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Research article

Finite element simulations of V-bending Enhanced by V-grooving Process

Quoc-Nguyen Banh[1,2], Viet-Khai Le[1,2], Tuan-Kiet Vo[1,2], Anh-Son Tran[1,2], Minh-Tuan Ho[1,2,*]

ABSTRACT

The V-grooving process is a pivotal technique in the realm of sheet metal forming, specifically designed to enhance the precision of V-bending operations. V-bending, a prevalent method for creating sharp folds in metal parts, often meets the issue of springback. This phenomenon, where elastic materials strive to return to their original form post-deformation, poses a significant challenge to the accuracy of metal forming. The study in question delves into the impact of V-groove depth on mitigating springback during the V-bending of SUS 304 stainless steel, a material known for its widespread use in the industry. Employing finite element analysis through the Abaqus Learning Edition 2023 software, the research simulates the V-bending process complemented by V-grooving to find the optimal groove depth that minimizes springback without leading to over-deformation of the metal. The findings suggest that a specific depth of V-grooves can significantly restrain the metal's tendency for elastic recovery post-bending, thereby enhancing the dimensional quality of the final product. This depth acts as a constraint, ensuring the metal keeps the desired angle after bending. While deeper grooves have been associated with reduced springback, they also carry the risk of causing excessive deformation, which can be just as detrimental to the part's integrity. The study identifies an optimal groove depth that strikes a balance, effectively minimizing springback across various bending heights. However, it acknowledges that the ideal depth may vary based on different applications and requirements. These insights are invaluable for industries that rely heavily on sheet metal forming, offering a pathway to improved dimensional control in V-bending processes. By optimizing the V-grooving technique, manufacturers can achieve greater accuracy in their metal parts, which is crucial for the functionality and aesthetic of the final products. The study's conclusions serve as a guide for future applications, potentially leading to advancements in manufacturing practices and the quality of metal-formed components.

Key words: Finite element simulation, Sheet metal forming process, Springback phenomenon, V-bending process, V-grooving process

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INTRODUCTION

Sheet metal bending is a process that involves applying force to a metal sheet to create a curved shape. The shape and size of the bent product depend on the design specifications and the bending method used. Sheet metal bending has applications in various industries, such as automotive, aerospace, and marine, where it can produce parts with complex geometries and high strength. A key challenge in sheet metal bending is to control the bending angle accurately, as the material tends to recover its original shape after bending, resulting in spring back [1] . This can affect the quality and functionality of the bent product.

To reduce springback, various empirical methods have been proposed and evaluated by researchers, such as a die design method based on displacement adjustment [2] , using high temperature while bending [3] , or using electric current density to decrease flow stress [4] . However, these methods often require an enormous number of trials and errors, which can be costly and time-consuming for the tool design and maintenance. Numerical methods based on finite-element analysis (FEA) have been proven to be effective and widely used tools for predicting and minimizing springback [5] . FEA allows for a numerical simulation of the process, which reduces the time and cost of design and analysis compared to experimental methods.

Several studies have used finite element analysis (FEA) to investigate the factors and solutions that influence springback. For example, Chou I and Hung C [6] used finite element simulations to explore various springback reduction methods in U-channel bending (arc bottoming, pinching die, spanking, and movement techniques), optimized settings for each method, and minimize springback. Yao and Liu [7] examined how different numerical parameters affect the prediction of springback using dynamic explicit FEA codes. Ling et al. [8] explored how adding a step to

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a metal stamping die can reduce springback, saving time and iterations in prototype testing and die design. Panthi S et al[9] found springback is influenced by geometrical parameters, material properties, and lubrication conditions. The research utilized Total-Elastic-Incremental-Plastic (TEIP) algorithm incorporated in a Finite Element software was used to predict and investigate its impact, with the simulation results validated through experiments. Schlep et al.[10] showed that the simultaneous stretching and bending process can effectively reduce springback, as confirmed by both simulation and experiment. Abhinav[11] evaluated the formability of various sheet metals for a forming process.

The aim of this research is to explore the effects of the V-grooving process on the springback behavior of sheet metal. The V-grooving process is a technique that creates V-shaped notches on the sheet metal surface to decrease the bending stiffness and increase the plastic deformation. In this study, the V-bending processes of V-grooved workpieces were simulated to examine the influence of various parameters of the V-grooving process the springback reduction and the quality of the formed parts.

FINITE-ELEMENT SIMULATION SETUP

Modeling of die and punch

The simulation model of the V-bending process is based on a realistic setup shown in Figure 1, where i_r is the punch tip radius and V is the die shoulder width. The punch and die are fixed on a support to prevent them from moving. The die has a groove with a specific bending angle, such as 90° as in this setup or other angles. The sheet is bent by the punch that presses it into the groove. Figure 1 illustrates the simulation setup of the V-bending process that is used to create the simulation model.

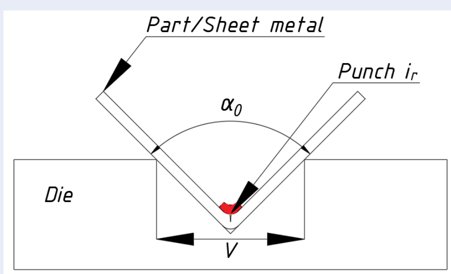

Figure 1: The V-bending process setup: punch tip radius ir, die shoulder width V, desired bending angle α0 [Source: The authors]

The simulation parameters of punch and die are based on the AMADA catalogue model[12] , which has a punch tip radius i_r of 2.3 mm and a die shoulder width V of 14 mm.

Modeling of sheet metal with V-groover

V-grooving process is a method that involves creating a V-shaped notch along the bending line of a sheet metal part, which reduces the metal thickness at the bending line and enables the production of a small outside bending radius. V-groove can be done by using V-grooving machine, depending on the material type and thickness. In the V-groover, the crucial parameter is depth of V-groove d_v (Figure 2) which directly affects the angle of sheet metal after bending a (Figure 3).

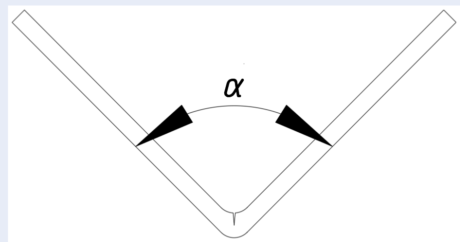

Figure 3: Angle of sheet metal post-bending α [Source: The authors]

The depth of V-groove, denoted as $\bar{d_v}$ (%), depicted Figure 3 , is determined by using (1):

$$\bar{d_v} = \frac{d_v}{t}.100 \quad (1)$$

Where t represents the thickness of the sheet metal or part. For this study, the thickness is set at 1 mm. Regarding Figure 3, the angle error $\bar{\alpha}$ (%), is computed by (2):

$$\bar{\alpha} = \left| \frac{\alpha - \alpha_0}{\alpha_0} \right| \quad (2)$$

Where α_0 is desired angle and α is angle of sheet metal post-bending. In this research, the target angle is established at 90 degrees.

Material of sheet metal

Stainless steel is a metal alloy that has chromium as a main element, which gives it the property of resisting corrosion and rust. Another term for stainless steel is inox steel, which comes from the French expression "inoxydable". One of the most widely used stainless steel grades is SUS 304, which contains at least

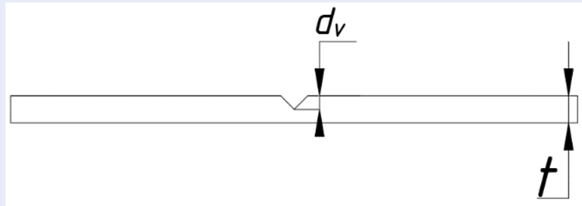

Figure 2: Depth of V-groover dv and thickness of the sheet metal t [Source: The authors]

18% chromium and 8% nickel. This grade of steel is suitable for applications that demand good formability and corrosion resistance. The specimens for the simulation are sheets of SUS 304 with a thickness of 1 mm. The material composition of SUS 304 used for simulations is shown in Table 1[13].

Table 1: Material composition of SUS 304

Composition detail	
C (carbon)	0.0372 %
Cr (chromium)	18.150 %
Mn (manganese)	1.051 %
Ni (nickel)	8.050 %
P (phosphorus)	0.0326 %
S (sulfur)	0.0024 %
Si (silicon)	0.476 %
Physical properties	
Density	8.06 x 10^3 (kg/m^3)
Mechanical properties	
Young's modulus	195.122 GPa

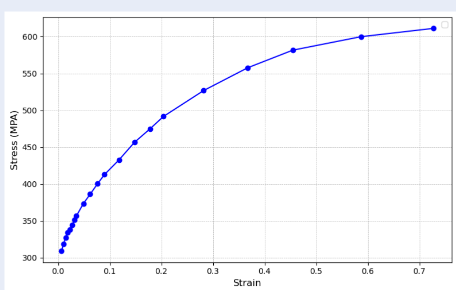

Figure 4: The stress-strain curve of SUS 304 [Source: The authors]

Conway J et al[13] conducted a short-term experiment to measure the stress-strain curve of AISI 304 (SUS 304) stainless steel in air at 21^{o}C and an axial strain rate of 4x10^{-3} sec^{-1}. The specimen had a diameter of 0.250 in (6.35 mm). Figure 4 shows a stress-strain curve of SUS 304. The x-axis represents the strain (unitless), which is the change in length of the material divided by its original length. The y-axis represents the stress (MPa), which is the load applied to the material divided by the original cross-sectional area of the material. The curve starts at the origin (0, 0 MPa) and increases linearly up to a point called the yield point (0.0064, 309.033 MPa). The yield point is the point at which the material begins to deform plastically, meaning that the deformation is permanent, and the material will not return to its original shape when the stress is removed. Beyond the yield point, the curve deviates from the linear behavior and starts to curve upwards. This region is known as the strain hardening region. In this region, the material becomes stronger as it is deformed, and more stress is required to cause further deformation. The curve eventually reaches a peak at the ultimate strength point (0.8755, 613.792 MPa), which is the maximum stress that the material can withstand before it fractures.

FINITE-ELEMENT SIMULATIONS

In operations such as V-bending, which is a type of sheet metal forming process, the selection of the right solution technique is essential for ensuring precision, productivity, and control of the final bend form and springback traits. Different explicit integration methods, each having unique methodologies, serve as beneficial instruments for the simulation and study of V-bending.

Explicit methods prove beneficial for problems involving high-speed impacts and significant nonlinearity. However, for low-speed issues, where the durations are typically extended, the use of explicit methods becomes inefficient due to the immense computing time required, as it necessitates extremely small integration time steps.

Explicit dynamic in Abaqus use the explicit time integration method (Half-step central difference method)[14,15] .

$$\ddot{D}_n = \frac{D_{n+\frac{1}{2}} - D_{n-\frac{1}{2}}}{\triangle t}$$

$$\dot{D}_{n+\frac{1}{2}} = \frac{D_{n+1} - D_n}{\triangle t} \quad (3)$$

The computation of $D_{n+\frac{1}{2}}$ and D_{n+1} solely relies on historical data, allowing for an explicit calculation of the current response. This eliminates the need for iterations within a time step, making the completion of a time step, or cycle, highly efficient. However, to ensure a stable solution, the integration time of the cycle must be kept minimal.

At the start of a cycle, the displacement, the displacement D_n and velocity $\dot{D}_n$ from the previous cycle are already known. Using this data, the strain and strain rate are determined for each element. The volume change for each element is then computed using the equation of state, which subsequently updates the mass density. Following this, stresses are calculated based on the relationships between stresses and strains/strain rates. These stresses are integrated over the elements, and external loads are incorporated to form the nodal forces.

$$\ddot{D}_n = \frac{F_n}{m} + \frac{b}{\rho} \quad (4)$$

Where b represents the body force, m stands for the nodal mass, and ρ is the mass density. The calculation of nodal velocities at time $t_{n+\frac{1}{2}}$ is done using (3), while Equation 4 is used to compute the nodal displacements at time t_{n+1}.

When it comes to explicit methods, the typical time step for integration ranges from nanoseconds to microseconds. A standard simulation time is approximately one millisecond to one second, necessitating thousands or even millions of cycles.

The simulations are conducted using ABAQUS Learning Edition 2023 software (Dassault Systèmes, Inc) which is used to deploy models and predict springback. The problem model in Figure 5 is based on AMADA model catalogue. The sheet metal is bent by using 86° V-die and 83° punch, the die and punch are modeled as analytical rigid, which is not meshing, fewer equations, and improved contact behavior leading to faster simulation. The base of the die is fixed, and the punch applies a downward direction on the sheet metal, causing it to deform. The mesh model of the plate consists of 584 elements.

In the context of finite element analysis, mesh quality is crucial for obtaining accurate results. The sheet metal/part described its division into three bodies and varying mesh densities, reflects a strategic approach to meshing. The coarser mesh on the upper and lower edges of the two bodies is due to their minimal deformation, which requires less computational power to solve. Conversely, the areas with the highest expected deformation—the upper and lower edges of the central body—have the finest mesh to capture the detailed stress and strain distribution. The V-groover edges with the second finest mesh suggest a moderate level of deformation, needing a balance between accuracy and computational efficiency. This tiered meshing strategy is effective in optimizing the simulation process, ensuring that the areas of greatest interest receive the most detailed analysis while conserving resources on less critical sections.

RESULTS AND DISCUSSION

Post-process

Figure 6 illustrates the sheet metal at the point when the punch reaches the desired height. The area highlighted in red, known as the bend radius, is where the sheet metal is under tension. The presence of a V-groove results in a smaller and sharper bend radius compared to when a V-groove is absent.

In Figure 7, it is seen that the part exhibits a tendency to revert to its original shape. The presence of a V-groove is instrumental in reducing this effect. Figure 6 and Figure 7 show that the bend angle is the most deformed, while two bodies next to it have little deformed.

The observation in Figure 7 suggests that the part has a natural tendency to return to its original form. The incorporation of a V-groove plays a crucial role in mitigating this effect, allowing for a more stable and desired shape after deformation. Figure 6 and Figure 7 highlight that the bend angle undergoes significant deformation, in contrast to the adjacent sections which exhibit minimal change, indicating a localized impact of the applied forces.

Effect of V-groover on springback

The Table 2 shows the effects of five different depths of V-groove $\bar{d}_v$ with same bending height and springback errors.

The graph (Figure 8) presents the correlation between the V-groove depth and the sheet metal's springback, which is the metal's inclination to revert to its first form post-bending. The springback of the sheet metal lessens as the V-groove depth augments. However, when the V-groove depth hits 60% of the sheet

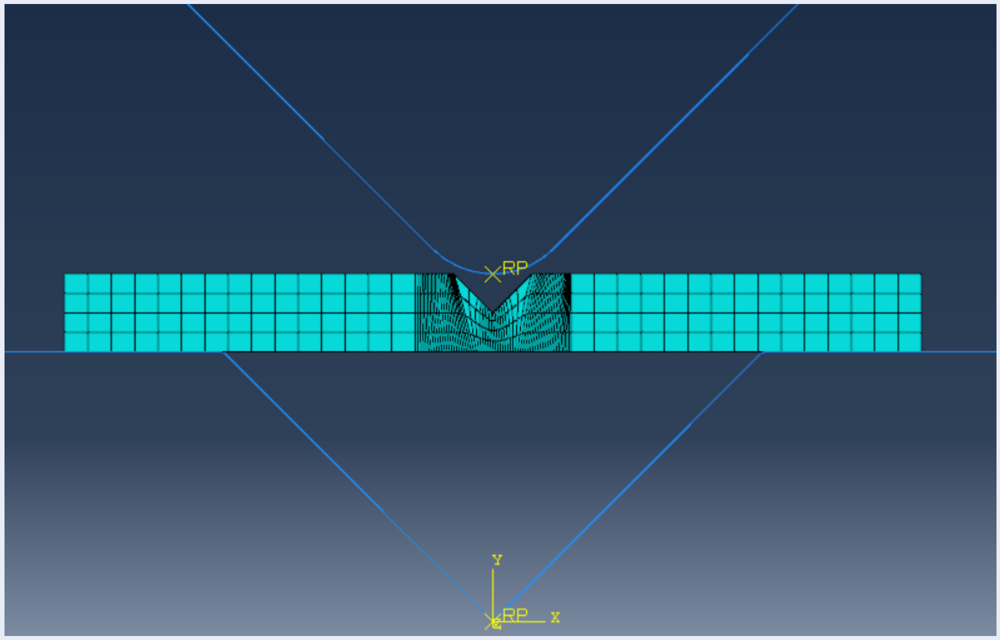

Figure 5: Mesh structure of model. [Source: The authors]

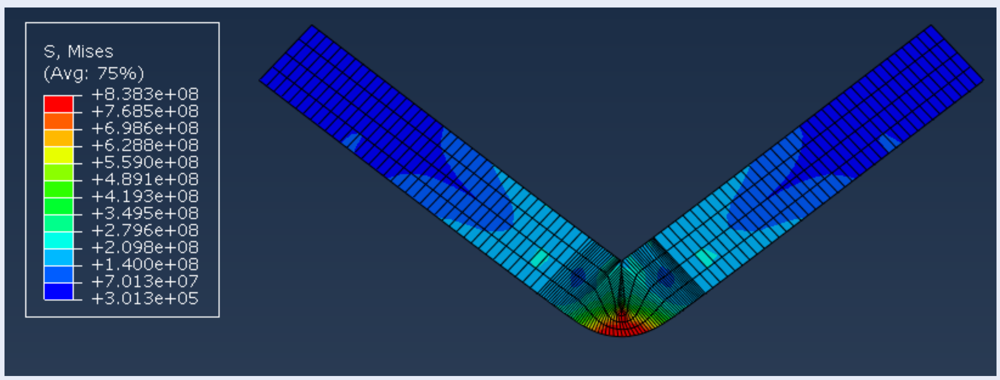

Figure 6: Sheet metal while the punch reaches desired height. [Source: The authors]

Table 2: **Resulted Springback**

No.	Depth of V-groove $\overline{d}_v$	Angle post-bending α	Springback errors $\overline{\alpha}$
1	0.2	92.15	2.39
2	0.3	91.24	1.38
3	0.4	90.55	0.61
4	0.5	90.17	0.19
5	0.6	89.21	0.88

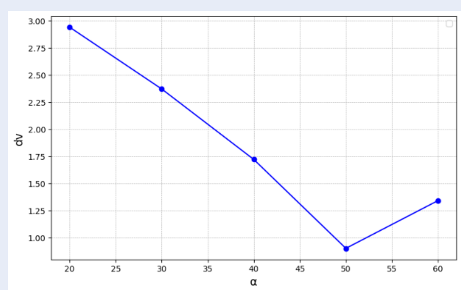

Figure 8: The relationship between dv (depth of V-groover) and α (Angle of sheet metal after bending) [Source: The authors]

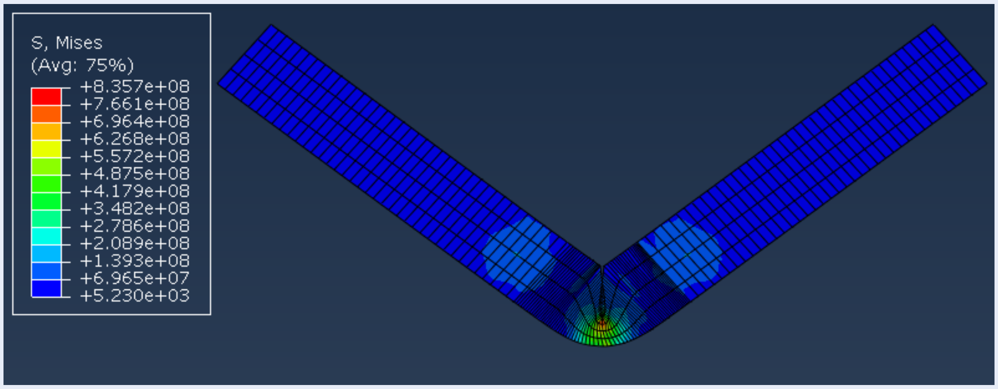

Figure 7: Sheet metal while springback occurred. [Source: The authors]

thickness, the metal is susceptible to over deformation. This happens because the restriction enforced by the V-groove becomes excessive, leading it to deform past the anticipated shape. Various depths (20%, 30%, 40%, 50%, and 60%) are contrasted with post-elastic recovery. Remarkably, sheets with a V-groove depth of 50% consistently display the smallest springback angle across all bending heights, emphasizing the considerable effect of V-grooving depth on springback behavior. Nonetheless, it is vital to keep in mind that the perfect depth might differ based on the specific application's demands, considering both the pros and cons of deeper grooves.

CONCLUSION

The study demonstrates the effectiveness of the V-grooving process in enhancing the accuracy of V-bending in SUS 304 stainless steel sheet metal. It shows that V-grooves can significantly reduce springback, a common issue in V-bending, by creating more constraint on the bent sheet metal, thereby preventing it from recovering elastically. The depth of the V-grooves plays a crucial role in this process. As the depth increases, the springback decreases. However, when the depth reaches 60% of the sheet thickness, the metal tends to over deform due to excessive constraint. The study finds that a V-groove depth of 50% consistently results in the lowest springback angle across all bending heights. Nevertheless, the optimal depth may vary depending on the specific requirements of the application, and both the benefits and drawbacks of deeper grooves should be considered. These findings provide valuable guidelines for optimizing the V-grooving technique for better dimensional control in V-bending of SUS 304 stainless steel sheet metal. The study's results could have significant implications for industries that rely on sheet metal forming processes.

COMPETING INTERESTS

The author(s) declare that they have no competing interests.

AUTHOR CONTRIBUTIONS

Quoc-Nguyen Banh: Conceptualization, Writing – original draft preparation, Project Administration.
Viet-Khai Le: Methodoloy, Validation, Formal analysis, Visualization.
Tuan-Kiet Vo: Validation, Investigation, Data curation.
Anh-Son Tran: Software, Writing – review and editing, Supervision, Funding accquisition.
Minh-Tuan Ho: Methodology, Writing – review and editing, Supervision.

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Bài nghiên cứu

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TÓM TẮT

Quá trình bào rãnh chữ V là một kỹ thuật quan trọng trong lĩnh vực tạo hình kim loại tấm, được ứng dụng nhằm nâng cao độ chính xác của quá trình uốn chữ V bằng cách giảm thiểu hiện tượng hồi đàn — hiện tượng vật liệu có xu hướng phục hồi hình dạng ban đầu sau khi dỡ bỏ tải trọng, gây ảnh hưởng lớn đến độ chính xác kích thước sản phẩm. Nghiên cứu này tập trung khảo sát ảnh hưởng của chiều sâu rãnh V đến khả năng giảm hồi đàn trong quá trình uốn thép không gỉ SUS 304 thông qua mô phỏng phần tử hữu hạn bằng phần mềm Abaqus Learning Edition 2023. Kết quả cho thấy việc kết hợp bào rãnh với chiều sâu phù hợp có thể làm giảm đáng kể xu hướng phục hồi đàn hồi của vật liệu, giúp duy trì góc uốn mong muốn và nâng cao chất lượng sản phẩm cuối cùng. Tuy nhiên, mặc dù chiều sâu rãnh lớn hơn có khả năng giảm hồi đàn hiệu quả hơn, chúng cũng có thể gây biến dạng quá mức và ảnh hưởng đến tính toàn vẹn của chi tiết. Do đó, nghiên cứu đã xác định được chiều sâu rãnh tối ưu nhằm cân bằng giữa việc hạn chế hồi đàn và tránh hư hại vật liệu ở nhiều chiều cao uốn khác nhau. Những kết quả này mang ý nghĩa thực tiễn cao đối với các ngành công nghiệp gia công kim loại tấm, góp phần cải thiện khả năng kiểm soát kích thước, nâng cao độ chính xác, chất lượng và tính thẩm mỹ của các sản phẩm kim loại trong sản xuất hiện đại.

Từ khoá: Mô phỏng phần tử hữu hạn, quá trình tạo hình kim loại tấm, quá trình uốn chữ V, hiện tượng đàn hồi ngược, quá trình bào rãnh chữ V

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