A study on experiment and simulation to predict the spring-back of SS400 steel sheet in large radius of V-bending process

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Abstract

The spring-back phenomenon is one of the key problems in sheet metal forming process, especially with a complex shape. In this paper, the experiments of spring back have been first carried out to study the effect of punch strokes (different bending angles) on the spring-back angle for 6 (mm) thickness of SS400 sheet steel by V-bending process. The experimental results are then validated by finite element analysis (FEA) of ABAQUS software. To simulate spring-back of V-bending, deformed results of V-shape from a dynamic forming simulation in Abaqus/Explicit would be imported into Abaqus/Standard, and then a static analysis will calculate the spring-back of V-bending. Simulation studies have shown that there are different variations in the initial bending angle and the spring-back angle after the removal of the bending force based on isotropic and kinematic hardening models. Therefore, the combined hardening model has been proposed to overcome the mismatch between prediction results and the corresponding experiments. Based on the accuracy of FEM simulation, this study also verifies the effect of parameters such as a thickness of the sheet, punch radius and punch stroke on the spring-back angle in order to select the optimum input parameters by using Taguchi method.

1. Introduction

Bending is the forming of sheet metal where angled or ring-shapes parts are produced. The process consists of uniform straining flat sheets of metal around a linear axis, but it also may be used to bend tubes, drawn profiles bars, and wire. In bending, the plastic state of the material is caused by the bending load. In fact, one of the most common processes for sheet metal forming is bending, which is used not only to form pieces such as L, U or V-profiles. Bending process is widely applied in the automotive, shipbuilding, aircraft and defense industries to manufacture any kinds of sheet metal products [1]. In recent years, the high accuracy productions according to the design are a main goal of the sheet metal industry in order to decrease the post-forming processes resulting in cost and time reduction. The problem of post-forming operations is more pronounced for thick sheets due to the weight of bent parts. Spring-back is the recovery of the elastic part of the plastic deformation after removal of the external load that is applied during the bending operation; this phenomenon is a key factor of inaccuracies in bending process [2]. There are various studies have focused on Spring-back calculation [3–9], however, a universal solution has still not been found [10]. The previous studies indicate the complex nature of Spring-back, depending on the behavior of material and process parameters. Plastic deformation of the sheet sheets requires, at the design stage of manufacturing, taking into account specific properties of the sheet material, i.e., Young’s modulus, yield stress, ratio of yield stress to ultimate tensile stress, and microstructure of the material [11].

Spring-back could not be eliminated, but there are a few methods to minimize the elastic recovery of the formed part. One of the methods is a suitable design of the die and punch which takes into consideration the amount of Spring-back. Furthermore, the change in selected bending process parameters could affect to the spring-back [11]. There are effects of various parameters such as punching speed, elevated temperatures, friction conditions, etc on spring back of the V-bending process. Where the effect of punching speed will correspond to
the effects of strain rate on the spring-back relative to the behavior of stress-strain curves at various strain rates. The faster the strain rate, the higher the flow stress curve leads to increase spring-back phenomenon as referring by various researchers [12–14]. In order to minimize the spring-back, Taguchi experiment design method coupled analysis of variance (ANOVA) could be applied to select optimal parameters [12]. The idea of correction of the die shape consists of additional over-bending of the material [15]. Among the many advanced methods of predicting the final shape of the deep drawing parts, the finite element method (FEM) is the most often used [16, 17]. FEM is the main technique used to simulate sheet metal forming processes in order to determine the distribution of stresses and deformations in the material, forming forces and potential locations of the defects. The finite element modeling technique provides a relatively easy to implement the approach with a wide range of ready-to-use commercial software. Although, an implemented finite element model may be slow, with appropriate mesh parameters reasonable simulation times are feasible [2]. Despite prior research on Spring-back calculation [18] efforts on studying the behavior of thick sheets (more than 4 millimeters) of high-strength steels with large radius punches have been limited. Relevant input data along with a correct solution scheme provide a solid foundation for an accurate finite element solution. The material modeling and corrected material properties are necessary factors to obtain an accurate simulation. Additionally, a finite element model for bending of sheet metal is sensitive for a wide range of parameters, e.g. friction coefficient, Young’s modulus, yield stress and so on. Recently, a number of researchers have focused on developing numerical models or recognizing parameters of hardening models [2, 3, 10, 19, 20] based on well-known models of Chaboche [19] and Chung et al [20]. However, to apply this model, too many procedures for obtaining material parameters are required. Therefore, this study aims at proposing a simplified method for obtaining material parameters applying for SS400 steel and performing a thorough discussion of spring-back behavior based on the Taguchi experiment design method coupled analysis of variance (ANOVA) for V-bending of SS400 steel.

In sheet metal V-bending process, there is Bauschinger effect of deformation mode which could be predicted by using isotropic, kinematic or combination hardening laws [18–22]. This paper studies the mechanical properties and the V-shaped deformation process of SS400 thick sheet material in order to understand the effects of properties, material models, geometric parameters, sheet thickness and bending angle on the spring-back of V-bending after plastic deformation and unloading process from which to propose solutions to limit the impact of the causes of spring-back by using simulation and experiment. First, the specimens are cut in the rolling direction of the sheet metal and performed to show the stress-strain curve and deformed V-shapes after bending 90°; 123.5° and 150° by using the testing machine. In order to verify the effects of the hardening model on spring-back prediction, the kinematic and isotropic hardening models were then used to simulate corresponding V-bending shapes by using ABAQUS/Explicit software. The comparative results show the mismatch of both hardening models compared to corresponding experiments. Therefore, this study proposed a new method to determine the coefficients of combined hardening law to improve spring-back prediction based on the spring-back angle measurements and errors of V-bending shapes between pure kinematic and isotropic hardening laws versus corresponding experimental data. The predicted simulation results show in good agreement compared with corresponding experiments. The obtained coefficients of combined hardening law finally used to simulate V-bending shapes according to the orthogonal array plan of Taguchi L9 with 3 input parameters such as sheet thickness, punch stroke and punch radius. The Minitab software also used to analyze the ANOVA (Analysis of Variance), evaluate the effects of each parameter on the spring-back prediction and select the optimal parameters to set the corresponding experiment.

2. Material and hardening model

2.1. Materials

The material used in this study is SS400 steel sheet, according to JISG 3101 [23] with a chemical composition as table 1.

The tensile test pieces are cut on a wire cutting CNC machine, the tensile specimens were cut from the sheet in parallel to the rolling direction in order to carry out uni-axial tensile tests. After that, the tensile specimens are honed smoothly with a armor paper. The shapes and dimensions of the specimens were prepared in accordance with TCVN 197-85 (197-2000) [24], as show in figure 1.

| Table 1. Chemical composition of SS400 steel sheet. |
|---------------------------------|
| C | Si | Mn | P | S | Cr |
| 0.19 – 0.21 | 0.05–0.17 | 0.4–0.6 | 0.04 | 0.05 | ≤0.3 |
According to the tensile test data, the stress-strain curves for the SS400 Steel sheet have been obtained by using Voce’s hardening law [25] as shown in figure 2 and equation (1). The SS400 sheet material properties are also depicted in table 2.

\[ \sigma = \sigma_Y + A(1 - \exp(-B\varepsilon_{eq}^p)) \]  

(1)

where A and B are the plastic coefficients, \( \varepsilon_{eq}^p \) and \( \sigma_Y \) are the equivalent stress, equivalent strain, and tension yield stress, respectively.

2.2. The hardening models
The nonlinear combined hardening model was developed by Armstrong—Frederick [26] and then Chaboche [19]. Chung et al [20] proposed the modification of the hardening model. However, to determine the parameters of hardening law proposed by Chung et al’s method [20], there are too many complicated experiments for obtaining required material parameters. This study developed a simplified and effective method to obtain material parameters for SS400 steel. The basic equations for pure isotropic, kinematic and combined hardening laws, that are used in FEM simulation commercial software, can be expressed from equation (2) to equation (8). Here, due to the test material samples were cut along the rolling direction (0°), so that it is possible to consider the material parameters according to the isotropic material model.
The Von-Mises yield surface both translates and expands with plastic strain and is defined as equation (2).

\[ f(\sigma) = \frac{1}{2} \xi_j; \quad \xi_j = \frac{1}{3} \sigma_{\text{iso}}^2 \]

Where \( \sigma_{\text{iso}} \) is the uni-axial equivalent yield stress, and \( \xi \) is the stress difference measured from the center of the yield surface, as shown in equation (3), where \( \alpha \) is the back stress.

\[ \xi_j = S_j - \alpha_j \]

The deviatoric part of the current stress is:

\[ S_j = \sigma_j - \sigma_m I \]

where \( \sigma, \sigma_m \) are the current values of the stress and mean stress, and \( I \) is the identity matrix.

With the pure isotropic hardening case, there is only size evolution of the yield locus then the back stress \( \alpha \) is zero and the stress difference \( \xi \) is equal to the deviatoric stress \( S \). Equation (2) is rewritten as equation (5):

\[ f(\sigma) = \frac{1}{2} S_j; \quad S_j = \frac{1}{3} \sigma^2 \]

For simple kinematic hardening model, the size of yield surface does not grow ( \( \sigma_{\text{iso}} = 0 \) ) and the von Mises yield condition is written in terms of the stress difference \( \xi \) with only the translation of yield locus following back stress \( \alpha \) as equation (2). Then the co nsistency condition for kinematic hardening is written as equation (6):

\[ \dot{f}(\sigma) = \frac{1}{2} \dot{\xi}_j; \quad \dot{\xi}_j = 0 \]

The kinematic hardening evolution is depicted by back stress increment as a function of equivalent plastic strain.

\[ d\alpha_j = C_b (\sigma_j - \alpha_j) d\varepsilon_{\text{eq}}^p - \gamma \alpha_j d\varepsilon_{\text{eq}}^p \]

The back-stress \( \alpha \) curve was first obtained by offsetting tensile stress-strain curve data about yield stress value \( (\sigma_y) \) then fitting method based on the back-stress evolution law equation (8).
where \( C \) and \( \gamma \) are the unknown material coefficients refer to kinematic behavior.

### 2.2.1. Isotropic hardening model

In the pure isotropic hardening case, there is only the size evolution of the yield locus then the back stress \( \alpha \) in equation (8) is zero and the equation (5) used for the plastic function of the material.

When isotropic hardening law was used to simulate the uniaxial tension/compression tests then only parameters, \( \sigma_Y \), \( A \), and \( B \) in equation (1) are adopted as input data. To determine the isotropic hardening parameters \( A \) and \( B \) in equation (1), it is combined with the experimental data in figure 2 and using the least-squares method of Excel software, the corresponding values of \( \sigma_Y \), \( A \), and \( B \) can be determined as 348 (MPa), 188.86 (MPa) and 28.3293, respectively.

### 2.2.2. Kinematic hardening model

To introduce the Bauschinger effect, a kinematic hardening model was implemented to simulate tension/compression test and predict stress-strain curves evolution. To determine the kinematic hardening parameters \( C \) and \( \gamma \) in equation (8), back-stress \( \alpha \) curve was first obtained by offsetting tensile stress-strain curve data about yield stress value \( (\sigma_Y) \) (figure 3) then fitting method based on the back-stress evolution law equation (8) was utilized to calculate calibration parameters \( C \) and \( \gamma \) as 5350.272 MPa and 28.329, respectively.

### 3. Experimental and finite element verification

#### 3.1. Experimental setup

In order to obtain materials behavior of the steel sheet, the specimens were performed consisting of tensile tests and bending tests on the HungTaH-200kN tensile testing machine, with a capacity of 30 tons as shown in figure 4.

The tooling dimensions are shown in figure 5, where \( \Delta Y \) is the vertical movement of the punch stroke. In this study, \( \Delta Y \) was selected as 18 mm, 14 mm and 8 mm corresponding to bending angles of 90°, 123.5° and 150°.

#### 3.2. V-Bending experiment

The experimental bending tests were performed with the sheet of 160 × 55 (mm × mm), here, the tests were executed along the rolling direction. Figure 6 presents spring-back experimental investigations performed on the SS400 steel sheet with the punch strokes of 18 mm, 14 mm, and 8 mm corresponding to the bending angle of 90°, 123.5° and 150°, respectively. As the experimental results (figure 6), in case of small values of bending angle, the material is mainly affected by elastic deformation then the spring-back value increases. When the internal bending angles are increasing then the spring-back value will decrease because the sheet is subjected to more...
plasticity deformation and its strength increases as a result of the tensile phenomenon. Some similar results for other steel and alloy material could be referred [1, 6, 26–29].

3.3. Finite element investigation
3.3.1. Uni-axial tension/compression simulation
To apply kinematic and isotropic hardening models into predicting stress-strain curves in uni-axial tension and compression stages, the obtained data from tensile test experiments and calculated coefficients in section 2.2 were input to ABAQUS/Explicit to simulate uni-axial tension/compression specimens. Here, the uni-axial tension/compression testing modeling was modeled using shell elements S4R, where the average element dimensions of the elements was about 1.5 mm in width and 3.0 mm in length.

In order to simulate tension/compression behavior by using the pure isotropic hardening model, plastic coefficients ($A, B$) and the equivalent stress $\sigma_Y$ as shown in equation (1) and table 2 are needed to declare in FEM simulation. Besides, when pure kinematic hardening model is adopted for simulation then calculated parameters $C$ and $\gamma$ in equation (8) should be inputted to the material properties of ABAQUS/Explicit. The results of the tension/compression testing simulation are shown in figure 7. The stress-strain curve predictions using pure kinematic and isotropic hardening laws were compared with corresponding tensile test experimental data as shown in figure 8.
3.3.2. V-bending simulation

ABAQUS/Explicit software was also used to simulate the deformation for the V-bending process. The parameters of material models are needed to be declared as simulation inputs according to Voce’s model equation (1) and corresponding isotropic or kinematic hardening laws similar to above Uni-axial tension/compression simulation. However, to predict the spring-back phenomenon of V-bending process, the deformed results from ABAQUS/Explicit must be used to import into ABAQUS/Standard module, 3D Experience® 2016 HF2 (2016 HF2, Dassault Systèmes Simulia Corp., Providence, RI, USA, 2016) [8]. The V-bending models are depicted in figure 9 corresponding to the experimental setup of figure 5. Specifically, reduced-integration eight-node linear brick elements (C3D8R) are utilized for the blank. The die/tool and clamping parts are assigned as the rigid body. The size of the element for all parts corresponds to approximately 2 × 2 × 8 mm (Thickness × width × length). The boundary conditions in the model are as follows: a die part—ENCASTRE condition; a punch part: vertical movement; a sheet part: symmetrical boundary condition with respect to the center of the sheet.

Figure 10 presented the simulation results after spring-back occurrence for the case bending angle of 90°, 123.5° and 150°. As shown in figure 10, isotropic hardening law overestimated the hardening component by missing the Bauschinger effect and transient behavior; and kinematic hardening law underestimates the hardening of material and exaggerates the Bauschinger effect after reverse loading occurrence. The comparisons

![V-bending simulation images](image-url)
of the experimental and finite element results are depicted in table 3. The error ($\Delta \alpha$) between simulation and experimental result can be calculated as equation (9).

$$\Delta \alpha = \alpha_{\text{Simulation}} - \alpha_{\text{Experimental}}$$  \hspace{1cm} (9)

The data in table 3 shows that the spring-back deviations angle between simulation and corresponding experiments are quite large up to nearly 2°.

Figure 7. Deformed shape of tensile specimens in FE simulation for tension/compression tests.

Figure 8. The predictions for stress-strain curves for kinematic hardening and isotropic hardening law.
To overcome and improve the accuracy of spring back predictions, various studies proposed some new equations and complicated methods to determine new parameters of hardening models [3, 5, 6, 20, 22]. This study developed a simplified and effective method to accurately predict V-bending by using combined hardening model as shown in equation (10).

Figure 9. V-bending modeling.

Figure 10. Simulation result of V-Bending at (a) 90°, (b) 123.5° and (c) 150° after spring-back based on kinematic and isotropic hardening models.
Where the material coefficients $A$, $B$, $C$, and $\gamma$ need to determine by proposed method by using combined hardening model. The new parameters of the proposed hardening law are determined based on the comparison between experimental data and corresponding spring-back prediction results by using pure isotropic and kinematic models of the V-bending process for various bending angles, where, the errors spring-back data ($\Delta \alpha$) between V-bending experiment and simulation of pure kinematic and isotropic hardening laws at different strain position could be collected based on table 3 and then utilized to determine the new back-stress ($\alpha_n$) by proposed ratio method as equation (11).

\[
\alpha_n = \left( \frac{\Delta \alpha_{iso}}{\Delta \alpha_{iso} - \Delta \alpha_{kin}} \right) \alpha
\]

(10)

where $\Delta \alpha_{iso}$ and $\Delta \alpha_{kin}$ are average errors of spring-back angle between V-bending experiment and simulation by using pure kinematic and isotropic hardening laws, respectively. From spring-back results between experiments and corresponding predictions (table 2) back-stress can be obtained as $\alpha_n = 0$, 6685.$\alpha$.

The new relationship between back-stress $\alpha_n$ and equivalent strain equation (11) will be used to determine parameters $A$, $B$, $C$, and $\gamma$ by least-square method as 2012.3 MPa and 33.527, respectively. Then, the equivalent yield function equation according to the equivalent strain value must be recalculated using equation (12) and figure 11.

\[
\bar{\sigma} = \sigma_Y + A_1(1 - \exp(-B_1 \varepsilon_{eq}^{pl})) + C_1 \frac{1}{\gamma_1}(1 - e^{-\gamma_1 \varepsilon_{eq}^{pl}})
\]

(10)

The data obtained from equation (11) are then used to determine hardening parameters $A_1$ and $B_1$ as 60.02 MPa and 33.527, respectively, as fitting method by equation (13)

\[
\bar{\sigma}_{iso} = \sigma_Y + A_1(1 - \exp(-B_1 \varepsilon_{eq}^{pl}))
\]

(13)

Spring-back simulation results of V-Bending using new combined hardening model after bending 90°; 123.5° and 150° are shown in figure 12 and table 4.
The data in Table 4 show that the new combined hardening model has high accuracy during the prediction of V-bending spring-back. It is concluded that the new combined hardening law could be used to predict and verify the effect of various parameters on spring-back angle.

### 4. Taguchi orthogonal array

In order to verify the effect of parameters on the spring-back angle prediction ($S (^{\circ})$) by FEM simulation, three parameters such as thickness of the sheet ($t$), punch radius ($R$) and punch strokes ($H$) were selected according to Taguchi method. Table 5 lists the levels of parameter selection.
During the simulation, there are 3 selected levels of each parameter. The L9 orthogonal array will be then used to design the experimental statistical method. At least 9 experiments are needed to test the effect of changing parameters on simulation results. The use of the Taguchi orthogonal algorithm will reduce the number of experimental designs from 27 to 9 experiments. The results of the simulated Taguchi experiments are shown in table 6.

The mean S/N ratio ($\eta_i = -10 \log_{10}(S_i^2)$) for each bending parameter at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the corresponding simulation. The means of the S/N ratio for each level of bending parameters are also presented in table 6. Figure 13 shows the S/N ratio response graph for the spring-back angle, here, a high S/N ratio for a smaller variance of spring-back angle around the desired value. Nevertheless, the relative importance among the input parameters for the spring-back angle still required to be identified. The optimal combinations of the input parameter levels can be determined more accurately using the analysis of variance (ANOVA).

In order to investigate the effect of each parameter on the spring-back angle, an ANOVA analysis was used to calculate. This goal could be achieved by splitting the variability of the S/N ratios that is measured by the sum of the squared deviations from the total mean S/N ratio, in the contributions of each bending parameters and the error as shown in table 7.
The F-Ratio test is a statistic tool to verify which design parameters affect significantly in the quality characteristic. It is defined as the ratio of the mean squared deviations to the mean squared error. The analysis of the F-Ratio values reveals that the thickness of the sheet \( t \) is the most significant parameters. The thickness of the plate contributed with 76.2%, followed up by the punch stroke \( H \) and the radius of the punch \( R \), respectively, with 19.4% and 4.4% contribution. The optimal parameters for the best spring-back angle are the thickness of the sheet \( t \) at level 3 of 7 mm, the punch radius at level 2 of 40 mm and the punch stroke \( H \) at level 3 of 18 mm.

Figures 14 and 15 present the simulation and corresponding experimental results for optimal parameters of V-bending as \( t = 7 \) mm, \( R = 40 \) mm and \( H = 18 \) mm. The comparative result shows in good agreement.

### 5. Conclusion

The study of spring-back behaviors of SS400 Steel sheet in large radius V-bending is presented in this article. Samples cut along the rolling direction are employed. Experimental tests are conducted to compare with the
numerical simulation results. In this research, the spring-back effect is evaluated under various punch strokes corresponding to bending angles of (90°, 123.5° and 150°). FEA Study has also been done with the support of ABAQUS software. It has been observed that as the bending angle of sheets increases the spring back angle increases too, from 2.46° to 5.92° (show in table 5) for a given bending angles. The experimental and simulation results are in good agreement so that ABAQUS software could be used in Spring-back prediction for V-bending SS400 Steel sheet. This study also used a combination of ABAQUS simulation and TAGUCHI method to calculate and select the improvement parameters for V-bending of SS400 Steel sheet. By FEM simulation, the most important factor affecting the spring-back angle of the V-bending product and also optimum values have been determined such as the punch stroke - H = 18 mm, the thickness of the plate – t = 7 mm and the punch radius—R = 40 mm.

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