rãi trong công nghiệp nhờ khả năng tích hợp với hệ thống điều khiển số, cho phép dễ dàng điều chỉnh thông số và kiểm soát chính xác chuyển vị của chày nhằm giảm thiểu hiệu ứng đàn hồi ngược. Tính linh hoạt này giúp phương pháp đặc biệt phù hợp với nhiều ứng dụng công nghiệp đa dạng về loại vật liệu và độ dày. Nghiên cứu này tập trung phân tích các thông số chính của quá trình chấn chữ V tự do, bao gồm bán kính khuôn, độ dày vật liệu và góc uốn, dưới ảnh hưởng của hiệu ứng đàn hồi ngược. Hai góc khuôn phổ biến là 28° và 85° được chọn để đại diện cho các điều kiện vận hành thực tế. Nghiên cứu tập trung vào vật liệu thép không gỉ SUS304, loại vật liệu được sử dụng rộng rãi trong công nghiệp nhờ khả năng chống ăn mòn và tính chất cơ học tốt. Các thí nghiệm ảo trong nghiên cứu này được thực hiện thông qua phương pháp mô phỏng, mang lại lợi thế đáng kể về tiết kiệm chi phí và dễ dàng điều chỉnh thông số, cho phép khảo sát hiệu quả nhiều trường hợp khác nhau. Quy hoạch thực nghiệm được áp dụng nhằm đảm bảo đánh giá có hệ thống và đáng tin cậy về ảnh hưởng của từng thông số. Kết quả cho thấy hiệu ứng đàn hồi ngược của SUS304 trong quá trình chấn chữ V tự do bị ảnh hưởng nhiều nhất bởi góc uốn, tiếp theo là độ dày vật liệu, trong khi góc khuôn là yếu tố có tác động ít nhất. Những kết quả này cung cấp hướng dẫn thực tiễn có giá trị cho các kỹ sư nhằm cải thiện độ chính xác kích thước trong các nguyên công tạo hình kim loại tấm.
Từ khoá: Chấn/uốn, Góc uốn, Bán kính khuôn, Mô phỏng, Hiệu ứng đàn hồi ngược (Spring-Back), SUS304

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