JAST, Vol. 5, No. 1, pp 45–50

JAST Journal of Aerospace Science and Technology

RESEARCH NOTE

U-Bending Analysis with an Emphasis on Influence of Hardening Models

M. Kadkhodayan[1], I. Zafarparandeh[2]

In this paper, the effect of different hardening models on simulating the U-bending process for AA5754-O and DP-Steel, taking a benchmark of NUMISHEET'93 2-D draw bending, has been discussed. The hardening models considered in simulations are: isotropic hardening, pure (linear) kinematic hardening and combined (nonlinear kinematic) hardening. The influence of hardening models on predicting springback and final state variables such as equivalent plastic strain, sheet thickness and punch force has been studied. The combined hardening model predicted the springback parameters well, while the isotropic hardening over-predicted the springback. The results of springback prediction have been compared with the results reported in the literature. A relation between the level of the final equivalent plastic strain and the amount of springback has been found. The obtained results show that attaining a higher amount of equivalent plastic strain in the sheet leads to less springback after unloading. Comparison between the two materials demonstrates that the aluminum alloy requires lower punch force which means superior formability and exhibit smaller springback.

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 a relatively simple tool set [1]. One of the most widely used sheet metal forming processes is bending, which 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 [2]. The precision in dimension is a major concern in sheet metal bending process because of the considerable elastic recovery during the unloading process which might lead to springback. The springback is normally measured in terms of change in radius of curvature due to elastic recovery. Elastic recovery is influenced by a combination of various process parameters such as tool shape and dimension, contact friction condition, material properties, thickness, etc. [3]. Ragai *et.al.* [4] investigated the effect of sheet anisotropy on the springback of stainless steel 410 draw-bend specimens experimentally as well as through finite element simulations. Moreover, they studied the influence of blankholder force and coefficient friction on the amount of the final springback.

In recent years, the rapid development of computer technologies enables numerical simulation of sheet metal forming operations by employing finite element codes in an industrial environment. The springback prediction of bending operation using FEA has been employed by many researchers in the past. For instance, Cho *et.al.* [5] carried out numerical investigation on springback characteristics in the plane strain 'U' bending process by thermo-elastoplastic FEA. Li *et.al.* [6] mainly dealt with material hardening and modulus to analyze 'V' bending by simulation and showed that the material-hardening model directly affects the springback simulation accuracy. Choudhry and Lee [7] considered inertial effects in the FEA of sheet metal forming process. Papeleux and Ponthot

1. *Associate Professor, Dept. of Mech. Eng., Ferdowsi Univ., Mashhad, Iran, Email: kadkhoda@um.ac.ir.*
2. *MSc Graduate, Dept. of Mech. Eng., Ferdowsi Univ., Mashhad, Iran.*

[8] discussed numerically the effect of blank holder force, friction, spatial integration, etc. on the forming response. Chou and Hung [9] 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 [10] 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. [11] analyzed the free bending and square cup deep drawing to predict the springback, stress distribution, etc. for stainless steel using finite element method (FEM).

To obtain accurate numerical solutions, mechanical models implemented in FEA should use reliable descriptions of materials' elastoplastic behavior, namely a description of anisotropy and work hardening behaviors. Thus, more sophisticated constitutive models, which take into account non-linear kinematic hardening and more complex internal state variables are expected to allow an improvement in the accuracy of the sheet metal forming simulation. The Bauschinger effect is not present in an isotropic hardening; thus, when the material undergoes reverse loading, inaccurate springback is predicted. The linear kinematic hardening proposed by Prager [12] and Ziegler [13] can only be applied into materials with linear stress-strain curve and it usually under-estimates the springback. A non-linear kinematic hardening rule was first used by Armstrong and Frederick [14]. The non-linear kinematic hardening rule presented by Lemaitre and Chaboche [15] introduced a recall term to realize the smooth elastic-plastic transition upon the change of loading path.

In this paper, the influence of different hardening models in simulating the U-bending process by utilizing the finite element code, ABAQUS 6.5 [16], has been investigated. Using different hardening models, several internal state variables such as final sheet thickness, equivalent plastic strain, punch force etc. have been studied. Also, the springback prediction through different hardening models has been explored and verified with the experimental results in literature [17].

FINITE ELEMENT SIMULATION

Computer simulation of the stamping process is conducted in two major steps. In order to determine the sheet metal deformation during the stamping process, first, a forming analysis is conducted, including the blank and tooling, and secondly, the sheet metal springback deformations following the removal of the stamping tooling are computed. There are some fundamental differences in the characteristics of both computation phases. The forming process is controlled

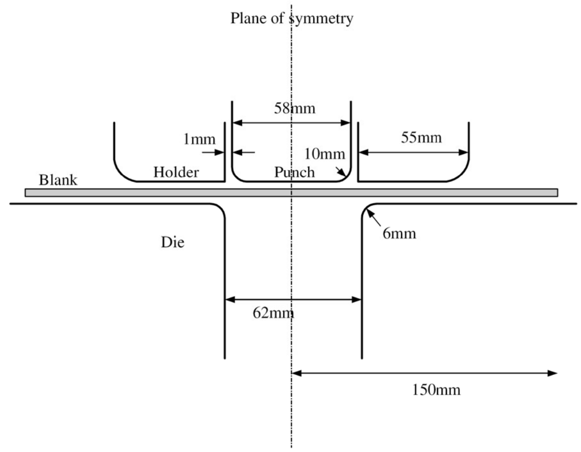

Figure 1. The U-bending process.

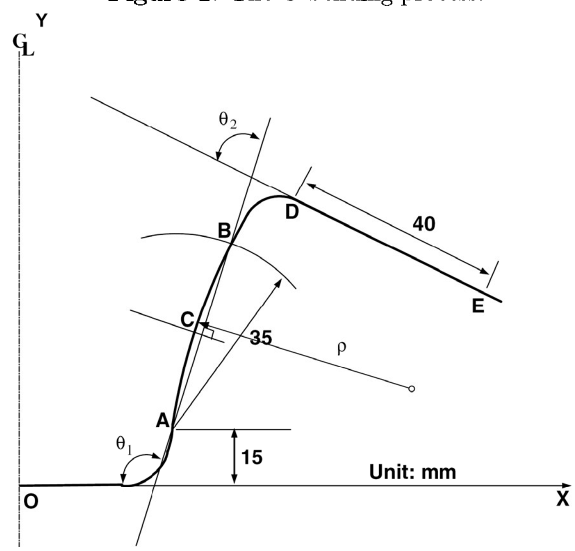

Figure 2. Parameters for springback in the U-bending process.

by the time-dependent interactions of the blank and stamping tooling through a frictional contact-interface which 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 small, compared to the sheet thickness. These deformations 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 to better handle contact as well as its relatively low computational cost 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 2D drawing bending problem in NUMISHEET'93 as shown in Figure 1 is a case studied in this paper for two materials: AA5754-O and DP-Steel [17]. The materials basic properties are summarized in Table 1. For efficiency, the simulation of the U-bending 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. Half of the blank is modeled with a total of 800 shell elements (S4R) and 9 integration points through the thickness which is suggested for the bending process in the literature [16-19], with the symmetry boundary conditions. For definition of contact in ABAQUS/Explicit, the general contact algorithm was utilized. The Hill48 [20] 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 [17]. The initial dimension of the sheet was 300 mm (length) $\times$ 35 mm (width) with the 70 mm total punch stroke for two test materials. To verify the results of the springback, the blankholder force was considered to be 25 KN as used in reference [17]. The friction coefficient between tools and the sheet blank was assumed to be constant and equal to 0.1. The punch velocity was speeded up to 10 m/s in the dynamic explicit code without mass scaling and resulted in very small oscillations in the kinetic energy, which is acceptable for a quasi static process. The springback parameters θ_1 and θ_2 studied by this benchmark are shown in Figure 2.

RESULTS AND DISCUSSIONS

Three hardening models are considered in the simulations: the combined isotropic-kinematic based on the Lemaitre and Chaboche work [15] (ISO-KIN), the pure isotropic (ISO), and the pure kinematic (KIN). Figure 3 shows a sample point and the path 1 which are used in the following parts of the paper to compare the results of different parameters. Path 1 and sample point are located at the bottom edge of the sheet.

Table 1. Basic materials properties [17].

	AA5754-O	DP-Steel
Thickness (mm)	1.5	1.2
Young's Modulus (GPa)	73.25	205.35
Poisson's ratio	0.3	0.3
Yield strength (0.2% offset) (MPa)	102.4	358.7
Ultimate tensile strength (MPa)	234.2	570.9

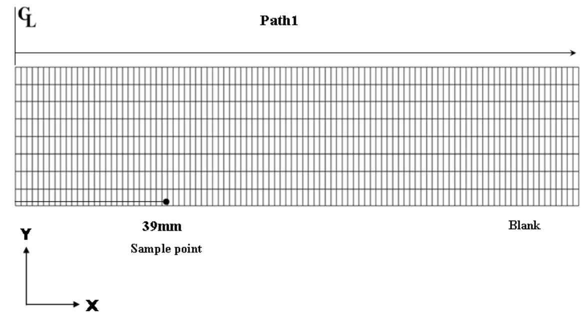

Figure 3. Meshed blank.

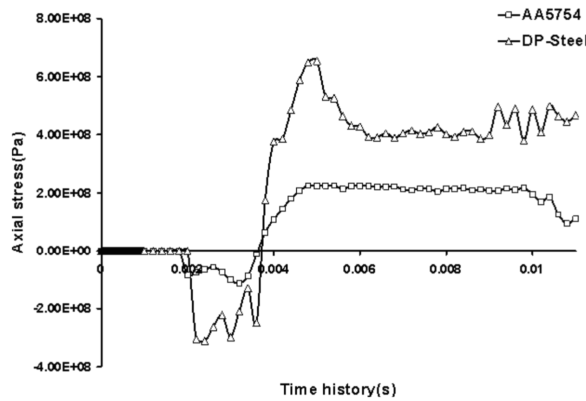

Figure 4. Axial stress for the sample point.

Axial Stress

History of the axial stress in the U-bending process during deformation indicates the status of loading in the elements of the material, *i.e.*, whether the material undergoes any reversal loading or not. Consequently, when the reversal loading occurs in the process, the hardening model type used in the finite element simulation of the process becomes important and should be taken into account. Figure 4 displays the axial stress for the sample point defined in Figure 2, and compares this state variable for the two test materials. It is to be pointed out here that the axial stress is considerably larger than the other stress components, and is almost near the effective stress level; thus, its variation may help us to estimate the condition of the loading. As can be observed in the figure, the element is initially subjected to compression when it slides over the die shoulder. Finally, after passing over the die shoulder, the element undergoes tension, where the stretching is dominant. Comparing the two test materials reveals that the aluminum alloy experiences a smaller amount of axial stress in both compression and tension than the steel. Another important conclusion that can be understood from the figure is that there are several points in the sheet which undergo reversal loading during the process; therefore, hardening models should be considered important and effective during simulation of the U-bending process.

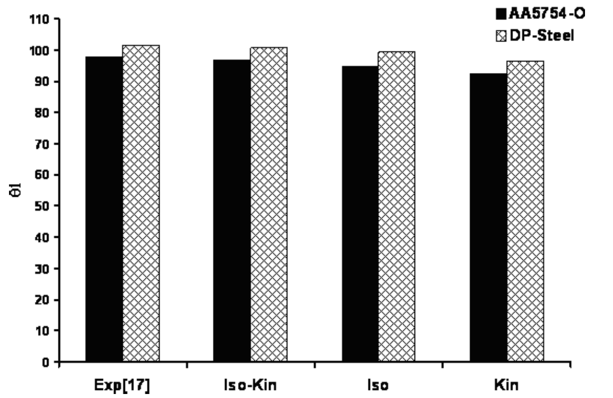

Figure 5. Springback parameter θ_1 predicted by different hardening models for the two test materials.

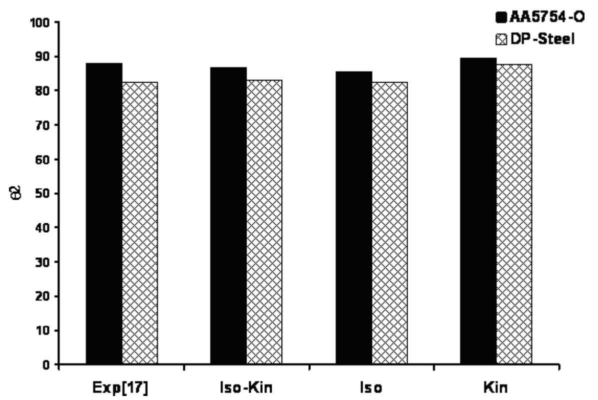

Figure 6. Springback parameter θ_2 predicted by different hardening models for the two test materials.

Springback

An important aspect of constitutive models in dealing with the large plastic deformation is the evolution of yield surface or the hardening behavior. The most commonly used rule is the so-called isotropic hardening, where the yield surface is expanding uniformly in all directions. It works reasonably well under continuous plastic loading, but suffers when dealing with reverse loading since it has no mechanism to capture the Bauschinger effect. One of the simplest models which is able to simulate the Bauschinger effect is the linear kinematic hardening model, where the size of the yield surface doesn't change; rather it is being pushed around in the stress space. The reality should lie somewhere in between. Several more elegant models have been developed, trying to remedy the shortcomings of both models (Mroz [21]; Mroz [22]; Chaboche [23]; and Lemaitre & Chaboche [15]). As there are several points in the lower layer of the sheet that experience reverse loading during the process, it is expected that the isotropic hardening may not predict the springback correctly. The results for the parameter θ_1 and θ_2 are presented and compared for the two test materials in Figure 5 and 6, respectively. A larger amount for θ_1 or smaller amount for θ_2 indicates a larger springback. For both test materials, the combined hardening (ISO-KIN) has predicted the springback properly. However, the isotropic hardening has over-estimated the springback, but the difference between the results of these two models is not significant because there is not any obvious reverse forming in the process. For instance, only the points located at the bottom of the sheet undergo reversal loading. The results obtained from the linear kinematic hardening model highly differ from the results of the other models. It should be emphasized that linear kinematic hardening has been suggested for materials with linear stress-strain curve, and is not advisable for other materials. Comparing the results of the two test materials shows that the aluminum alloy displays the smaller springback than the steel.

Equivalent Plastic Strain

The equivalent plastic strain has an important role in definition of constitutive equations of metal plasticity such as hardening models. The equivalent plastic strain is defined as:

$$\bar{\varepsilon}^{pl} = \sqrt{\varepsilon_{ij}^{pl}\varepsilon_{ij}^{pl}} \quad (1)$$

Figure 7 shows the equivalent plastic strain predicted by the hardening models and evaluated along the path 1 for the aluminum alloy. As it is observed, the level of the equivalent plastic strain predicted by the combined hardening is between two other hardening models. Moreover, the isotropic hardening model has predicted the lowest level of equivalent plastic strain. As can be understood from Figure 5 and 6, the higher the amount of equivalent plastic strain predicted by the hardening model, the smaller the amount of the springback. Figure 8 illustrates the level of the equivalent plastic strain along the path 1 for the two test materials. The aluminum alloy that has a smaller Young's modulus achieves a higher

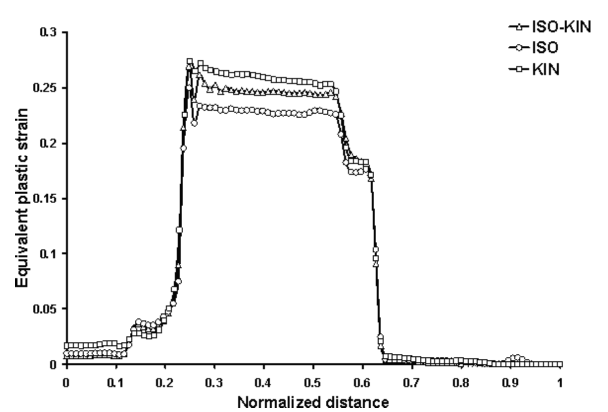

Figure 7. Equivalent plastic strain distribution along the path 1 predicted by different hardening models for AA5754-O.

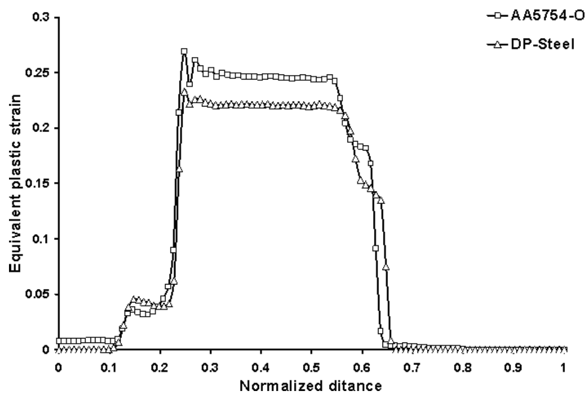

Figure 8. Equivalent plastic strain distribution along the path1 for the two test materials.

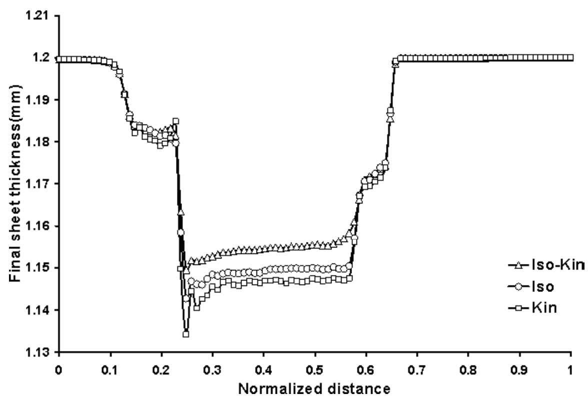

Figure 9. Final sheet thickness distribution along the path1 for DP-Steel.

level of equivalent plastic strain. Comparing the final amount of springback results for the considered materials reveals that the material with the higher level of the equivalent plastic strain leads to smaller amount of springback.

Sheet Thickness

The accuracy and fitness of the design of the final sheet thickness in aerospace and automotive industries is of vital importance in order to have complete confidence in the assembly of the final parts and to prevent common defects such as localized necking and tearing in the formed sheet. In Figure 9 the thickness distribution along the path1 at the end of the forming stage predicted by different hardening models for DP-Steel is presented. Combined hardening has predicted the smaller change, and the isotropic hardening has predicted the bigger change in the sheet thickness.

Punch force

The type of material is an effective factor that may affect the final amount of springback. Therefore, designers should be careful in choosing the appropriate material and optimizing the other factors in order to reduce the final springback. A comparison of the required punch forces for the two test materials is shown in Figure 10. The U-bending of DP-Steel need a higher amount of maximum punch force because of having larger yielding strength in contrast to AA5754-O. It also leads to higher springback. This confirms one of the advantages of utilizing aluminum alloys in aerospace and automobile industries in addition to their lower weight. In Figure 11 the maximum punch forces predicted by different hardening models for the two test materials are shown. The isotropic hardening has predicted the largest punch force whereas the kinematic hardening has predicted the smallest one. For instance, as the isotropic hardening does not consider the Bauschinger effect, and there are several points in the sheet that undergo reversal loading, this hardening model over-estimates the maximum punch force.

CONCLUSIONS

In this paper, the U-bending process has been studied based on a specific emphasis on the hardening models. The springback occurring in the sheet after unloading was investigated in detail. The relationship between the hardening models, springback and final state variables such as equivalent plastic strain and sheet thickness was explored. It was found that the amount of final equivalent plastic strain had an effective role on determining the amount of springback, the higher the level of equivalent plastic strain, the

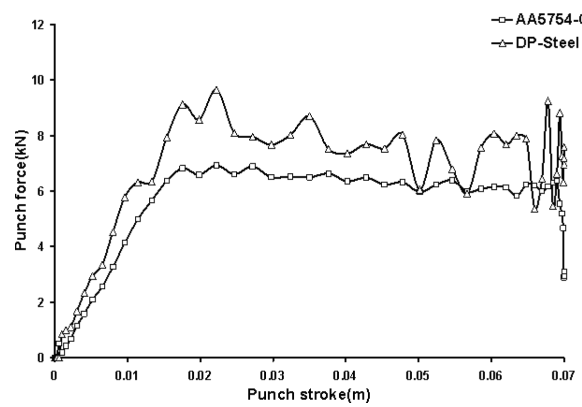

Figure 10. Punch force for the two test materials.

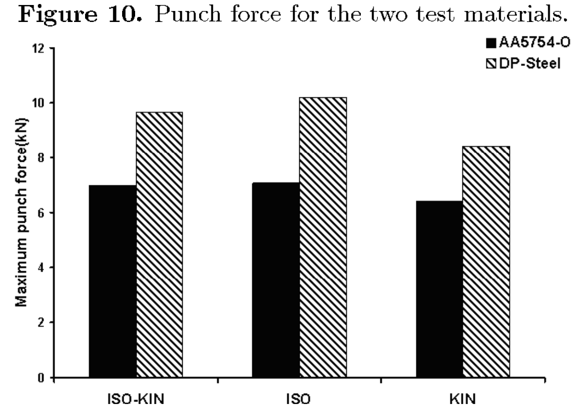

Figure 11. Maximum punch force predicted by different hardening models for the two test materials.

lower the springback. Hence, in order to compensate for the springback, the effective parameters such as blankholder force should be chosen deliberately, which lead to higher levels of equivalent plastic strain at the end of the process. Furthermore, comparing the level of equivalent plastic strain predicted by different hardening models demonstrates that higher levels of equivalent plastic strain lead to lower levels of final sheet thickness as well as higher levels of punch force. It was also found that the aluminum alloy required smaller maximum punch force and exhibited smaller springback after unloading.

REFERENCES

1. Lingbeek R., Huetink J., Ohnimus S., Petzoldt M., Weiher J., "The Development of a Finite Element Based on Springback Compensation Tool for Sheet Metal Products", *Journal of Materials Processing Technology*, **169**, PP 115-125(2005).
2. Panthi S. K., Ramarishnan N., Pathak K. K., Chouhan J. S., "An Analysis of Springback in Sheet Metal Bending Using Finite Element Method (FEM)", *Journal of Materials Processing Technology*, **186**, PP 120-124(2007).
3. Esat V., Darendeliler H., Gokler M. I., "Finite Element Analysis of Springback in Bending of Aluminum Sheets", *Journal of Materials and Design*, **23**, PP 223-229(2002).
4. Ragai I., Lazim D., Nemes J. A., "Anisotropy and Springback in Draw-Bending of Stainless 410: Experimental and Numerical Study", *Journal of Materials Processing Technology*, **166**, PP 116-127(2005).
5. Cho J. R., Moon S. J., Moon Y. H., Kang S. S., "Finite Element Investigation on Springback Characteristics in Sheet Metal U-Bending Process", *Journal of Materials Processing Technology*, **141**, PP 109-116(2003).
6. Li X., Yang Y., Wang Y., Bao J., Li S., "Effect of Material-Hardening Mode on the Springback Simulation Accuracy of V-Free Bending", *Journal of Materials Processing Technology*, **123**, PP 209-211(2002).
7. Choudhry S., Lee J. K., "Dynamic Plain-Strain Finite Element Simulation of Industrial Sheet-Metal Forming Processes", *International Journal of Mechanical Sciences*, **36**, PP 189-207(1994).
8. Papeleux L., Panthot J. P., "Finite Element Simulation of Springback in Sheet Metal Forming", *Journal of Materials Processing Technology*, **125-126**, PP 785-791(2002).
9. Chou I. N., Hung C., "Finite Element Analysis and Optimization on Springback Reduction", *International Journal of Machine Tools and Manufacturing*, **39**, PP 517-536(1999).
10. Math M., Grizelj B., "Finite Element Approach in the Plate Bending Process", *Journal of Materials Processing Technology*, **125-126**, PP 778-784(2002).
11. Lei L.P., Hwang S.M., Kang B.S., "Finite Element Analysis and Design in Stainless Steel Sheet Forming and it's Experimental Comparison", *Journal of Materials Processing Technology*, **110**, PP 70-77(2001).
12. Prager W., "Recent Developments in the Mathematical Theory of Plasticity", *International Journal of Applied Mechanics*, PP 78-493(1956).
13. Ziegler H., "A Modification on Pragr's Hardening Rule", *Quarter of Applied Mathematic*, PP 17-55(1959).
14. Armstrong P.J., Frederick, "A Mathematical Representation of the Multiaxial Bauschinger Effect", *G.E.G.B. Report RD/d/B/N*, (1966).
15. Lemaitre J., Chaboche J.-L., *Mechanics of Solid Materials*, Cambridge University Press, PP 161-241(1990).
16. Hibbit, Karlsson & Sorensen, "ABAQUS/Standard User's Manual, Version 6.5", (2003).
17. Lee M. G., Kim D., Kim C., Wenner M. L., Chung K., "Springback Evaluation of Automotive Sheets Based on Isotropic-Kinematic Hardening Laws and Non-Quadratic Anisotropic Yield Functions, Part III: Applications", *International Journal of Plasticity*, **21**, PP 915-953(2005).
18. Jiang W., "Study of Two-Surface Plasticity Theory", *Journal of Engineering Mechanic*, **120**, PP 2179-2200(1994).
19. Lee C., Cao J., "Shell Element Formulation of Multi-Step Inverse Analysis for Axisymmetric Deep Drawing Process", *International Journal of Numerical Methods in Engineering*, **50**, PP 681-706(2001).
20. Hill R., "A Theory of the Yielding and Plastic Flow of Anisotropic Metals", *Proc. Roy. Soc. Lond. A 193*, PP 281-297(1948).
21. Mroz Z., "On the Description of Anisotropic Work Hardening", *Journal of Mech. Phys. Solids*, **15**, PP 163(1967).
22. Mroz Z., "An Attempt to Describe the Behavior of Metals under Cyclic Loads Using a more General Work Hardening Model", *Acta. Mech.*, **7**, PP 199(1969).
23. Chaboche J. L., "Viscoplastic Constitutive Equation for the Description of Cyclic and Anisotropic Behavior of Metals", *Bulletin de L'Academie Polonaise des Sciences*, **25**, PP 33-41(1977).