Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 8, 2008, No. 3

A NUMERICAL STUDY ON THE INFLUENCE OF BAUSCHINGER EFFECT ON SPRINGBACK IN REVERSE BENDING

MEHRAN KADKHODAYAN*, **IMAN ZAFARPARANDEH**

Department of Mechanical Engineering, Ferdowsi University of Mashhad,
91775-1111, Mashhad, Iran
**Corresponding Author: kadkhoda@um.ac.ir (M. Kadkhodayan)*

Abstract

It is essential to model the Bauschinger effect correctly for sheet metal forming process simulation and subsequent springback prediction when material points are subjected to cyclic loading conditions. For an accurate prediction of springback, the Bauschinger effect must be considered to determine accurately the internal stress distribution within the sheet metal after deformation. In this paper the influence of Bauschinger effect on springback in reverse bending process is investigated numerically. Simulations are preformed for two materials, AA6111-T4 and high strength steel (HSS), while considering three different values of die radiuses and clearances. The obtained results show that the influence of Bauschinger effect is much more significant for the aluminum alloy rather than the HSS. Three different hardening models are utilized and their influences on springback prediction are studied. The isotropic hardening model predicts the same maximum punch load for bending and reverse bending and estimates the required maximum punch load for the second stage nearly twice that of the first stage.

Key words: bauschinger effect, springback, reverse bending

1. INTRODUCTION

As a fundamental and traditional process in metallic forming technologies, sheet metal forming is widely being employed in almost all industrial fields. Needless to say, it is because a final sheet product of desired shape and appearance can be quickly and easily produced with relatively simple tool set (Lingbeek et al., 2005). One of the most widely used sheet metal forming process is bending. This is employed in automobile industry, construction of large spherical and cylindrical pressure vessels, curved structural components in aerospace industry, etc. Bending is a process in which a planar sheet is plastically deformed to a curved one (Panthi et al., 2007).

In the bending process, after removing the load by withdrawal of the punch, an elastic recovery occurs because of releasing the elastic stresses. This elastic recovery is called springback. Springback is an important and decisive parameter in obtaining the desired geometry of the part and design of the corresponding tooling. In manufacturing industry, it is still a practical problem to predict the final geometry of the part after springback and to design appropriate tooling in order to compensate for springback (Mattiasson et al., 1995; Xia et al., 1998). Conventional approaches, which involve using empirical formulae and several trial-and-error procedures, can result in wastage of material, time and efforts. In recent years, finite element analysis FEA has been considered as an effective way of simulating bending operations and predicting springback. FEA provides numerical trial and error procedures, which lead to a less-time-consuming and more economical way of

ISSN 1641-8581

designing and producing dies. In particular, some commercially available FEA codes provide effective and powerful tools and environments to model and simulate various operations such as metal-forming applications. These codes include useful and user-friendly graphical user interfaces, which facilitate pre- and post-processing stages. Also, as aluminum is a relatively expensive material, FEA is employed in the design stages in order to reduce material and production costs (Lee et al., 2005).

The springback prediction of bending operation using FEA has been employed by many researchers in the past. For instance, Cho et al. (2006) carried out numerical investigation on springback characteristics in plane strain 'U' bending process by thermo-elastoplastic FEA. Li et al. (2002) mainly dealt with material hardening and modulus to analyze 'V' bending and showed that the material-hardening model directly affects the springback simulation accuracy. Choudhry and Lee (1994) accounted inertial effects in the FEA of sheet metal forming process. Papeleux and Ponthot (2002) discussed numerically the effect of blank holder force, friction, spatial integration, etc. on the forming response. Chou and Hung (1999) carried out FEA of several springback reduction techniques such as over bending, stretching, arc bottoming, pinching die, spanking and movement (double bend) techniques used in 'U' channel bending. Math and Grizelj (2002) reported springback and residual stresses of bent plates, designed for assembling spherical tanks made of steel, using elastic–plastic incremental FE calculations and experimental validation. Lei et al. (2001) analyzed the free bending and square cup deep drawing to predict the springback, stress distribution, etc. for stainless steel using finite element method (FEM).

In a typical sheet metal forming practice, material points may experience cyclic loads; for example, bending–unbending on the die shoulder and reverse bending unbending at the punch. In this case, transient cyclic behavior of the material must be modeled properly for a realistic simulation of the sheet metal forming process and subsequent springback prediction. Prager (1949, 1956) and Ziegler (1959) initiated some fundamental frame-work for kinematic hardening rules. Major difference of two models comes from the moving direction of the center of the yield surface. Both linear kinematic hardening models can only provide rough approximations to the Bauschinger effect with a single constant hardening modulus. From the experimental observations, many authors (Drucker, Palgen, 1981; Dafalias, 1984; Lemaitre, Chaboche, 1990) concluded that the correct nonlinearity of stress–strain loop is important to describe the hardening behavior of metals under cyclic loading. Recently, nonlinear kinematic hardening models of Armstrong and Frederick (1996) type have gained some popularity. These models capture nonlinear hardening behavior and smooth transition from elastic to plastic deformation relatively well. However, they all have a common characteristic of generating reversal flow stress curves that saturate to the monotonic loading curve, thereby having difficulties to model a possible offset in flow stress when the load is reversed. Recent development and associated theories are well documented by Chaboche (1997), Lemaitre and Chaboche (1990), and Khan and Huang (1995).

The aim of this paper is to numerically study the influence of the Bauschinger effect on springback in the reverse L-bending process. Three different values of die radiuses, clearances and also hardening models are examined in the simulations.

2. FE SIMULATION

In this part, the computer simulation of the stamping process is conducted in two major steps. Firstly a forming analysis is conducted, including the blank and tooling, in order to determine the sheet metal deformation during the stamping process, and secondly the sheet metal springback deformations following the removal of the stamping tooling are computed using the forming stress distribution and the deformed geometry along with thickness distribution. There are some fundamental differences in the characteristics of both computation phases. The forming process is controlled by the time-dependent interactions of the blank and stamping tooling through a frictional contact-interface, and results in gross shape changes of the sheet metal. Consequently, the computational modeling of the forming process necessitates an incremental formulation due to the geometrically non-linear kinematics of sheet metal deformation involving large displacements, large rotations and finite plastic strains. On the other hand, the springback deformations of a typical stamping part are comparatively small compared to the sheet thickness, and are mainly caused by the unbalanced through-thickness stresses of the sheet once it is taken out of stamping tooling. With the progress of FE methods along with the computational hardware and software technologies, the explicit and implicit incremental formulations have been developed for the process modeling and analysis. The explicit dynamic and static incremental methods have found widespread use in the modeling and analysis of 3-D sheet metal forming due to its ability of better contact handling and relatively low computational cost when compared to the implicit static incremental method. In the forming analysis phase, an initially flat sheet is placed between the stamping die elements usually involving the die, punch and blankholder. It is common in sheet metal forming analysis to include only the surface of the tooling in the FE model, rather than the complete geometry, as rigid geometric entities.

The reverse L-bending process (Gau, Kinzel, 2001) as shown in figure 1 is a case study in this paper in order to investigate the influence of the Bauschinger effect on springback for two materials: AA6111-T4 and high strength steel (HSS). The materials basic properties are summarized in Table 1. To increase the computational efficiency, the simulation of the process is modeled in the finite element program ABAQUS\Explicit, while the springback analysis is simulated in ABAQUS\Standard as it would take a long time to obtain a quasi-static solution of springback analysis in ABAQUS\Explicit. The blank is modeled with a total of 300 shell elements (S4R) and 9 integration points through the thickness. For definition of contact in ABAQUS/ Explicit, the general contact algorithm was utilized. The Hill48 anisotropic yield function is utilized to consider the material anisotropy. Mass densities used for dynamic explicit code are 2.7 gr/cm^3 for the aluminum alloy and 7.8 gr/cm^3 for the high strength steel. The initial dimension of the sheet was 127 mm (length) × 25.4 mm (width) × 1.016mm (thickness) with the 70 mm total punch stroke. The contact between tools and the sheet blank is simulated as a frictionless choice in the FE code, while lubricant is used in experimental procedure. The punch velocity was speed up to 3 m/s in the dynamic explicit code.

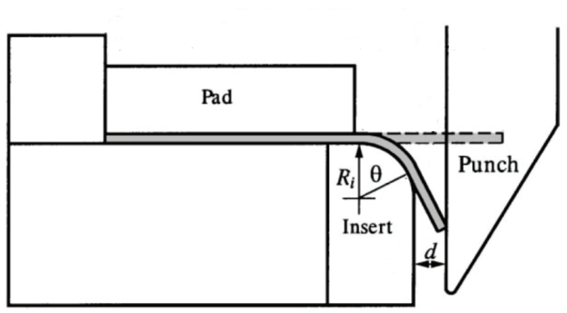


***Fig. 1.** Reverse bending process.*

***Table 1.** Basic materials' properties*

	AA6111-T4	HSS
Young's Modulus (GPa)	75.25	200
Poisson's ratio	0.33	0.3
Yield strength (MPa)	149.1	341
Ultimate tensile strength (MPa)	279.3	525

3. RESULTS AND DISCUSSIONS

The amount of parameter θ after unloading is the definition of springback for the bending process. The higher amount of θ means lower springback. Four steps are considered in the simulations: forward bending, springback (B), reverse bending and final springback (BR). In order to study the Bauschinger effect on springback in the reverse bending process for the two selected materials, the following three different cases are considered and compared with the reported experimental data:

- A: die radius is 12.7 mm and die clearance is 1.55mm
- B: die radius is 9.525 mm and die clearance is 1.35mm
- C: die radius is 4.7625 mm and die clearance is 1.1mm

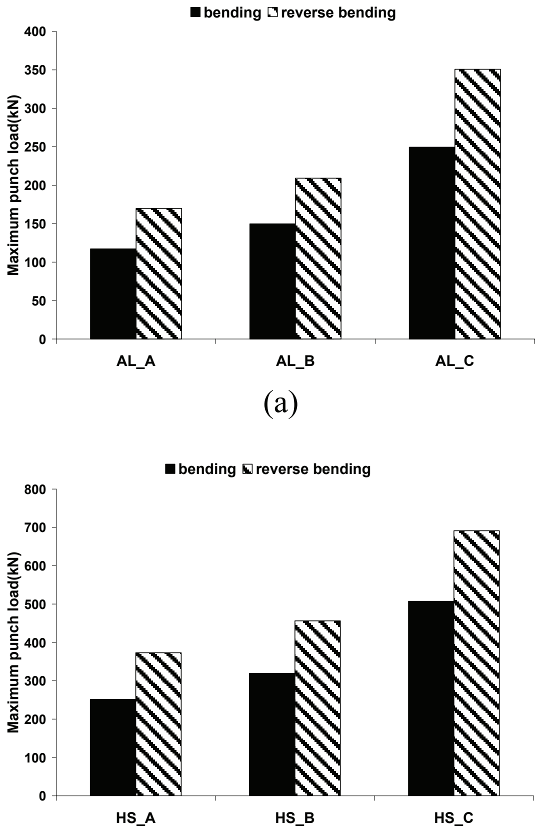
The results of springback are presented in Table 2 for AA6111-T4 and HSS.

***Table 2.** Springback results for the two materials*

	θ(°)			
	B		BR	
	Experiment Gau and Kinzel, 2001	Numerical	Experiment Gau and Kinzel, 2001	Numerical
AL_A	74.75	76.45	73.03	75.60
AL_B	77.41	78.40	76.09	77.87
AL_C	80.03	81.82	79.30	80.53
HS_A	75.04	78.64	75.60	78.85
HS_B	77.08	80.40	76.99	80.21
HS_C	79.90	83.04	79.86	83.05

It is found that, although the deformation pass is the same for both steps, springback results are not the same, especially for the aluminum alloy that may be attributed to the influence of Bauschinger effect. In fact, this effect causes the elements of blank deform easier because of having a lower yield point in the reverse process.

The amounts of maximum required punch loads for the different cases are shown in figure 2. Excluding the influence of Bauschinger effect, it could be expected that the required maximum punch load for the second stage be twice of that for the first stage because the second stage consists of both unbending and bending. However, the obtained results show that it is less than the expected value. In fact, the material encounters some softening during the second stage. For instance in the case A, the punch load becomes 1.45 and 1.48 times that the required load in the first step for AA6111-T4 and HSS, respectively.

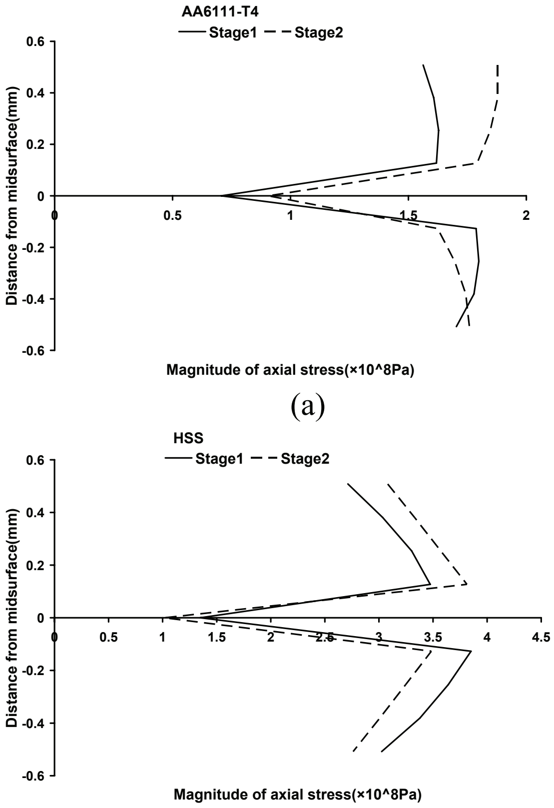


(a)

(b)

Fig. 2. The influence of Bauschinger effect on the amount of maximum punch load for the two stages of forming, (a) AA6111-T4 and (b) HSS.

The springback phenomenon depends basically on the through-thickness stress gradients (Oliveira et al., 2007). Figure 3 demonstrates the distribution of axial (longitudinal) stress through the blank thickness at the end of each stage. In order to understand the status of the element at the end of each stage the magnitude of stress is also presented. It may be clearly seen that the springback of aluminum alloy is affected more by the Bauschinger effect in stage two than the steel one. For instance, the stress gradient through the thickness changes significantly in the second stage for aluminum alloy while the HSS blank exhibit nearly the same stress gradient in both stages.



(a)

(b)

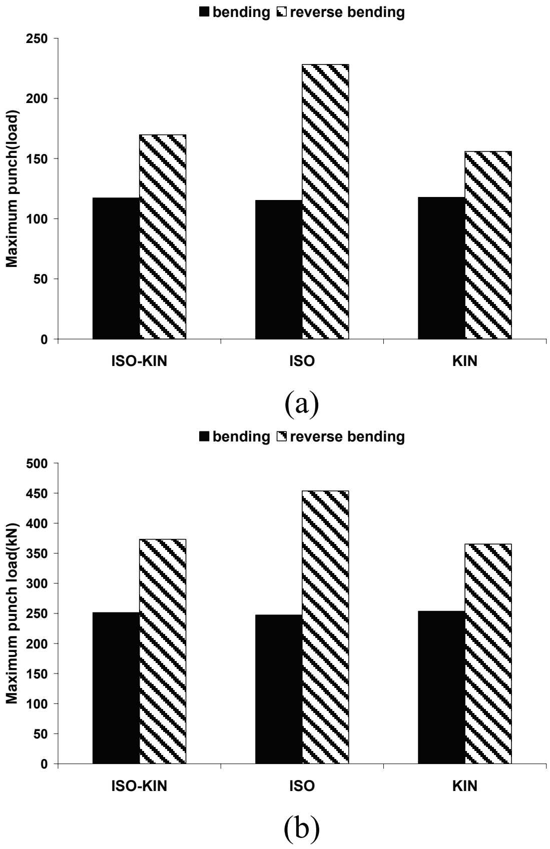
Fig. 3. Distribution of axial stress through the blank thickness at the end of both stage for elements located 80mm away from the left corner of the blank: (a) AA6111-T4 and (b) HSS.

In order to study the influence of hardening model on springback, three different models are utilized, ISO-KIN (based on the Lemaitre and Chaboche model), ISO (isotropic) and KIN (kinematic). In Table 3 the predicted results of springback by hardening models for AL_A and HS_A are summarized. As the isotropic hardening model does not consider the Bauschinger effect, springback results are close to each other especially for AA6111-T4 that suffers from the effect more significantly. The kinematic model predicts the change in springback more acceptable although it has been proposed for the materials with linear stress-strain curve.

Table 3. The results of springback predicted by different hardening models

	θ(°)			
	AL_A		HS_A	
	B	BR	B	BR
Exp. Gau and Kinzel, 2001	74.75	73.03	75.04	75.60
ISO-KIN	76.45	75.60	78.64	78.85
ISO	76.35	76.01	78.57	78.17
KIN	76.14	75.96	78.59	78.53

Figure 4 presents the results of maximum punch load for different hardening models and two materials. It is observed that the maximum punch load predicted by the isotropic model for the first stage is approximately twice the load for the second stage.



(a)

(b)

Fig. 4. *The influence of Bauschinger effect on the amount of maximum punch load for the two stages of forming predicted by the different hardening models, (a) AA6111-T4 and (b) HSS.*

4. CONCLUSIONS

The reverse bending process was utilized and the influence of Bauschinger effect on springback was investigated in detail. Different cases were considered for the values of die radiuses and clearances. Moreover, various hardening models were also examined in the simulations. It was observed that the results of springback for the aluminum alloy were more dependent to the Bauschinger effect whereas the high strength steel did not suffer from that effect significantly. The reduction of maximum punch load in the second stage was observed which was a direct result of Bauschinger effect. Investigating the distribution of axial stress through the blank thickness revealed that stress gradient changed considerably in the second stage for the aluminum alloy, although it was almost the same in both stages for HSS. As it was expected, the isotropic model predicted the required maximum punch load for the second stage nearly twice that of the first stage.

REFERENCES

Armstrong, P.J., Frederick, 1966, *A mathematical representation of the multiaxial Bauschinger effect*, G.E.G.B. Report RD/d/B/N.

Chaboche, J.L., 1977, Viscoplastic Constitutive equations for the description of cyclic and anisotropic behavior of metals, *Bull. de l'Acad. Polonaaise des Sciences*, Sevie Sc. et Techn.

Cho, J.R., Moon, S.J., Moon, Y.H., Kang, S.S., Finite element investigation on springback characteristics in sheet metal U-bending process, *J. Mat. Proc. Techn.*, 141, 109-116.

Chou, I.N., Hung, C., 1999, Finite element analysis and optimization on springback reduction, *Int. J. Machine Tools and Manufacturing*, 39, 517-536.

Choudhry, S., Lee, J.K., 1994, Dynamic plain-strain finite element simulation of industrial sheet-metal forming processes", *Int. J. Mech. Sci.*, 36, 189-207.

Dafalias, Y.F., 1984, *A modeling cyclic plasticity: simplicity versus sophistication, Mech. Engineering Materials*, Wiley, New York.

Drucker, D.C., Palgen, L., 1981, On stress-strain relations suitable for cyclic and other loadings, *J. Applied Mechanics*, 21, 173.

Lemaitre, J., Chaboche, J.-L., 1990, *Mechanics of solid materials*, Cambridge University Press, London.

Li, X., Yang, Y., Wang, Y., Bao, J., Li, S., 2002, Effect of material-hardening mode on the springback simulation accuracy of V-free bending, *J. Mat. Proc. Techn.*, 123 (2), 209-211.

Lingbeek, R., Huetink, J., Ohnimus, S., Petzoldt, M., Weiher, J., 2005, The development of a finite elements based springback compensation tool for sheet metal products, *J. Mat. Proc. Techn.*, 169, 115-125.

Gau, J.T., Kinzel, G.L., 2001, An experimental investigation of the influence of the Bauschinger effect on springback predictions, *J. Mat. Proc. Techn.*, 108, 369-375.

Khan, A.S., Huang, S., 1995, *Continuum theory of plasticity*, Wiley-Interscience, New York.

Lee, M.G., Kim, D., Kim, C., Wenner, M.L., Chung, K., 2005, Springback evaluation of automotive sheets based on isotropic-kinematic hardening laws and non-quadratic anisotropic yield functions, part III: applications, *Int. J. of Plasticity*, 21, 915-953.

Lei, L.P., Hwang, S.M., Kang, B.S., 2001, Finite element analysis and design in stainless steel sheet forming and its experimental comparison, *J. Mat. Proc. Techn.*, 110, 70-77.

Math, M., Grizelj, B., 2002, Finite element approach in the plate bending process, *J. Mat. Proc. Techn.*, 125-126, 778-784.

Mattiasson, K., Thilderkvist, P., Strange, A., Samuelsson, A., 1995, Simulation of springback in sheet metal forming, *Proc. Conf. NUMIFORM'95*, eds. Shen, S.F., Dawson, P., Ithaca, 115-124.

Oliveira, M.C., Alves, J.L., Chaparro, B.M., Menezes, L.F., 2007, Study on the influence of work-hardening modeling in springback prediction, *Int. J. of Plasticity*, 23, 516-543.

Panthi, S.K., Ramarishnan, N., Pathak, K.K., Chouhan, J.S., 2007, An analysis of springback in sheet metal bending using finite element method (FEM), *J. Mat. Proc. Techn.*, 186, 120-124.

Papeleux, L., Ponthot, J.P., 2002, Finite element simulation of springback in sheet metal forming, *J. Mat. Proc. Techn.*, 125-126, 785-791.

Prager, W., 1949, Recent developments in the mathematical theory of plasticity, *J. Applied Physics*, 20, 235.

Prager, W., 1956, A new method of analyzing stresses and strains in work-hardening plastic solids, *ASME J. Applied Mechanic Transactions*, 78, 493.

Xia, Z.C., Tang, S.C., Carnes, J.C., 1998, Accurate springback prediction with mixed solid/shell elements, *Proc. Conf. NUMIFORM'98*, eds., Huetink, J., Baaijens, F.P.T., Enschede, 813-818.

Ziegler, H., 1959, A modification on Prager's hardening rule, *Quart. Appl. Math.*, 17, 55.

NUMERYCZNA ANALIZA WPŁYWU EFEKTU BAUSCHINGERA NA SPRĘŻYSTY NAWRÓT PRZY CYKLICZNYM ZGINANIU

Streszczenie

Poprawne uwzględnienie efektu Bauschingera ma kluczowe znaczenie dla symulacji procesów tłoczenia i dla przewidywania występującego w tych procesach nawrotu sprężystego, szczególnie kiedy materiał jest poddawany cyklicznym obciążeniom. Dla dokładnego obliczenia wielkości nawrotu sprężystego, efekt Bauschingera musi być wzięty pod uwagę, ponieważ jest to niezbędne dla wyznaczenia rozkładu naprężeń wewnętrznych w odkształconej blasze. W niniejszej pracy badano metodami numerycznymi wpływ efektu Bauschingera na wielkość nawrotu sprężystego przy cyklicznym zginaniu próbki. Symulacje zostały wykonane dla dwóch materiałów, AA6111-T4 i stali o podwyższonej wytrzymałości (HSS). Rozważono trzy różne wielkości promienia matrycy i prześwitu. Uzyskane wyniki wykazują, że wpływ efektu Bauschingera jest znacznie większy dla aluminium niż dla stali HSS. W obliczeniach zastosowano trzy różne modele umocnienia materiału i badano ich wpływ na przewidywanie nawrotu sprężystego. Model umocnienia izotropowego przewiduje takie samo maksymalne obciążenie stempla przy zginaniu i przy odginaniu oraz przewiduje niemal dwukrotnie większe maksymalne obciążenie w drugim cyklu zginania.

Submitted: March 31, 2008
Submitted in a revised form: June 9, 2008
Accepted: June 14, 2008