Numerical Prediction of Springback and Side-Wall Curl in U-bending of Anisotropic Sheet Metals

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Finite Element method (FEM) is becoming an important modeling tool in sheet metal forming industry. The knowledge of the sheet metals' springback after forming is necessary to control the manufacturing process. This paper deals with the springback and side-wall curl in 2-D draw bending. An anisotropy property for material is considered. A general finite element code "ELFEN" has been applied for numerical simulation. The modeling of problem is performed by the explicit method for loading stage and the combination of the implicit and explicit method for unloading stage. Different significant parameters are examined within the framework of the present investigation. For instance, the influences of the blankhoder force and friction coefficient are investigated in detail.

Keywords: springback, side-wall curl, anisotropic sheet metal, U-bending

1- Introduction

Computer modeling techniques are being used at an increasing rate for simulation of metal deformation processes involving sheet metal forming operations because they allow understanding of physical phenomena involved in the processes. Indeed, the prediction of some details at the design stage and reducing of expensive trial and error methods in developing new processes or operations, are the most important consequences of computer modeling. In sheet forming operations, the blank being formed conforms closely to the die shape when it is in press. When the load is released and the part taken out of the press, there is a change in the shape. In some cases, the magnitudes of permanent plastic and recoverable elastic deformation are comparable; therefore, elastic recovery or springback may be significant.

The U-shaped part is a common element in sheet metal forming and actual forming operation such as 2-D draw bending is used to assess practical springback. It appears in many auto-body cover panels like side members and beams. This geometry is the most studied of springback cases because of its practical importance and obvious measurable presence of side-wall curl. Side-wall curl results from complicated bending, unbending and stretching deformations and it is a consequence of residual stress through the side-wall thickness. On the other hand, cold rolling induces preferred orientation of polycrystalline where grains anisotropy can be assessed by measured plastic anisotropy.

Generally, several researchers from different points of view have studied the topic by semi-analytical and numerical approaches in the last decade. Although the main aim of all investigations was to explore the effect of different factors on springback results, some

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methods, however, have been suffering from particular difficulties. For instance, the membrane element cannot be used for prediction of springback because it neglects the bending effect and sheet is treated as being infinitely thin with no gradients in thickness direction, therefore it is impossible to calculate springback directly [1-8]. However, some complementary approaches, i.e. hybrid approach, were developed to compensate the lack of conventional methods [9-10]. Nevertheless, some methods still cannot handle the springback because of mesh-orientation dependence and approximate 3-D bending stiffness [11]. Hence, it seems that the area is still open and researchers may continue their studies to evaluate numerical factors influencing springback more effectively.

Lee and Yang showed that the blank element size and the number of corner elements are the most significant parameters influencing springback in U-bending [12]. Li presented a model for evaluating of springback in sheet metal forming processes based on the explicit finite element method and the orthogonal regression analysis [13]. With the aid of this method, he established the explicit relationship between the springback and some design parameters. Samual used a finite element program to analyse the effects of tool geometry and blank holder force on the final shape after springback in axisymmetric U-bending process [14]. Liu et al. improved dimensional accuracy and forming quality by using of variable blank holder force for 2D draw bending problems [15].

The purpose of this paper is to investigate the stamping of anisotropic plates in order to simulate the springback and side-wall curl in 2-D operation under plane strain conditions, numerically. A general finite element code, ELFEN [16], is used for the numerical simulation of stamping process. The modeling of the problem is performed by the explicit method for loading and by the combination of the implicit and explicit methods for unloading stage. The normal anisotropy behavior of material is taken into account. Some relevant parameters are examined within the framework of the present investigation. For instance, the effects of blank-holder force and friction coefficient on the final shape after springback are discussed.

2- The Basic Formulations of the Method

For dynamic equilibrium of a body in motion, irrespective of material behavior, the principle of virtual work is used to write the following equation at time station t_n [18],

$$\int_{\Omega}[\delta\varepsilon_n]^T\sigma_n d\Omega-\int_{\Omega}[\delta u_n]^T[b_n-\rho_n\ddot{u}_n-c_n\dot{u}_n]d\Omega-\int_{\Gamma_t}[\delta u_n]^T t_n d\Gamma=0\,, \tag{1}$$

where δu_n , $\delta\varepsilon_n$, b_n , t_n , σ_n , ρ_n , c_n denote the virtual displacements, associated virtual strains, applied body force, surface traction, stresses, mass density and damping parameter, respectively. The domain of interest Ω has two boundaries Γ_t and Γ_u to specify tractions t_n and displacements u_n, respectively. Based on the explicit dynamics integration and direct solution of equation or implicit form, there are two types of solver used by most FE codes. For explicit method, this equation can be written as follows,

$$M\ddot{u}_n+C\dot{u}_n+P(u_n)=F(t_n), \tag{2}$$

where u_n, $P(u_n)$ and $F(t_n)$ represent the displacement vector, the internal force contribution from the element stress field and the external force arising from the applied traction and contact condition at time t_n, respectively, where as M and C are the mass and damping matrices. The introduction of central difference approximation for the velocity and acceleration in terms of displacements, together with the use of mass lumping procedure and the assumption of mass proportional damping, leads to the following uncoupled recurrent relation

$$u_{n+1}^{I} = \left[M^{I}(1+\alpha\Delta t/2)\right]^{-1}\left\{\Delta t^{2}\left(F_{n}^{I} - P_{n}^{I}\right) + 2M^{I}u_{n}^{I} - M^{I}(1-\alpha\Delta t/2)u_{n-1}^{I}\right\}, \tag{3}$$

where α is the mass proportional damping coefficient. This expression permits the evaluation of displacement on an individual node based on inter-nodal coupling occurring through the calculation of the internal forces P_n.
In the implicit method, equation (1) can be written as follows,

$$k\Delta u = F_n - P_n, \tag{4}$$

$$u_{n+1} = u_n + (K_n)^{-1}(F_n - P_n) \tag{5}$$

where K_n is stiffness matrix at time t_n. Generally, the explicit solver is more suitable for simulation of sheet metal forming, because the computer time required to solve any industrial forming problem with implicit method is too large to be practical. In this study, the explicit method is used for loading and both implicit and explicit methods are used for springback simulation.

3- Description of Material Behaviour and Mechanical Modeling

The effective stress-strain relation is given in the following form:

$$\sigma = K\left(\varepsilon_0 + \varepsilon_p\right)^n \tag{6}$$

where σ, K, ε_0, ε_P and n are the effective stress, strength coefficient, a constant value, plastic strain and strain-hardening exponent, respectively.
The sheet material is assumed to have planar isotropic characteristic. The normal anisotropy of the sheet can be represented by a single parameter r, which is defined as

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{7}$$

where w and t refer to the width and thickness of strip, respectively. An average value of r is

$$R = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{8}$$

where r_0, r_{45} and r_{90} denote the value of r at 0^o, 45^o and 90^o with respect to the rolling direction of the sheet, respectively. In this problem, it is assumed that the material is orthotropic along the thickness with using Hill material model [18]. Thus,

$$\begin{aligned} &\sigma_{11} = \sigma_{22} = \sigma_Y, \\ &\sigma_{33} = \sigma_Y\sqrt{\frac{1+R}{2}}, \\ &\sigma_{12} = \sigma_{13} = \sigma_{23} = \frac{\sigma_Y}{\sqrt{3}}, \end{aligned} \tag{9}$$

where σ_y is the reference or uniaxial yield stress. Directions 1, 2 and 3 are related to the length, width and thickness of blank, respectively. The values of the material parameters adopted in the computation are E = 206000 N/mm^2, ν = 0.3, ρ = 7.8E-8 kg/mm^3, σ_Y = 261.6 N/mm^2, K= 680.61 N/mm^2, n = 0.2182, ε_0 = 0.0125 and R= 1.66. The thickness of plate was taken as t = 2mm and the friction coefficient for all contact surfaces was employed as $\mu = 0.129$. The dimensions of the blank holder and the punch assumed to be height = 100mm, 100mm, length = 35mm, 50mm and width = 25mm, 25mm, respectively. The blank holder, die and punch have the same Young's modulus, Poisson's ratio and Density. A schematic diagram of the U-bending process is shown in Fig. 1 and the parameters used for characterizing the springback, i.e. angle θ_1 and θ_2 are displayed in Fig. 2. The node C is located on the side-wall of the unloaded deformed sheet and shows the position that the direction of curvature of the side-wall is changed.

4- Results and Discussion

Figure 3 displays the effect of the blank holder force on the angles θ_1 and θ_2. It is found from these results that the holder force affects on the springback considerably. At the beginning and for the lower values of the blank holder forces, i.e. less than 2.4 KN, the springback becomes larger when the holder force increases. When the blank holder force goes further, however, i.e. more than 2.4 KN, the springback reduces. Figure 4 demonstrates the influence of friction coefficient between the workpiece and contact surfaces on the amount of springback. It is observed from this figure that when the friction rises to certain values more springback is produced. However, when the coefficient of friction goes beyond those values, for instance 0.15, springback does not reduce significantly. Hence, it can be concluded here that the alteration of friction between the sheet and the other contact surfaces is not a practical way to decrease the springback and cannot be highly recommended. The current results in both figures 3 and 4 have been compared with those of Papeleux and Ponthot [19]. It has to be mentioned, however, that the results of Ref [19] have been achieved using different conditions such as thickness of sheet = 0.74mm (2 mm in our case), length of blank holder length = 55 mm (35 mm in our case) and the average value of normal anisotropy of the sheet (R) = 1.75 (1.66 in our case).Therefore, as may be seen from the figures, although the trend of variations in both results are similar but some differences in their quantities can be observed that may be attributed to those mentioned dissimilarities.

The mechanism of springback variation may be explained more clearly as follow. At some parts of the plate, the bending and membrane stresses act in the different directions, i.e. compressive and tensile. However, when the blank holder force is increased, the development of the plastic zone produced by tensile bending moment and membrane force will have the dominant effects on plastic strain development and, in turn, on the springback. For instance, to observe the influence of holder force on springback more accurately, two different levels of forces, i.e. the high load = 19.6 KN and the low load = 2.45 KN, may be reconsidered, Fig. 5. This figure shows the effective strain at the bottom of the sheet and the parameter “distance” refers to the remoteness of a node from the center line of the workpiece. It is demonstrated that generally with the more blank holder force, more effective strain will be obtained in the side-wall of the sheet. However, between the 83mm and 98mm (around the top corner area) different trend can be seen. For this case, it may be easily attributed to the mechanism of sheet bending-drawing. While using upper load level of blank holder force, more stretching appears in the side-wall area and also at the bottom of sheet at the base corner. Where as, at the bottom of top corner area still the bending effect is dominant. Therefore, increasing of holder force that produces positive tangential stress reduces the plastic zone locally in that area and it causes more springback.

5- Conclusions

In this study, the U-bending process of anisotropic sheets has been studied numerically. It is found that the blank holder force can play an important role in reducing the springback and side-wall curl if it can be adjusted properly. However, the effect of friction coefficient to control the springback is not so significant.

6- Acknowledgment

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References

[1] Taylor, L., Cao, J., Karafillis, A.P., and Boyce, M.C., "Numerical Simulations of Sheet-Metal Forming," Journal of Materials Processing and Technology, Vol. 50, pp.168-179 (1995).

[2] Mattiasson, K., Strange, A., Thilderkvist, P., and Samuelsson, A., "A Simulation of Springback in Sheet Metal Forming," Proceedings of NUMIFORM 95, pp. 115-124 (1995).

[3] Pourboghrat, F., and Chu, E.,"Springback in Plane Strain Stretch/draw Sheet Forming," International Journal of Mechanical Sciences, Vol. 37(3), pp. 327-341 (1995).

[4] Joannic, D., and Gelin, J.C., "Accurate Simulation of Springback in 3D Sheet Metal Forming Processes", Proceedings of NUMIFORM 95, pp. 729-740 (1995).

[5] Pourboghrat, F., and Chu, E., "Prediction of Springback and Side-Wall Curl in 2-D Draw Bending," Journal of Materials Processing and Technology, Vol. 50, pp. 361-374 (1995).

[6] Apostolos, P., Karafillis, M., and Boyce, C., "Tooling and Binder Design for Sheet Metal Forming Processes Compensating Springback Error," International Journal of Machine Tools and Manufacture, Vol. 36(4), pp. 503-526 (1996).

[7] Zhou, D., Sriram, S., Jinka, A., and Wagoner R.H., "Bending and Springback Using Membrane Elements," Engineering Systems Design and Analysis, New York, ASME Vol. 3, pp. 135-142 (1996).

[8] Leu,, D.K., "A Simplified Approach for Evaluating Bendability and Springback in Plastic Bending of Anisotropic Sheet Metals," Journal of Materials Processing and Technology, Vol. 66, pp. 9-17 (1997).

[9] Pourboghrat, F., Chung, K., and Richmond, O., "A Hybrid Membrane/Shell Method for Rapid Estimation of Springback in Anisotropic Sheet Metals," Journal of Applied Mechanics, Vol. 65, pp. 671-684 (1998).

[10] Pourboghrat, F., Karabin, M., Becker, R., and Chung, K., "A Hybrid Membrane/Shell Method for Calculating Springback of Anisotropic Sheet Metals Undergoing Axisymmetric Loading," International Journal of Plasticity, Vol. 16, pp. 677-700 (2000).

[11] Siriram, S., and Wagoner, R.H., "Adding Bending Stiffness to 3-D Membrane FEM Programs," International Journal of Mechanical Sciences, Vol. 42, pp.1753-1782 (2000).

[12] Lee, S.W., and Yang, D.Y., "An Assessment of Numerical Parameters Influencing Springback in Explicit Finite Element Analysis of Sheet Metal Forming Process," Journal of Materials Processing and Technology, Vol. 80, pp. 60-67 (1998).

[13] Li, G.Y., Tan, M.J., and Liews, K.M.," Springback Analysis for Sheet Forming Processes by Explicit Finite Element Method in Conjunction with the Orthogonal Regression Analysis," International Journal of Solids and Structures, Vol. 36, pp. 4653-4668 (1999).

[14] Samuel, M., "Experimental and Numerical Prediction of Springback and Side-Wall Curl in U-bendings of Anisotropic Sheet Metals," Journal of Materials Processing and Technology, Vol. 105, pp. 382-393(2000).

[15] Liu, G., Lin, Z., Xu, W., and Bao, Y., "Variable Blank-Holder Force in U-shaped Part Forming for Eliminating Springback Error," Journal of Materials Processing and Technology, Vol. 120, pp. 259-264 (2002).

[16] ELFEN Level 3.0.3 Manual and Worked Examples, Rockfield Software Ltd., University of Wales Swansea, Swansea (1998).

[17] Hill, R., "The Mathematical Theory of Plasticity", The Oxford University Press, Oxford, London (1998).

[18] Owen, D.R., and Hinton, E., "Finite Element in Plasticity: Theory and Practice," Pineridge Press Limited, U.K. (1980).

[19] Papeleux L., and Ponthot, J.P., "Finite Element Simulation of Springback in Sheet Metal Forming," Journal of Materials Processing and Technology, Vols. 125-126, pp. 785-791 (2002).

Nomenclature

b_n	body force	P_n	internal force
C	damping matrix	r	normal anisotropy of the sheet
E	Young modulus	R	average value of r
F	internal force	t	thickness of strip
K	strength coefficient	t_n	surface traction
K_n	stiffness matrix	u	displacement vector
M	mass matrix	w	width of strip
n	strain-hardening exponent		

Greek symbols

α	damping coefficient	ν	Poisson's ratio
ε_p	plastic strain	ρ	material density
ε_0	a constant value	σ	effective stress
Γ	boundary of domain	σ_Y	uniaxial yield stress
μ	friction coefficient	Ω	domain

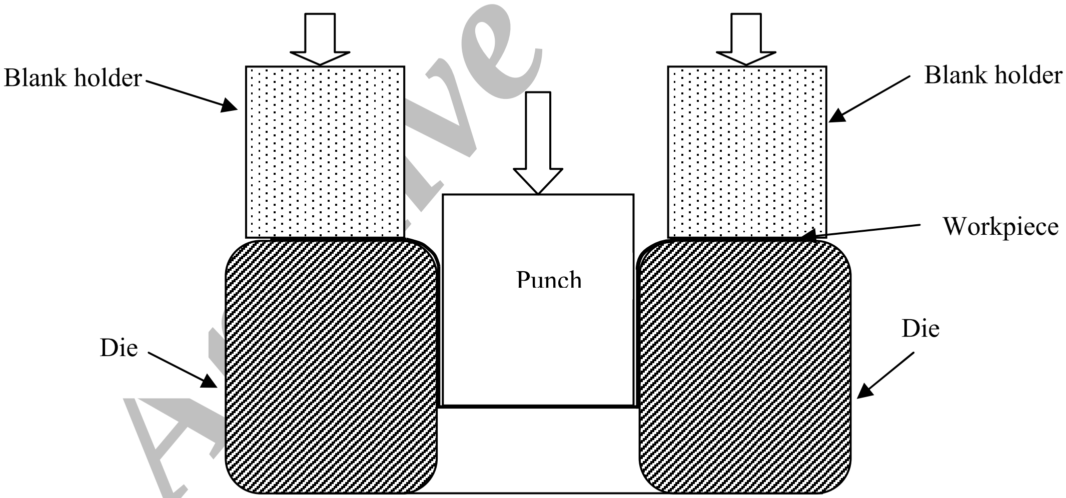

Figure 1 Schematic diagram for U-bending process

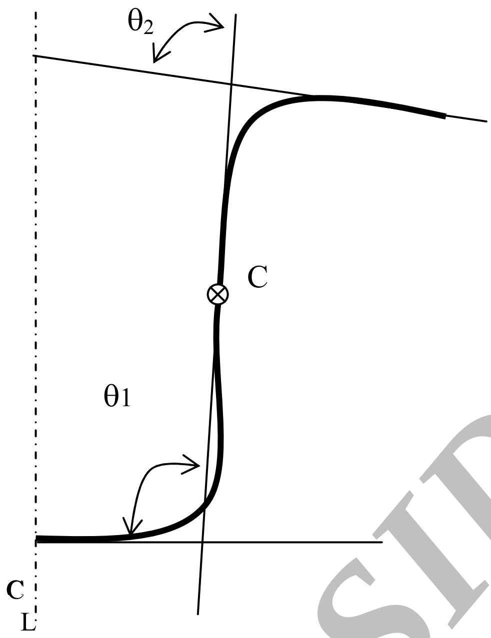

Figure 2 Schematic diagram for workpiece after unloading

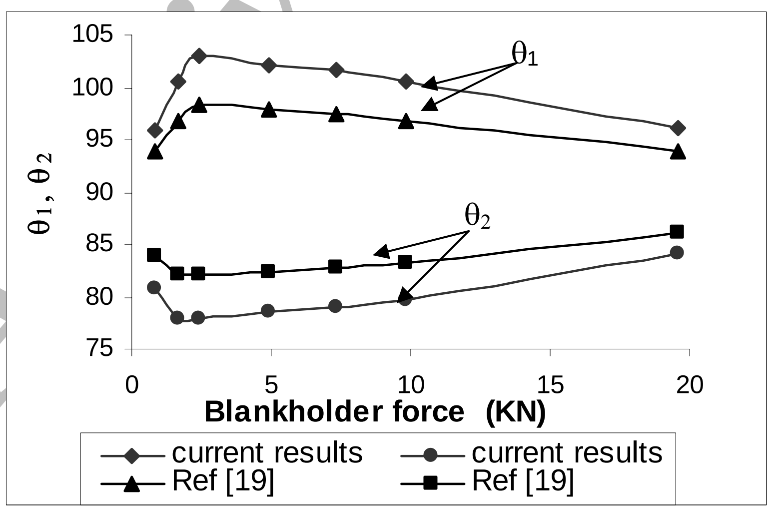

Figure 3 Effect of blank holder force on the final shape of workpiece

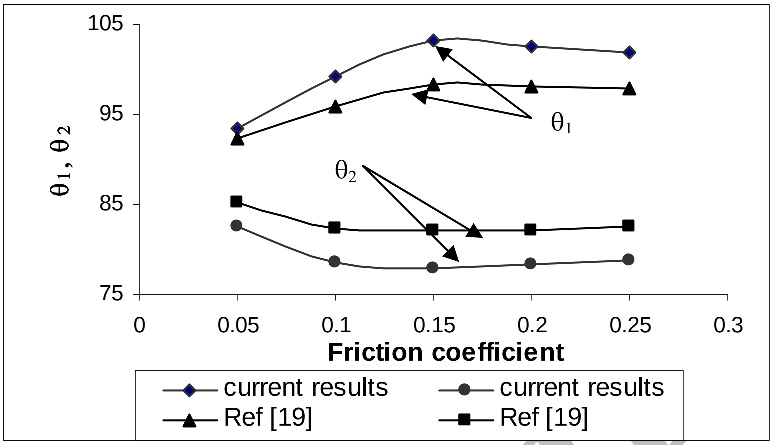

Figure 4 Effect of friction coefficient on the final shape of workpiece

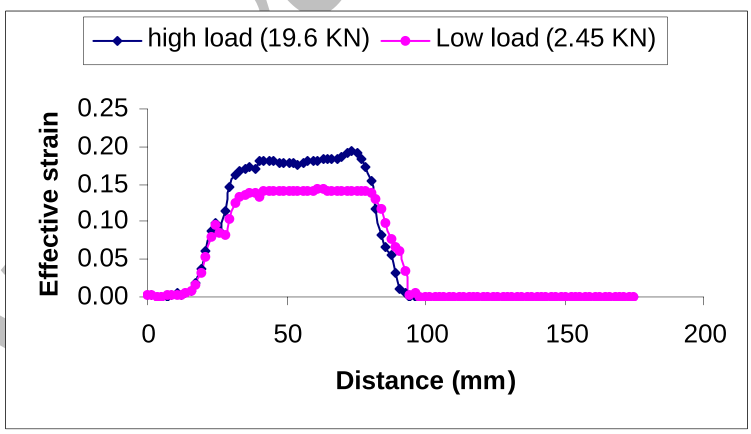

Figure 5 Variation of the effective strain at the bottom of sheet with the distance from the center line of the sheet

چکیده:

روش اجزای محدود ابزاری قوی در مدل سازی در صنعت شکل دهی صفحات نازک می باشد. به منظور کنترل فرآیند تولید، داشتن اطلاعات کافی در مورد میزان بازگشت فنری ضروری است. این مقاله به بازگشت فنری و چرخش دیواره در خمش همراه با کشش دو بعدی می پردازد. مواد به کار رفته غیر ایزوتروپیک فرض می شوند. یک کد اجزای محدود بنام ELFEN برای شبیه سازی عددی فرآیند بکار گرفته شده است. در مدلسازی مسئله از روش صریح در بخش بارگذاری و ترکیب روشهای صریح و ضمنی در بخش باربرداری استفاده شده است. پارامترهای گوناگونی در چهارچوب مقاله فعلی مورد بررسی قرار گرفته اند. بطور مثال، اثرات نیروی نگهدارنده و ضریب اصطکاک بطور دقیق مورد مطالعه قرار گرفته اند.