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

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Abstract

In this paper the effect of different hardening models in 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 simulation of the process is modeled using the finite element code, ABAQUS 6.5. The influence of hardening models on predicting springback and final state variables such as equivalent plastic strain, sheet thickness etc. has been studied. 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.

Keywords: *U-bending - Finite element - Hardening models*

Introduction

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 planer sheet is plastically deformed to a curved one [1]. In this paper, the influence of different hardening models in simulating the U-bending process by utilizing the finite element code, ABAQUS 6.5 has been investigated.

Finite element simulation

The 2D drawing bending problem in NUMISHEET'93 as shown in Fig. 1 is a case studied in this paper for two materials: AA5754-O and DP-Steel [2]. 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.

Results and discussion

There are three hardening models considered in this paper: the combined isotropic-kinematic based on the Lemaitre and Chaboche work [3] (ISO-KIN), pure isotropic (ISO) and pure kinematic (KIN). Fig. 2 shows a sample point and the path1.

Axial stress

Axial stress shows the status of loading, meaning that whether the material undergoes reversal loading or not. Fig. 3 displays the axial stress for the sample point (Fig. 2). This figure demonstrates that some points maybe found in the model which undergo reversal loading during the process, thus, hardening models can be assumed as important parameters during simulating the bending process.

Springback

Fig. 4 shows the amount of the springback predicted by hardening models for two test materials. It may be concluded that aluminum alloy leads to lower amount of springback. Also, the combined hardening predicts the springback well.

Equivalent plastic strain

The equivalent plastic strain has an important role in constitutive equations of metal plasticity such as hardening models. Fig. 5 shows the equivalent plastic strain for the test materials evaluated for path1 (Fig. 2). Comparing to the Fig. 4, the higher level of the equivalent plastic strain results in lower amount of springback.

Sheet thickness

The accuracy and fitness with the design of the final sheet thickness in aerospace and automotive industries is of vital importance due to having complete confidence in assembly of final parts. The effect of different hardening models in predicting final sheet thickness for DP-steel is shown in Fig. 6.

Punch force

The comparison between the required punch forces for two test materials is shown in Fig. 7. The U-bending of DP-Steel needs the higher punch force because of having larger yielding strength in contrast to AA5754-O and it leads to the higher amount of springback. This result is one of the advantages of utilizing aluminum alloys in aerospace industries.

Conclusions

The level of the final equivalent plastic strain has a special meaning to determine the amount of springback. The higher amount of equivalent plastic strain results in lower amount of springback, therefore, to compensate the springback, the effective parameters such as blankholder force must be chosen in such a way to increase the final amount of equivalent plastic strain. Furthermore, comparing the level of equivalent plastic strain predicted by different hardening models demonstrates that the higher level of equivalent plastic strain leads to lower final sheet thickness. The maximum punch force required for the aluminum alloy is smaller than the steel which means better formability.

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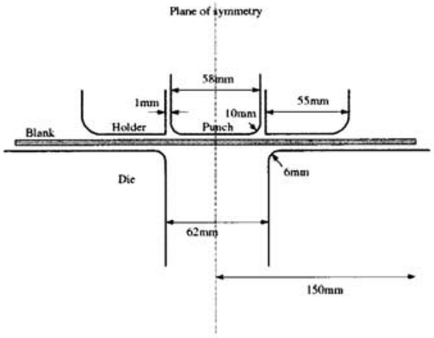

Fig. 1 U-bending process.

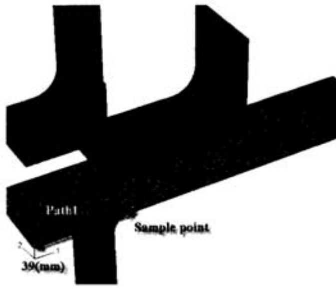

Fig. 2 3D model in ABAQUS.

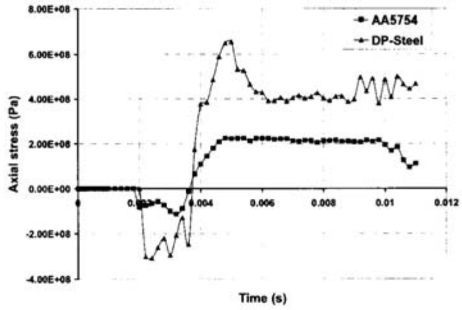

Fig. 3 Axial stress for the sample point.

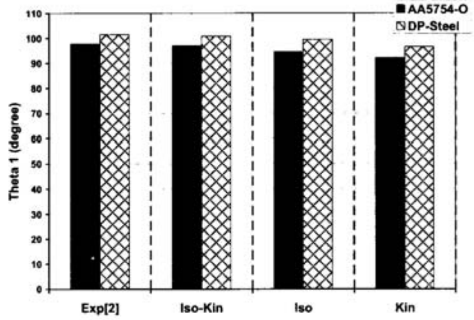

Fig. 4 Springback angel in punch corner predicted by different hardening models for the two test materials.

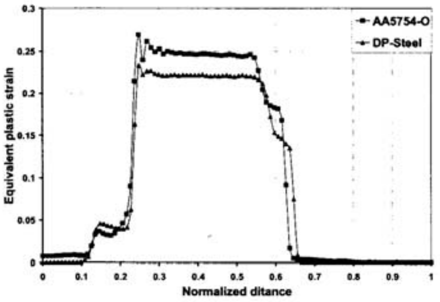

Fig. 5 Equivalent plastic strain distribution along the path1 for the two test materials.

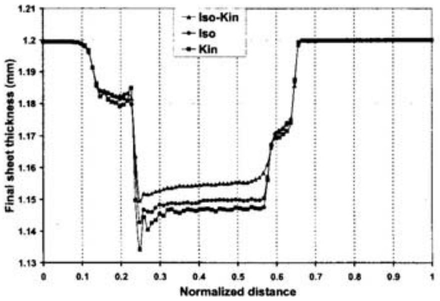

Fig. 6 Final sheet thickness distribution along the path1 for DP-Steel.

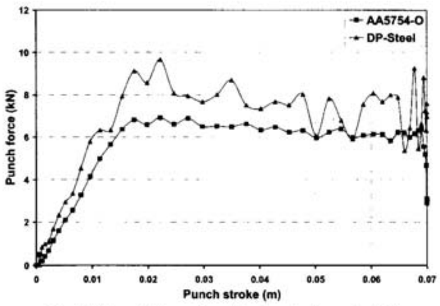

Fig. 7 Punch force for the two test materials.

References

1- Panthi S.K., Ramarishnan N., Pathak K.K. and Chouhan J.S., An Analysis of Springback in Sheet Metal Bending Using Finite Element Method(FEM), *Journal of Materials Processing Technology*, Vol. 186, 2007, pp. 120-124.

2- Lee M.G., Kim D., Kim C., Wenner M.L. and 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*, Vol. 21, 2005, pp. 915-953.

3- Lemaitre J., Chaboche J.-L., *Mechanics of Solid Materials*, Cambridge University Press, 1990, pp. 161–241.

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Abstract

In this paper the effect of different hardening models in 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 simulation of the process is modeled using the finite element code, ABAQUS 6.5. 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. Three hardening models are considered in simulations: 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 and the isotropic hardening overpredicted the springack. 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. Results show that attaining higher amount of the 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 exhibits smaller springback.

Keywords: *U-bending - Finite element - Hardening models*

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 [1]. 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 planer 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 unloading leading to springback. The springback is normally measured in terms of change in radius of curvature due to elastic recovery. In large sheets, even a small change in the radius of curvature results in a very large change in the displacement posing serious fabrication problems. Hence, the tool design, for a given sheet material and the final product dimension, should be capable of accurately incorporating the elastic recovery. The 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. Furthermore, they studied the influence of blankholder force and coefficient friction on the amount of the final springback.

U-bending process is often used to manufacture sheet parts like channels, beams and frames. In this process, the sheet metal usually undergoes complex deformation history such as stretch–bending, stretch–unbending and reverse bending. When the tools are removed, in addition to springback, sidewall curl often happens, which makes the prediction of springback become more difficult. Different methods, such as analytical method, semi-analytical method and finite element method (FEM), have been applied to predict the sheet springback of U-bending. Samuel [5] used a finite element (FE) program, MARC package to analyze the sheet metals axisymmetric U-bending process. He investigated the effect of tool geometry and blankholder force on the final shape after springback. Experimental prediction of springback and the determination of the final geometry within a reasonable tolerance is time consuming and expensive.

In recent years, the rapid development of computer technologies enables numerical simulation of sheet metal forming operations by finite element analysis code to be used in an industrial environment. The springback prediction of bending operation using FEA has been employed by many researchers in the past. For instance,

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Cho et al. [6] carried out numerical investigation on springback characteristics in plane strain 'U' bending process by thermo-elastoplastic FEA. Li et al. [7] 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 [8] accounted inertial effects in the FEA of sheet metal forming process. Papeleux and Ponthot [9] discussed numerically the effect of blank holder force, friction, spatial integration, etc. on the forming response. Chou and Hung [10] 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 [11] 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. [12] 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 considered in isotropic hardening, thus, when the material undergoes reverse loading, inaccurate springback is predicted. The linear kinematic hardening proposed by Prager [13] and Ziegler [14] 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 [15]. The non-linear kinematic hardening rule presented by Lemaitre and Chaboche [16] introduced a recall term to realize the smooth elastic-plastic transition upon the change of loading path.

Dongjuan et al. [17] proposed a stress–strain constitutive equation of non-linear combined hardening rule according to non-linear kinematic hardening theory of Lemaitre and Chaboche and Barlat89's yielding function. The algorithm of elastic predicting, plastic correcting and radial returning was applied to calculate the stress increment. Taking a benchmark of NUMISHEET'93 2-D draw bending problem as an example, the effects of different hardening rules and yielding functions were investigated. Comparison with NUMISHEET'93 experimental data indicated that the isotropic hardening rule over estimated springback since the predicted stress after forming was relatively larger, while the predicted springback by non-linear combined hardening rule coincides well with the experimental data. Lee et al. [18] developed the phenomenological continuum plasticity models considering the unusual plastic behavior of magnesium alloy sheet for a finite element analysis. A hardening law based on two-surface model was further extended to consider the general stress–strain response of metal sheets including Bauschinger effect, transient behavior and the unusual asymmetry. Verma and Haldar [19] investigated the effect of normal anisotropy on springback using finite element analysis for the benchmark problem of NUMISHEET'05. They developed an analytical model to cross check the trends predicted from the finite element analysis. Both the models (FE and analytical) predicted that higher anisotropy, in general, gave higher springback. Finite element analysis of the problem showed that springback is minimum for an isotropic material.

In this paper, the influence of different hardening models in simulating the U-bending process by utilizing the finite element code, ABAQUS 6.5 [20], has been investigated. Several internal state variables such as final sheet thickness, equivalent plastic strain, punch force etc. have been compared for the hardening models. Also, springback prediction by considering hardening models has been explored and verified with the experimental results in literature [21].

Finite Element Simulation

At present, 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, on the order of 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 2D drawing bending problem in NUMISHEET'93 as shown in Fig. 1 is a case studied in this paper for two materials: AA5754-O and DP-Steel [21]. 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, with the symmetry boundary condition along the Y axis. 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 300mm (length) × 35mm (width) with the 70mm total punch stroke for two test materials. To verify the results of the springback, the blankholder force considered to be 25 KN which is the high blankholder force used in the reference [21]. The friction coefficient between tools and the sheet blank assumed to be constant and equal to 0.1. The punch velocity was speed up to 10 m/s in the dynamic explicit code. The springback parameters θ_1 and θ_2 studied by this benchmark are shown in Fig. 2.

Results and Discussions

There are three hardening models considered in simulations: the combined isotropic-kinematic based on the Lemaitre and Chaboche work [16] (ISO-KIN), pure isotropic (ISO) and pure kinematic (KIN). Fig. 3 shows a sample point and the path1 which are used in the following parts of the paper to compare the results of different parameters. Path1 and sample point are located at the bottom edge of the sheet.

Axial Stress

History of the axial stress in the U-bending process during the deformation shows the status of loading in the elements of the material, meaning that whether the material undergoes 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. Fig. 4 displays the axial stress for the sample point defined in Fig. 2 and compares this state variable for the two test materials. As it 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 reaches to the larger amount of axial stress in the both compression and tension than the steel. The most important conclusion that can be drawn from the figure is that there are several points in the sheet which undergo reversal loading during the process history, therefore, hardening models maybe assumed important and effective in the course of simulating the process, namely the U-bending process.

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 1967; Mroz 1969; Chaboche 1977; and Lemaitre & Chaboche 1990).

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. In Fig. 5 the results for the parameter θ_1 and in Fig. 6 the results for the parameter θ_2 are presented and compared for the two test materials. The larger amount of θ_1 and the smaller amount of θ_2 are regarded as the larger springback. For both of the test materials, the combined hardening (ISO-KIN) has predicted the springback well whereas the isotropic hardening has over estimated the springback, but the difference between the results of these two models is not so significant because there does not exist obvious reverse forming in the process, on the other hand, only the points which are located on the bottom of the sheet undergo reversal loading. The results of the linear kinamatic hardening model highly differs from the results of the other models. It should be taken into consideration that the linear kinematic hardening has been suggested for materials with linear stress-strain curve and would not lead to logical results for other materials. Comparing the results of the two test materials shows that, for the defined parameters of the process, the aluminum alloy sheet leads to the smaller springback than the steel sheet.

Equivalent Plastic Strain

The equivalent plastic strain has an important role in definition of constitutive equations of metal plasticity such as hardening models. Eq. (1) defines the equivalent plastic strain

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

Fig. 7 displays the equivalent plastic strain predicted by the hardening models and evaluated along the path1 for the aluminum alloy. As it is observed, the level of the equivalent plastic strain predicted by the combined hardening is between the other hardening models. The isotropic has predicted the lowest level of equivalent plastic strain. Comparing to the Fig. 5 and Fig. 6, predicting the higher amount of equivalent plastic strain by the hardening model results in the smaller amount of springback. Fig. 8 illustrates the level of the equivalent plastic strain along the path1 for the two test materials. The aluminum alloy that has the smaller Young's modulus achieved the higher level of equivalent plastic strain. Comparing the final amount of the springback results for the considered materials reveals that the material with the higher level of the equivalent plastic strain leads to the smaller amount of springback.

Sheet Thickness

The accuracy and fitness with the design of the final sheet thickness in aerospace and automotive industries is of vital importance due to having complete confidence in assembly of final parts and preventing common defects such as localized necking and tearing in the formed sheet. In Fig. 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 less and the isotropic hardening has predicted the more change in the sheet thickness.

Punch force

The material type is one the various effective factors which affects on the final amount of the springback. Therefore, designer should be careful in choosing the appropriate material and optimizes the other factors in order to reduce the final springback. The comparison between the required punch forces for the two test materials is shown in Fig. 10. The U-bending of DP-Steel needs the higher amount of maximum punch force because of having larger yielding strength in contrast to AA5754-O and also, it leads to the higher amount of springback. This result confirms one of the advantages of utilizing aluminum alloys in aerospace and automobile industries in addition to their lower weight. In Fig. 11 the maximum punch force predicted by different hardening models for the two test materials is shown. The isotropic hardening has predicted the largest punch force and kinematic hardening has predicted the smallest. As the isotropic hardening does not consider the Bauschinger effect and there exist several points in the sheet that undergo reversal loading, this hardening model over estimates the maximum punch force.

Conclusions

In this paper, the finite element approach of the U-bending process has been studied in such a manner that the kind of the hardening model is emphasized. Furthermore, the springback occurred in the sheet after unloading is investigated. The relation between the hardening models, springback and final state variables such as the equivalent plastic strain and sheet thickness, is explored.

The amount of the final equivalent plastic strain has a special meaning to determine the amount of springback. The higher level of equivalent plastic strain results in lower amount of springback, therefore, to compensate the springback, effective parameters such as blankholder force should be chosen in such a way that leads to a higher level of equivalent plastic strain at the end of the process. Also, comparing the level of equivalent plastic strain predicted by different hardening models demonstrates that the higher level of equivalent plastic strain leads to lower level of final sheet thickness and higher level of punch force. Comparing the materials reveals that the aluminum alloy requires fewer maximum punch force and exhibits smaller springback after unloading.

References

1- Lingbeek R., Huetink J., Ohnimus S., Petzoldt M. and Weiher J., The Development of a Finite Elements Based Springback Compensation Tool for Sheet Metal Products, *Journal of Materials Processing Technology*, Vol. 169, 2005, pp. 115-125.

2- Panthi S.K., Ramarishnan N., Pathak K.K. and Chouhan J.S., An Analysis of Springback in Sheet Metal Bending Using Finite Element Method(FEM), *Journal of Materials Processing Technology*, Vol. 186, 2007, pp. 120-124.

3- Esat V., Darendeliler H. and Gokler M.I., Finite Element Analysis of Springback in Bending of Aluminum Sheets, *Journal of Materials and Design*, Vol. 23, 2002, pp. 223-229.

4- Ragai I., Lazim D. and Nemes J.A., Anisotropy and Springback in Draw-Bending of Stainless 410: Experimental and Numerical Study, *Journal of Materials Processing Technology*, Vol. 166, 2005, pp. 116-127.

5- Samuel M., Experimental and Numerical Prediction of Springback and Side Wall Curl in U-bending of Anisotropic Sheet Metals, *Journal of Materials Processing Technol*ogy, Vol. 105, 2000, pp. 382-393.

6- Cho J.R., Moon S.J., Moon Y.H. and Kang S.S., Finite Element Investigation on Springback Characteristics in Sheet Metal U-bending Process, *Journal of Materials Processing Technol*ogy, Vol. 141, 2003, pp. 109-116.

7- Li X., Yang Y., Wang Y., Bao J. and Li S., Effect of Material-Hardening Mode on the Springback Simulation Accuracy of V-Free Bending, *Journal of Materials Processing Technol*ogy, Vol. 123, 2002, pp. 209-211.

8- Choudhry S. and Lee J.K., Dynamic Plain-Strain Finite Element Simulation of Industrial Sheet-Metal Forming Processes, *International Journal of Mechanical Sciences*, Vol. 36, 1994, pp. 189-207.

9- Papeleux L. and Panthot J.P., Finite Element Simulation of Springback in Sheet Metal Forming, *Journal of Materials Processing Technol*ogy, Vol. 125-126, 2002, pp. 785-791.

10- Chou I.N. and Hung C., Finite Element Analysis and Optimization on Springback Reduction, *International Journal of Machine Tools and Manufacturing*, Vol. 39, 1999, pp. 517-536.

11- Math M. and Grizelj B., Finite Element Approach in the Plate Bending Process, *Journal of Materials Processing Technol*ogy, Vol. 125-126, 2002, pp. 778-784.

12- Lei L.P., Hwang S.M. and Kang B.S., Finite Element Analysis and Design in Stainless Steel Sheet Forming and Its Experimental Comparison, *Journal of Materials Processing Technol*ogy, Vol. 110, 2001, pp. 70-77.

13- Prager W., Recent Developments in the Mathematical Theory of Plasticity, *International Journal of Applied Mechanics*, 1956, pp. 78-493.

14- Ziegler H., A Modification on Pragr's Hardening Rule, *Quarte. of Applied Mathematic*, 1959, pp. 17-55.

15- Armstrong P.J. and Frederick, A Mathematical Representation of the Multiaxial Bauschinger Effect, G.E.G.B. Report RD/d/B/N, 1966.

16- Lemaitre J., Chaboche J.-L., *Mechanics of Solid Materials*, Cambridge University Press, 1990, pp. 161–241.

17- Dongjuan Z., Zhenshan C., Xueyu R. and Yuqiang L., Sheet Springback Prediction Based on Non-Linear Combined Hardening Rule and Barlat89's Yielding Function, *Journal of Computational Materials Science*, Vol. 38, 2006, pp. 256-262.

18- Lee M.-G., Wagoner R.H., Lee J.K., Chung K. and Kim H.Y., Constitutive Modeling for Anisotropy/Asymmetric Hardening Behavior of Magnesium Alloy Sheets, *International Journal of Plasticity*, 2007, In Press.

19- Verma R.K. and Haldar A., Effect of Normal Anisotropy on Springback, *Journal of Materials Processing Technol*ogy, Vol. 190, 2007, pp. 300-304.

20- ABAQUS User's Manual Version6.5, Hibbit, Karlsson & Sorensen, Inc., 2003.

21- Lee M.G., Kim D., Kim C., Wenner M.L. and 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,* Vol. 21, 2005, pp. 915-953.

Table 1 - Basic materials properties

	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

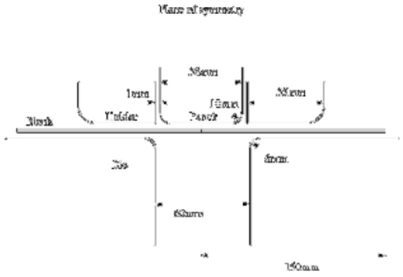

Fig. 1 U-bending process.

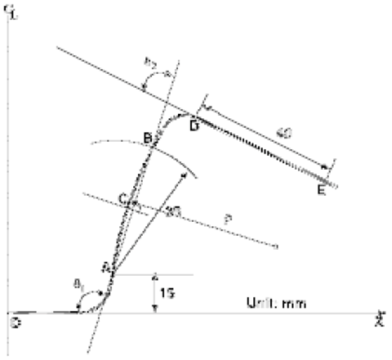

Fig. 2 Parameters for springback in U-bending process.

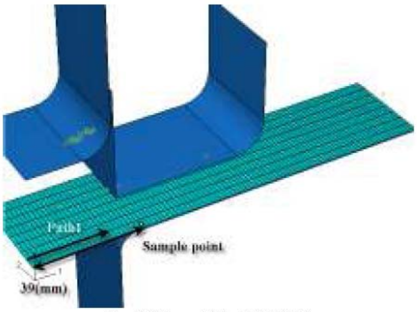

Fig. 3 3D model in ABAQUS.

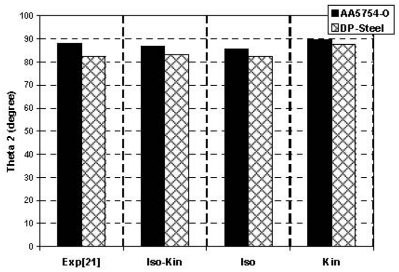

Fig. 6 Springback parameter θ_2 predicted by different hardening models for the two test materials.

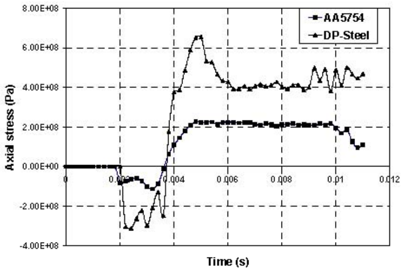

Fig. 4 Axial stress for the sample point.

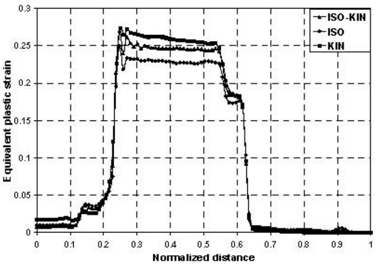

Fig. 7 Equivalent plastic strain distribution along the path1 predicted by different hardening models for AA5754-O.

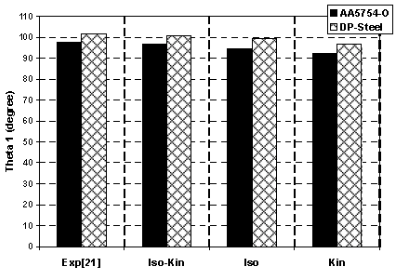

Fig. 5 Springback parameter θ_1 predicted by different hardening models for the two test materials.

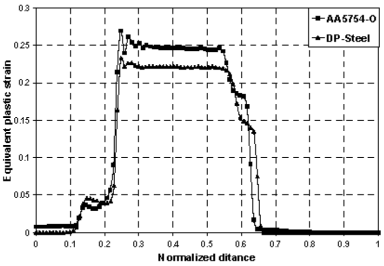

Fig. 8 Equivalent plastic strain distribution along the path1 for the two test materials.

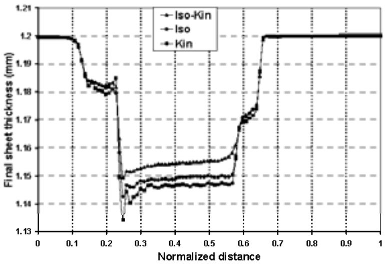

Fig. 9 Final sheet thickness distribution along the path1 for DP-Steel.

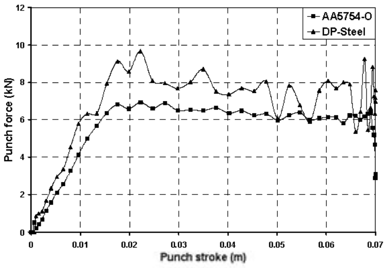

Fig. 10 Punch force for the two test materials.

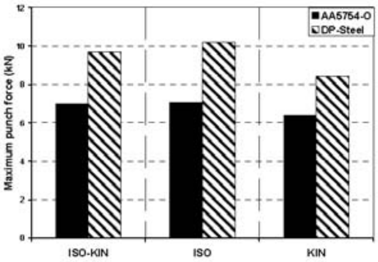

Fig. 11 Maximum punch force predicted by different hardening models for the two test materials.