Application of FEM Simulation and Abductive Network to Predict the Springback of U-Shaped Bending Process with Counter Force

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Abstract- This study applies the finite element method (FEM) in conjunction with an abductive network to predict springback's angle during the U-shaped bending process with counter force. To verify the prediction of FEM simulation for springback, the experimental data are compared with the results of current simulation. Bending force, effective stress distribution and springback are investigated for different process parameters, such as profile radius of die, blank holder force and counter force of U-shaped bending process, by finite element analysis. The abductive network is then utilized to synthesize the data sets obtained from numerical simulations. Finally, prediction model is established for predicting springback's angle under a suitable range of process parameters.

Keywords：*U-shaped bending process, springback, counter force, finite element method, abductive network.*

I. INTRODUCTION

Springback is a very important factor to influence the quality of sheet metal bending process. The prediction, control and reduction of springback have become very crucial in the sheet metal forming process. Springback is normally measured in terms of change in radius of curvature due to elastic recovery, and is influenced by a combination of various process and material parameters such as blank holder force, elastic modulus, strain hardening exponent and yield strength, etc.[1].

Experimental prediction of springback and the determination of the final geometry within a reasonable tolerance is time consuming and expensive. In recent years, Finite Element Analysis (FEA) has been considered to be an effective tool for simulating the bending process and predicting the springback [2]. The springback prediction of bending operation using FEA has been employed by many in the past. For instance, Cho et al. [3] carried out numerical investigation on springback characteristics in plane strain „U' bending process by thermo-elastoplastic FEA. Papeleux and Ponthot [4] discussed numerically the effect of blank holder force, friction, spatial integration, etc. on the forming response. Ihab et. al [5] discusses the effect of sheet anisotropy on the springback of stainless steel 410 draw-bend specimens. Ruffini and Cao [6] proposed neural network based models to minimize the springback in a channel forming process. It was shown that even for large variations in friction condition and material properties the springback is quite low.

All above researches are not focus on the counter force effect. Counter force is an important parameter for reducing the springback. This study applies the finite element method (FEM) in conjunction with an abductive network to predict springback's angle during the U-shaped bending process with counter force. To verify the prediction of FEM simulation for springback, the experimental data are compared with the results of current simulation. Bending force, effective stress distribution and springback are investigated for different process parameters, such as profile radius of die, blank holder force and counter force of U-shaped bending process, by finite element analysis. The abductive network is then utilized to synthesize the data sets obtained from numerical simulations. A prediction model for springback of strain-hardening material in u-shape bending with counter force is then established.

II. HELPFUL HINTS

A. Finite Element Molding

This study applies commercial finite element code DEFORM-3D [7] to simulate the plastic deformation behavior during the U-shaped bending process. The basic equations of the rigid-plastic finite element are as follows:
Equilibrium equation:

$$\sigma_{ij,j} = 0 \tag{1}$$

Compatibility and incompressibility equations:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right), \quad \dot{\varepsilon}_{v} = u_{i,i} = 0 \tag{2}$$

Constitutive equations:

$$\sigma'_{ij} = \frac{2\bar{\sigma}}{3\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij}, \quad \bar{\sigma} = \sqrt{\frac{3}{2}\left(\sigma'_{ij}\sigma'_{ij}\right)}, \quad \bar{\varepsilon} = \sqrt{\frac{3}{2}\left(\dot{\varepsilon}_{ij}\,\dot{\varepsilon}_{ij}\right)} \tag{3}$$

Boundary conditions:

$$\sigma_{ij} n_i = F_j \ \text{ on } \ S_F, \qquad u_i = U_i \ \text{ on } \ S_U \tag{4}$$

where σ_{ij} and $\dot{\varepsilon}_{ij}$ are the stress and the strain rate, respectively, $\bar{\sigma}$ and $\dot{\bar{\varepsilon}}$ are the effective stress and the effective strain rate, respectively, F_j is the force on the boundary surface of S_F, and U_i is the deformation velocity on the boundary surface of S_U.

The weak form of rigid-plastic FEM can be determined by applying the variational method to Eqs. (1) – (4), i.e.

$$\int_V \bar{\sigma}\delta \dot{\bar{\varepsilon}}\, dV + K\int_V \dot{\varepsilon}_V \delta \dot{\varepsilon}_V \, dV - \int_{SF} F_i \delta u_i dS = 0 \tag{5}$$

where V and S are the volume and the surface area of the material, respectively, and K is the penalty constant. The Newton–Raphson iteration method is applied to obtain the solution of the equations.The convergence criteria for the iteration are the velocity error norm $\|\Delta v\| / \|v\| \leq 0.01$ and the force error norm $\|\Delta F\| / \|F\| \leq 0.1$, where $\|v\|$ is defined as $\left(v^T v\right)^{1/2}$.

The most important and crucial part of simulation in software is the selection of appropriate material model. DEFORM-3D contains various material models (for elastic, elastic-plastic and rigid-plastic), and each model has different suitability, so selection of correct material model as per the requirement is the prime necessity to get the accurate output or simulated results. Most of the material models require detailed material properties such as young's modulus of elasticity, strain hardening exponent, anisotropy coefficient (R_0, R_{45} and R_{90}) and strength coefficient, etc., as input to preprocessor before running the solver. In addition to material properties, preprocessor also require input of detailed process parameters such as friction coefficient, punch velocity, blank holding force, sheet thickness, etc.

B. *Abductive Network Synthesis and Evaluation*

In the abductive network, a complex system can be decomposed into smaller, simpler subsystems grouped into several layers using polynomial functional nodes. The polynomial network proposed by Ivakhnenko [8] is a group method of data handing (GMDH) techniques. Theses nodes evaluate the limited number of inputs by a polynomial function and generate an output to serve as an input to subsequent nodes of the next layer. The structure of polynomial network is shown in Fig. 1. It consists of sigma (summation) units in the hidden layer and pi (product) units in the output layer. Output of a sigma unit is a weighted sum of its inputs, and output of a pi unit is a product of its input. Let the k^{th} input pattern to the network be specified by $X_k = [x_{0k}, x_{1k}, x_{2k}, \ldots, x_{nk}]$, and let the weight associated with connection from input unit i to hidden unit j be w_{ij}. Then, the output z_{jk} of the j^{th} sigma unit is given by

$$z_{jk} = \sum_{i=0}^{n} w_{ij} x_{ik} \tag{6}$$

and output y_k of the network is given by

$$y_k = \prod_{j=1}^{h} z_{jk} \tag{7}$$

where h is the number of hidden units in the network. Cobinining Eqs. (6) and (7), the general polynomial function in a polynomial functional node can be expressed as:

$$y_k = c_0 + \sum_{i=1}^{n} c_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} c_{ijk} x_i x_j x_k + \cdots \tag{8}$$

where x_i, x_j, x_k are the inputs, y_k is the output and c_i, c_{ij}, c_{ijk} are the coefficients of the polynomial functional nodes. In the present study, several types of polynomial nodes are used in polynomial network for predicting the maximum forging force and final face width under a suitable range of process parameters. For more detailed explanation of these polynomial functional nodes, please refer to the paper of Ivakhnenko [8]. To build a complete abductive network, the first requirement is to train the database. The information given by the input and output parameters must be sufficient. A predictive square error (*PSE*) criterion [9] is then used to automatically determine an optimal structure. The principle of the *PSE* criterion is to select the least complex yet still accurate network as possible. The *PSE* is composed of two terms, that is:

$$PSE = FSE + K_{\text{p}} \tag{9}$$

where *FSE* is the average square error of the network for fitting the training data and K_{p} is the complex penalty of the network, shown as the following equation:

$$K_p = CPM\,\frac{2\sigma_p^2 K}{N} \tag{10}$$

Where *CPM* is the complex penalty multiplier, *K* is a coefficient of the network, *N* is the number of training data to be used and is a prior estimate of the model error variance.

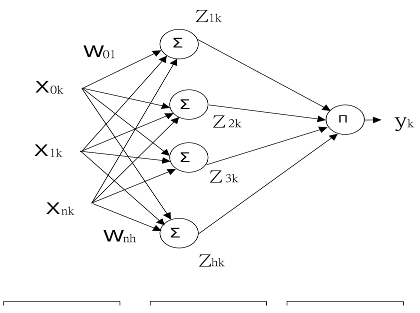


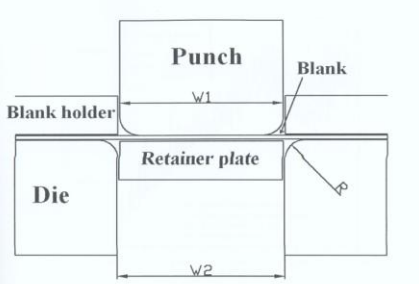
Fig. 1 Structure of polynomial network

III. HELPFUL HINTS

Figure 2 shows a schematic diagram of the U-shaped bending process with counter force. An initially flat thin rectangular metal workpiece is placed onto a U-shaped bending die and an adequate amount of pressure applied to the blank holder. The punch moves down to make contact with the rectangular sheet and to bend it into a U-shaped product. The counter force acted on retainer plate during the U-bending process. The retainer plate is supported by the spring. The counter force $\boldsymbol{F_C}$ is acted by the spring and expressed as :

$$F_C = K \times X \tag{11}$$

where $\boldsymbol{K}$ and $\boldsymbol{X}$ are the spring constant and the displacement of spring. During the analyses, the die, the punch and retainer plate are assumed to be rigid, whereas the metal workpiece is assumed to be elasto-plastic. Yang and Chang used DEFORM-3D software to simulate the springback of V-shaped bending process accurately. This study also used the DEFORM-3D software to predict the springback of U-shaped bending process with counter force. The dimensions of the punch and die are presented in Fig. 2. Figure 3 show the flow stress of workpiece. The material anisotropic parameters R_0 = 0.919, R_{45} = 0.795 and R_{90} = 1.453. The length, width and thickness of blank are 228.6 mm, 25.4 mm and 1.57 mm, respectively. The blank is modeled using four-node tetrahedral elements in the three dimensional simulation; 2100 nodes and 7500 elements were meshed in this study. The constant friction factor is assumed 0.01 at the interface between the metal sheet and die for good lubricated condition. Figures 4(a)–(c) present the current three-dimensional model for the material flow during different stages of the U-shape bending process in DEFORM-3D. Figure 4(a) shows the initial stage of the U-shape bending process. Figure 4(b) shows the stage of U-shape bend complete and begins to springback. Fig. 4(c) shows the final stage of U-bending process and the springback occurred in the sheet. Figure 5 shows the U-shaped product before and after the springback. Fig. 5(a) shows the shape before the springback of U-shape bending process. The θ_1 and θ_2, as shown in Fig. 5 (a), are equal to zero. After the springback occurred of U-shape bending process, the springback's angles θ_1 and θ_2 (Fig. 5(b)) are greater than zero. Fig. 6 shows the comparison of deformed shape for absent and present counter force. The sprinkback is small for the prsence of counter force. Fig. 7 shows stress distribution after unloading for different spring costant under the condition of $\boldsymbol{R}$ =5 mm, $\boldsymbol{P_h}$ = 11000 N and $\boldsymbol{C}$ = 4 mm. Large value of spring constant represent the high value of counter force. The stress distribution is more uniform for higher counter force. Large values of the counter force result in low values of maximum equivalent stress. Figure 8 shows the effective stress distribution before and after the unloading process under the condition of $\boldsymbol{K}$ = 75 N/cm, $\boldsymbol{R}$ =5 mm, $\boldsymbol{P_h}$ = 11000 N and $\boldsymbol{C}$ = 4 mm. The effective stress after the unloading is more uniform than that before the unloading. The maximum equivalent stress after unloading (946 MPa) is smaller than that before the unloading (1060 MPa).



(H = 40.0 mm, R = 9.525 mm, W1 = 76.2 mm,W2 = 82.047 mm)

Fig. 2 Schematic diagram of the U-shaped bending process

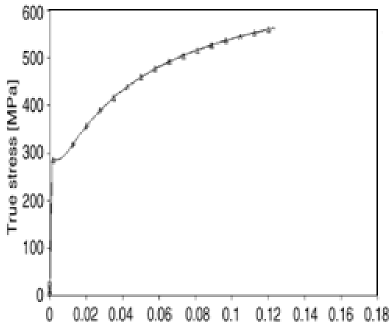
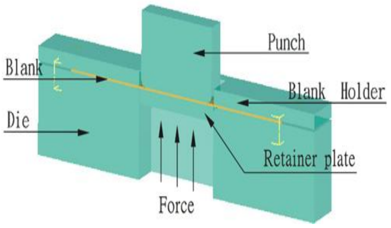
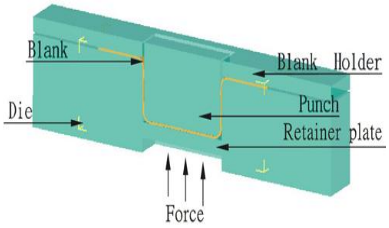


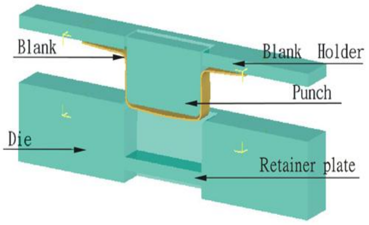
Fig.3 Flow stress of material



(a) Initial stage



(b) Stage of U-bending complete



(c) final stage

Fig. 4 DEFORM-3D simulation for different stages of the U-shape bending process

(a) before the springback of U-shaped bending

(b) after the springback of U-shaped bending

Fig. 5 Product of U-shaped bending (before and after the springback).

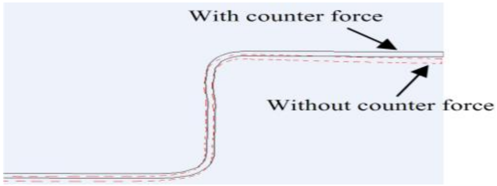
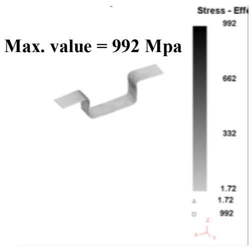
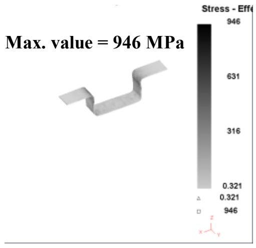


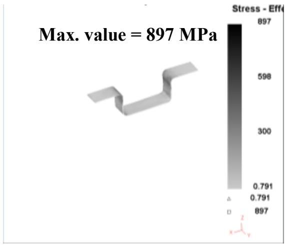
Fig. 6 Comparison of deformed shape after unloading for absent and present counter force.



(a) K=0 N / cm

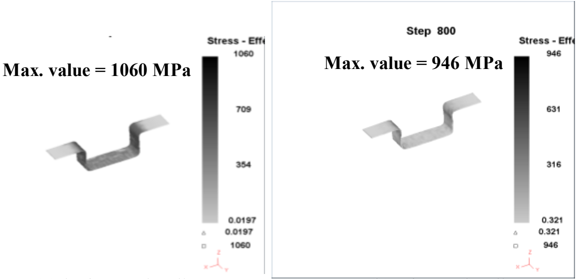


(b) K = 75 N / cm



(c) K=150 N / cm

Fig. 7 stress distribution after unloading for different spring constant.



(a) before unloading (b) after unloading

Fig. 8 Effective stress before and after the unloading

A. *Effect of Material Parameters on the Forming Force and Springback's Angle of Products*

To investigate the effects of process parameters, such as profile radius of die $\boldsymbol{R}$, blank holder force $\boldsymbol{P_h}$ and spring constant $\boldsymbol{K}$ on the forming load and springback during the U-shape bending process with counter force. Numerical analysis was performed for each change in these values. The clearance between punch and die $\boldsymbol{C}$ remains the constant value. Figure 9 shows the profile radius of die on the forming load under the condition of $\boldsymbol{P_h}$ = 11000 N, $\boldsymbol{K}$ = 0 N/cm and $\boldsymbol{C}$ = 4 mm for U-shape bending process. Large values of the profile radius of die result in low values of maximum forming load. The maximum value of bending force are approximately 21500 N, 16000 N, 12200 N for $\boldsymbol{R}$ =5 mm, 9.53 mm and 15 mm, respectively. Figure 10 shows the effect of blank holder force on the forming load under the condition of $\boldsymbol{R}$ =5 mm, $\boldsymbol{K}$ = 150 N/cm and $\boldsymbol{C}$ = 4 mm for U-shape bending process. The maximum forming load increases slightly as the blank holder force increases ($\boldsymbol{P_h}$ =11000 N – 22000 N). Figure 11 shows the effect of spring constant on the forming load under the condition of $\boldsymbol{R}$ =5 mm, $\boldsymbol{P_h}$ = 11000 N and $\boldsymbol{C}$ = 4 mm. The maximum value of bending force are approximately 21500 N, 24500 N, 27200 N for $\boldsymbol{K}$ =0 N/cm, 75 N/cm and 150 N/cm, respectively. Table 2 presents the effect of material parameters on the springback.

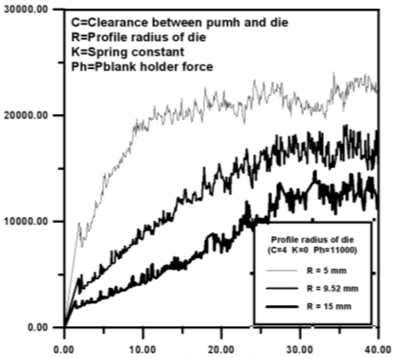


Fig. 9 Effect of profile radius of die on forming force

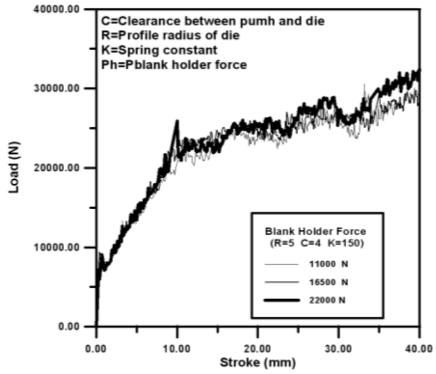


Fig. 10 Effect of blank holder force on forming force

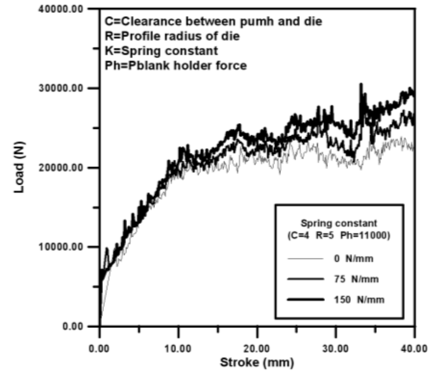


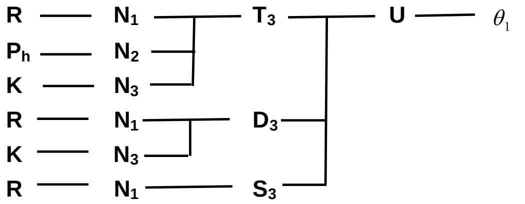
Fig. 11 Effect of spring costant on forming force

Table 1 Effect of process parameters on springback

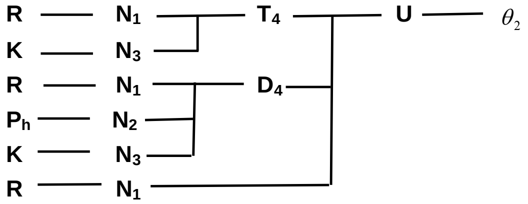
R (mm)	Ph (N)	K (N/cm)	θ1 (degree)	θ2 (degree)
5	11000	0	0.16	2.88
5	16500	0	0.89	4.09
5	22000	0	0.33	2.17
9.525	11000	0	0.73	1.03
9.525	16500	0	0.54	2.38
9.525	22000	0	1.41	1.25
15	11000	0	1.26	3.96
15	16500	0	0.26	0.99
15	22000	0	0.13	2.33
5	11000	75	0.53	1.15
5	16500	75	0.93	4.8
5	22000	75	0.6	1.64
9.525	11000	75	0.82	1.15
9.525	16500	75	0.27	1.4
9.525	22000	75	0.76	2.19
15	11000	75	0.46	3.55
15	16500	75	1.63	1.62
15	22000	75	1.38	3.03
5	11000	150	0.38	0.41
5	16500	150	0.36	1.03
5	22000	150	0.17	3.7
9.525	11000	150	0.34	0.56
9.525	16500	150	2.16	0.64
9.525	22000	150	0.28	0.93
15	11000	150	2.38	1.95
15	16500	150	0.1	2.84
15	22000	150	0.55	4.68

B. *Prediction Model for the Springback*

The profile radius of die is varied in the range of 5- 15 mm, while the other process parameters are selected by varying the blank holder force and spring constant in the ranges of 11000 - 22000 N, and 0 - 150 N/cm, respectively. Three process parameters variables and each of theses variables was set at three levels. Therefore, 27(3×3×3) combinations of process parameters are constituted totally and are shown in table 1. Base on the training database regarding to process parameters, the spingback angle θ_1 and θ_2 of U-shape bending process with counter force (Table 1), the abductive networks with a criterion of minimum square error can be developed for predicting the spingback angle θ_1 and θ_2 under a suitable range of process parameters. Figure 12 shows the network for predicting the spingback angle θ_1 and θ_2 of U-shape bending process. The predicted square error (PSEs) in Eq. (9) is 0.0538 for predictions of U-shape bending process.



(a) prediction network for θ_1



(b) prediction network for θ_2

Fig. 12 Prediction network for spingback's angle θ of U-shape bending process

To validate prediction model accuracy, another 7 data sets of the suitable range are tested for the spingback angle θ_1 and θ_2 of U-shape bending process. Tables 2 and 3 presents a comparison of spingback's angle θ_1 and θ_2 of U-shape bending process between the abductive network prediction and FEM simulation under various combinations of material parameters, which are around the border of a suitable range. Prediction results for spingback angle θ_1 and θ_2 of U-shape bending process are consistent with those obtained from FEM simulations quite well (Table 3). Therefore, the developed networks have a reasonable accuracy for the modeling of the spingback angle θ_1 and θ_2 of strain-hardening material in U-shape bending process.

Table 2 Comparison between FEM and Abductive network prediction results for θ_1

R (mm)	Ph (N)	K (N/cm)	Abductive network Prediction θ1 (degree)	FEM Simulation θ1(degree)	Error (%)
7	12000	40	0.66	0.71	7.60%
7	17000	120	0.59	0.56	4.68%
11	18000	50	1.37	1.45	6.11%
11	13000	85	0.84	0.78	7.14%
11	12000	120	0.78	0.81	3.29%
14	15000	50	1.61	1.61	0.19%
14	18500	90	1.16	1.14	1.88%

Table 3 Comparison between FEM and Abductive network prediction results for θ_2

R (mm)	Ph (N)	K (N/cm)	Abductive network Prediction Θ2 (degree)	FEM Simulation Θ2(degree)	Error (%)
7	12000	40	1.73	1.72	0.60%
7	17000	120	1.08	1.19	9.60%
11	18000	50	1.32	1.34	1.77%
11	13000	85	1.97	1.85	6.10%
11	12000	120	2.18	2.11	3.17%
14	15000	50	2.06	1.96	4.90%
14	18500	90	2.35	2.45	4.11%

IV. CONCLUSIONS

Springback is one of the main sources of geometrical and dimensional inaccuracy in sheet metal formed components. Prediction springback has become very crucial in the sheet metal bending process. This study established a prediction model for predicting spingback θ_1 and θ_2 of U-shape bending process with counter force using the FEM combined with an abductive network. Notably, FEM is utilized to investigate material flow characteristics of U-shape bending process with counter force. The effects of process parameters, such as profile radius of die, blank holder force and spring constant, on the forming force and spingback of U-shape bending process with counter force are also examined. The abductive network is then applied to synthesize datasets obtained from numerical simulation. Predicted results for spingback θ_1 and θ_2 from the prediction model are in good agreement with FEM simulation results. The predictive model provides valuable references for predicting spingback's angle under a suitable range of process parameters for the U-shape bending process.

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