Proceedings of NAMRI/SME, Vol. 40, 2012

Springback Prediction in Bending of AHSS-DP 780

N. Kardes Sever, O. H. Mete, Y. Demiralp, C. Choi, T. Altan
Center for Precision Forming (CPF, formerly ERC/NSM)
The Ohio State University
Columbus, OH

ABSTRACT
Forming of AHSS creates several challenges because these materials have higher strength and lower formability compared to low carbon steels. One of these challenges is springback that leads to dimensional inaccuracy in the formed part. In the present study, the effect of unloading apparent modulus (E- modulus) variation with strain on the accuracy of springback prediction in V-die bending and U-bending of DP 780 is investigated. A reliable methodology to measure springback which is very important is developed. Load-unload tensile tests were performed to obtain unloading apparent modulus variation. Springback in V-die bending and U bending was estimated by using FEA and a variable E-modulus. Compared with experimental data, the predictions gave reasonably accurate results.

KEYWORDS
V-die bending, U-bending, AHSS, Springback, E-modulus

INTRODUCTION

Advanced high strength steels (AHSS) are used in automotive industry to decrease the vehicle weight and increase crash performance. However, forming of AHSS is difficult due to their higher strength and lower formability. Furthermore, parts made from an AHSS exhibit relatively large springback leading to dimensional inaccuracy in the formed part. Springback cannot be avoided but can be minimized by several methods such as applying tension, overbending, warm and hot forming [1]. Finite element method (FEM) is widely used in industry to predict metal flow and springback. Based on the springback predictions obtained from FEM, the tool geometries are virtually modified to compensate for the springback before the tool is manufactured. Thus, tool manufacturing time and cost are significantly reduced.

Choosing the proper element type (solid vs. shell) and coefficient of friction affects the accuracy of the FE simulations. The accuracy of the predictions is also influenced by the mechanical properties of the sheet material. In general, hardening behaviour of the material is defined by fitting a curve to the flow stress data in FE simulations. Hollomon's equation ($\bar{\sigma} = K\bar{\epsilon}^n$), where $\bar{\sigma}$ is true stress, $\bar{\epsilon}$ is true strain, K is the strength coefficient and n is the work hardening exponent, is usually preferred for curve fitting. However, AHSS has a multi-phase microstructure and may experience phase transformation during deformation. Thus, it may not be accurate to use Hollomon's equation with constant K and n values in the simulations. Selection of correct hardening model, such as isotropic hardening, kinematic hardening or combination of both, is also critical in the prediction of springback. During elastic unloading / relaxation of the residual stresses, the elastic recovery of the sheet metal depends on the state of the stress and the unloading apparent modulus. Commonly, unloading apparent modulus is assumed to be constant with deformation and approximately 207 GPa is used in the calculations for AHSS. However previous studies indicated that the unloading apparent modulus decreases with deformation due to the multi phase structure of AHSS [2-7]. Similar results were also observed in load-unload tensile tests conducted at CPF [8].

Fei et al. ([4]) investigated the effect of unloading apparent modulus variation on springback prediction in V-die bending of TRIP steels. The relation between unloading apparent modulus and strain was defined by a linear equation and input to ABAQUS by USDFLD subroutine. It was reported that the FE simulations performed with variable apparent modulus gave better springback predictions than the simulations with constant apparent modulus. Cobo et al. ([3]) also conducted air bending experiments and FE simulations with DP steels to study the effect of apparent modulus variation on springback prediction. The variation of apparent modulus was incorporated in FE simulations by using USDFLD subroutine which in return increased the accuracy of the springback prediction. They predicted the springback more successfully for lower strength DP steels than for higher strength of DP steels.

The present study focused on accuracy of springback prediction by using FE method that considers the variation in unloading apparent modulus with strain. Reliable measurement of springback is also a very critical issue. Thus, the measurements were performed very carefully and in detail. V-die bending test shown in Figure 1 was selected for its simplicity. The sheet was bent at different bending angles to produce different stresses and strains by adjusting the punch stroke.

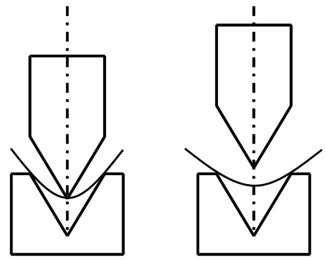


Figure 1. Illustration of springback in V-die bending before and after unloading.

Later, straight portion of an S-shape die illustrated in Figure 2 was utilized to conduct U-bending tests with and without stretching. Punch stroke was adjusted in U-bending test without stretching to obtain various stress and strain levels similar to V-die bending.

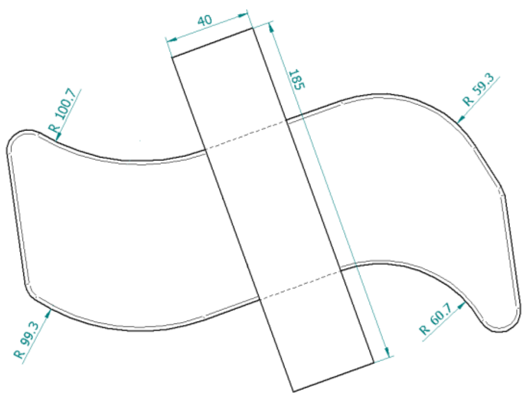


Figure 2. S-shape die used in U bending tests with and without stretching.

OBJECTIVES AND APPROACH

The objective of the study was to determine the effect of unloading apparent modulus variation with strain on the accuracy of springback prediction in V-die bending and U-bending of DP 780. For this purpose, first load-unload tensile tests were performed to obtain unloading apparent modulus variation with strain. Then, V-die bending and U-bending experiments were conducted. Bending angles before and after unloading were carefully measured by using several methods when possible. At the end of the study, results obtained from experiments and FE simulations were compared. DEFORM 2D and PAMSTAMP were used as FE codes.

LOAD-UNLOAD TENSILE TESTS

Tensile tests were performed on 8 samples from DP 780 steel by using a standard tensile testing machine, Instron 4204-145, at Edison Welding Institute (EWI). All measured data were recorded with a data acquisition system, Instron Blue Hill Test Data software. The samples were cut in the rolling (RD) and transverse (TD) directions by EDM according to the ASTM standard. The displacement on the tensile test samples were measured using mechanical contact extensometers. First, standard tensile tests were performed to obtain the uniform elongation. Table 1 shows the test matrix for load-unload tensile tests. As an example, true stress-true strain curve of one sample obtained from load-unload tensile test is given in Figure 3.

E-modulus for elastic region was calculated using the data up to 258 MPa where the initial loading curve was the straightest. The unloading apparent moduli were calculated from the slope of unloading curves using Microsoft Excel function linear trend line (LINEST) (or slope (SLOPE)).

Table 1. Load-unload tensile test matrix.

Testing parameters	Descriptions
Sheet thickness	1 mm
Engineering strain (%)	~ 1, 2, 3, 4, 6, 8, 9, 10, 11, 12
# of samples	3 per sheet orientation (RD and TD)

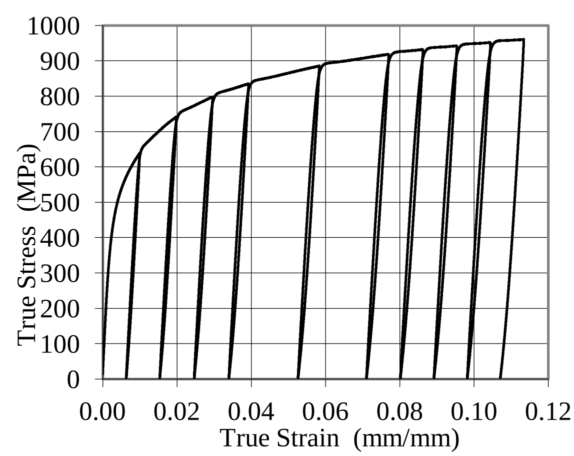


Figure 3. True stress-strain data obtained by load-unload tensile test.

The variation of unloading apparent modulus with strain is given in Figure 4. The unloading apparent modulus decreases nonlinearly with increasing strain until approximately 0.1 true strain and then becomes nearly constant.

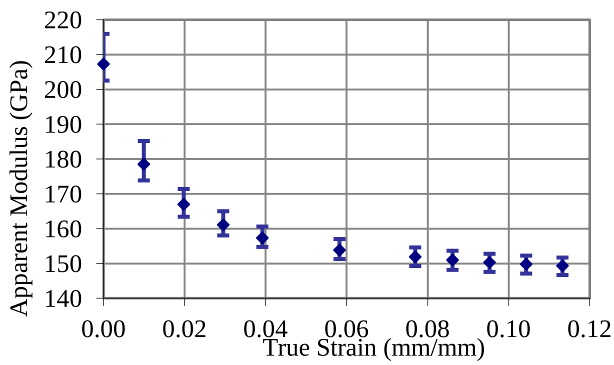


Figure 4. Variation of unloading apparent modulus with strain for DP 780.

V-DIE BENDING

V-die Bending Test Experimental Set-up

The tool geometry, used in V-die bending tests shown in Figure 5, was selected in such a way that punch and V-die pair do not cause fracture in the bent sheet and rubbing of sheet to the V-die side walls during tests. FE simulations were conducted with several tool geometries to ensure the absence of rubbing. A 90 Ton press brake, Cincinnati MAXFORM - 90MX8, with a maximum forming speed of 31.75 mm/sec (75 ipm) was used.

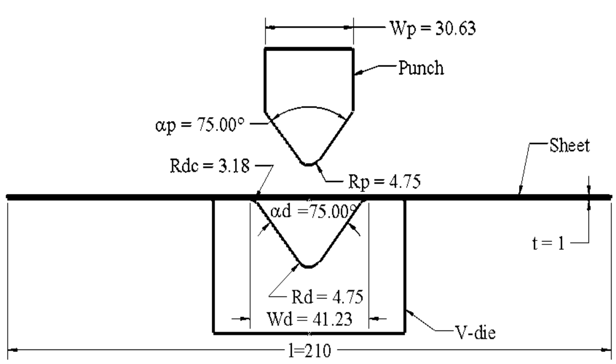
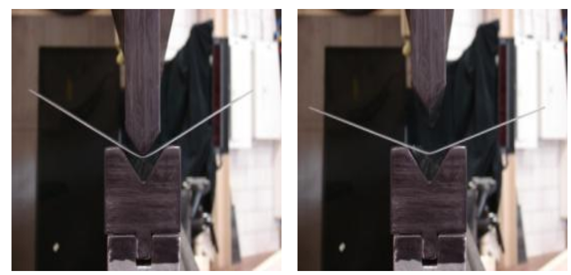


Figure 5. Tool geometry used in V-die bending dimensions are in mm).

Different bending angles correspond to different stress and strain distributions over the bending area. 60 mm wide sheet samples were bent at six different bending angles (170°, 160°, 150°, 140°, 120° and 90°) by adjusting the punch stroke. Pictures were taken under load (end of stroke) and after unloading as shown in Figure 6 to calculate the inner bending angle before and after unloading. The press brake dwells for maximum 10 seconds to allow enough time to take pictures with Sony DSC-H2 camera. Digital protractor and a coordinate measuring machine (CMM) were used to measure the inner bending angle after unloading. The effect of anisotropy on springback was also investigated by shearing the samples parallel and perpendicular to rolling direction (RD and TD). 3 samples were bent for each bending angle and sheet orientation.



a) under load b) after unloading.

Figure 6. Pictures of V-die bending: a) under load and b) after unloading.

The inner bending angle of each sample before unloading was calculated only by taking pictures. Later, the pictures were analyzed by using MATLAB code. This code picks points along the lines between which the bending angle needs to be measured as shown in Figure 7. The following procedure was followed to obtain inner bending angle before unloading (under load):

- Select the origin, A.
- Select three points on both x (B_x, C_x, D_x) and y (B_y, C_y, D_y) axes to generate the coordinate system.
- Select approximately 15 points (only 3 points (T1, T2, T3) are shown in Figure 7) on each leg of the bent part.
- The points should be selected from the straight section of the legs (region between the edge and die corner radius, Rdc).
- The number of points must be high for better straight line fitting.
- Fit two straight lines (y=ax+b) to the selected points.
- Calculate the slopes of two lines which give the angle between the legs of the bent part.
- After obtaining the coordinates of the points, LINEST function in Microsoft Excel was used to calculate the slopes and inner bending angles.

The bending angles after unloading were calculated from the pictures following the same procedure described above. They were also measured by digital protractor and CMM. CMM measurements are assumed to be more accurate compared to the digital protractor and picture. Hence, the measurement error was calculated based on CMM data. The maximum errors are 1.34% and 0.93% for picture and digital protractor respectively. It was concluded that springback angle can be calculated accurately by taking pictures and utilizing the MATLAB code.

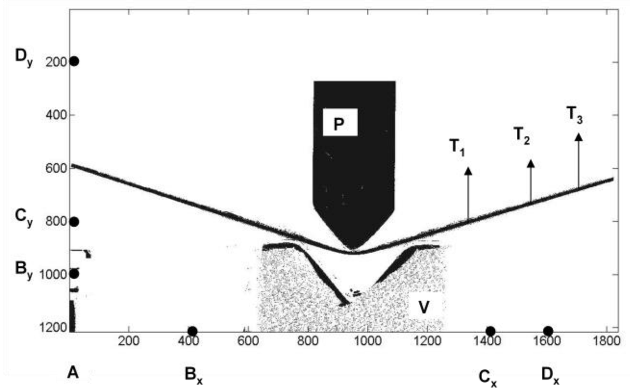


Figure 7. MATLAB window for point selection.

V-die Bending Test Experimental Results

The variation of the springback angle with bending angle under load for the samples sheared in RD and TD is shown in Figure 8. The springback angles were calculated by using the photos and the MATLAB code since it was not possible to measure the inner bending angle under load with any other method available in our lab.

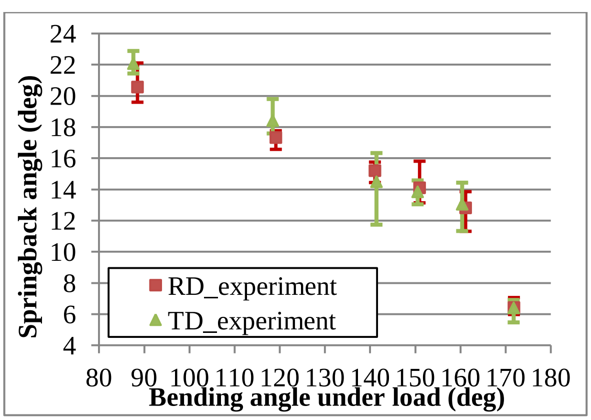


Figure 8. Springback angle vs. bending angle under load.

FE Simulation of V-die Bending Test

The main objective of FEA is to predict springback for V-die bending tests. The second objective is to compare the results obtained from different FE codes DEFORM 2D and PAMSTAMP. A half model was utilized for all FE simulations to save time. The simulation parameters and flow stress data used in all FE analyses are given in Table 2 and Figure 9.

Table 2. Simulation parameters used in V-die bending tests.

Parameters	**Descriptions**
Material type	Sheet - elastic plastic V-die and punch – rigid
Element Type	Solid (Brick – DEFORM 2D) Shell (PAMSTAMP)
Coefficient of friction, μ	0.12
E-modulus (constant and variable)	Constant: 207 GPa and 150 GPa (max. and min. values in Figure 3)
	Variable (See Figure 3)

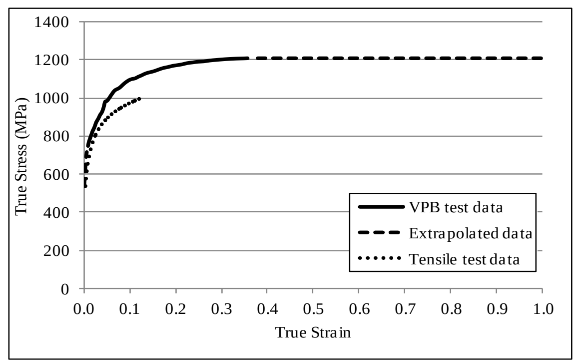


Figure 9. Flow stress data for DP 780 obtained from VPB test.

The flow stress data was obtained by viscous pressure bulge (VPB) test [10] starting from 0.01 true strain up to 0.35 true strain. The VPB test has been used by CPF to investigate the formability of sheet materials. The VPB test offers several advantages over the conventional tensile test i) a quick comparison of the formability of different materials/samples by observing "bulge height" and ii) material properties, such as true stress – true strain data points can be determined to the limiting strain level relevant to sheet forming operations. This is because VPB allows biaxial true stress- strain flow curves to be measured during the test to strain levels that are often two times greater than the maximum strain of the corresponding uniaxial true stress-strain curves.

Yield strength was found from tensile test and the VPB test data (solid line) was extrapolated for the regions where there is no experimental data (dashed line). (See Figure 9) The flow stress data was input in tabular form to the simulations instead of using Holloman's equation. In V-die bending there is no forward and reverse loading. Thus, isotropic hardening model (Von-Mises) is used in the FE simulations. Bauschinger effect and anisotropy is neglected. Unloading apparent modulus is considered constant in simulations with PAMSTAMP and DEFORM2D. In addition, a user subroutine was utilized for DEFORM 2D simulations to input the unloading apparent modulus as a variable (See Figure 4). The experimental data points were entered in tabular form into DEFORM 2D.

FE Simulation Results for V-die Bending Test

Comparison of springback angles obtained from DEFORM 2D, PAMSTAMP and experiments is given in Figure 10.

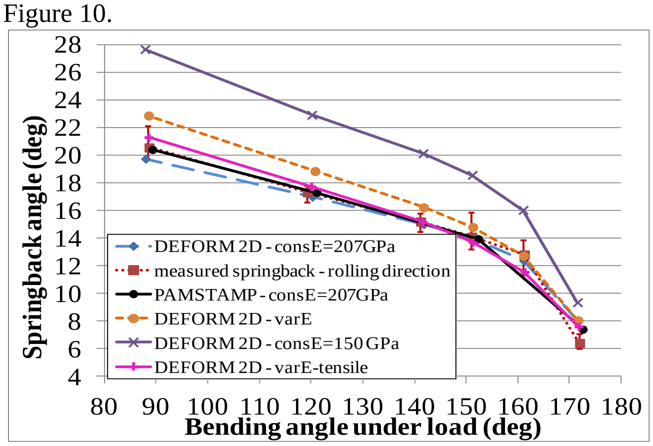
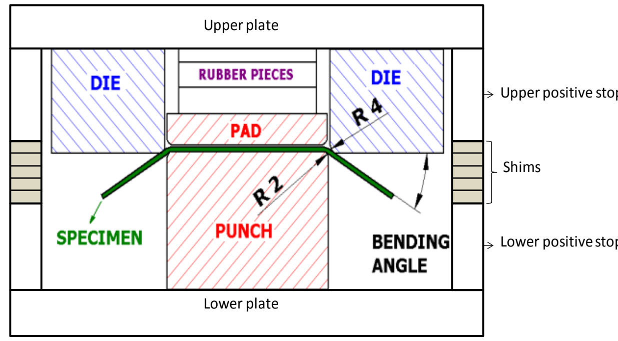


Figure 10. Comparison of springback angles obtained by FEA and experiments (using constant and variable E-modulus and the FEA codes PAMSTAMP and DEFORM 2D).

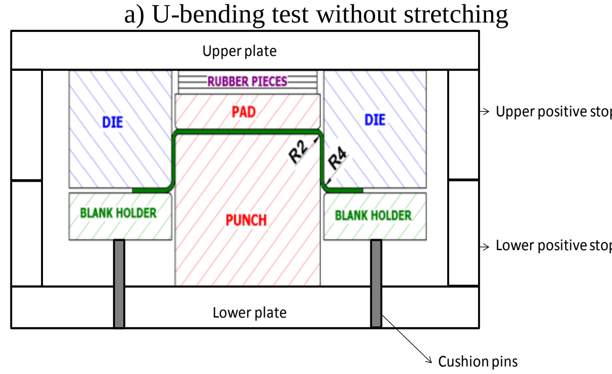
U-BENDING TESTS WITH & WITHOUT STRETCHING

In U-bending, two bends are produced simultaneously in a single die. Rectangular sheet blank is placed on the punch and the die attached to the ram of the press moves down to bend the sheet as shown in Figure 11.

160 and 40 tons hydraulic presses at CPF were utilized in the U-bending tests with and without stretching respectively. In order to perform U-bending test with stretching blank holder is utilized as shown in Figure 11b. Sheet can be bent at different bending angles by adjusting the die stroke (place shims with different thicknesses on the lower positive stop). By means of positive stops and shims, it is ensured that the die stroke is same for all sheet samples that are bent at the same angle.



a) U-bending test without stretching



b) U-bending test with stretching

Figure 11. Schematics of U-bending test a) without and b) with stretching.

In the absence of pressure pad force or application of insufficient pressure pad force, the portion of the sheet that is in contact with the top of the punch tends to lift up as the die moves down to bend the sheet. Thus, springback increases. In order to maintain the contact between the punch and the sheet, adequate pressure pad force needs to be applied. Pressure pad force was applied by compressing the rubbers between the pressure plate and the upper plate of the press as the die moved down (See Figure 12).

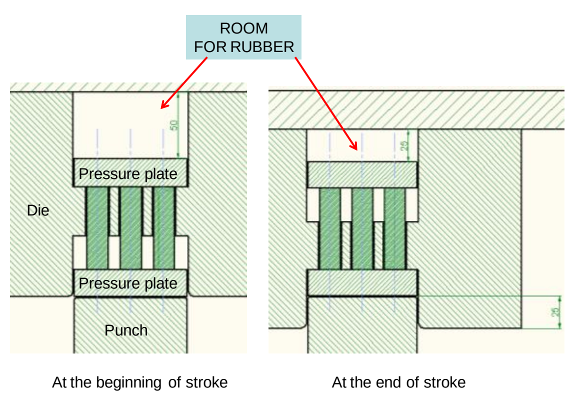


Figure 12. Schematic of the tooling used with a pressure pad.

Two types of rubber were available at CPF so-called soft and hard rubbers. Compression tests were conducted by utilizing a tensile test machine available at OSU. Same type of rubbers stacked and compressed. The initial total height of the stacked soft and hard rubbers were ~116 mm and ~61 mm respectively. The soft one was compressed from 116 mm to a height of ~25 mm. The hard one was compressed from 61 to 50 mm. The load and stroke were recorded during compression tests as shown in Figure 13. FE simulations were conducted to determine the required minimum pressure pad force to keep the sheet in contact with the punch by using PAMSTAMP. Based on the compression tests and PAMSTAMP simulation results, the pressure pad force used in the U-bending tests with and without stretching, Figure 13 was found to be adequate to keep the sheet in contact with the top of the punch.

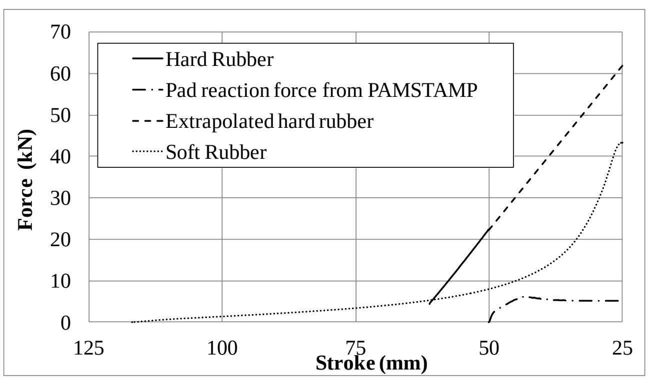
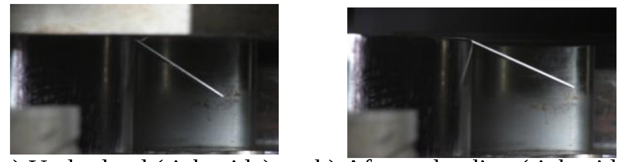


Figure 13. Force vs. stroke obtained from compression tests in evaluating the compressive behavior of rubber pads.

U-Bending Test without Stretching Experimental Set-up

Different bending angles correspond to different stress and strain distributions over the bending area similar to V-die bending test. 40 mm wide and 185 mm long sheet samples were bent at six different bending angles (10°, 15°, 25°, 40°, 65° and 90°) by adjusting the punch stroke. Pictures were taken under load (end of stroke) and after unloading as shown in Figure 14 to calculate the inner bending angle before and after unloading (See Figure 7). The effect of anisotropy on springback was also investigated by bending the sheets in RD (for all bending angles) and TD (only for 90°). Digital protractor was only used to measure the bending angle after unloading. For 90° bending angle soft rubbers and for 10°, 15°, 25°, 40° and 65° bending angles hard rubbers are used to apply the required pressure pad force. 3 samples were bent for each bending angle for repeatability. Punch and die corner radii are 2 and 4 mm respectively. Punch width is 83.26 mm and the clearance between punch and die is 1.1 mm.



a) Under load (right side) b) After unloading (right side)

Figure 14. U-bending test without stretching a) under load and b) after unloading.

The most important issue when taking photos to calculate bending angle under load and after unloading is the position of the camera with respect to the bent specimen. Taking photos from the right side of the bent specimen was much easier compared to the left side because of the S-shape of the punch. In Figure 15, the percentage error in the calculation of bending angle after unloading is shown assuming protractor measurements are accurate. As bending angle increased, the percentage error decreased. In addition, the percentage errors of the right side are smaller than the percentage errors of the left side.

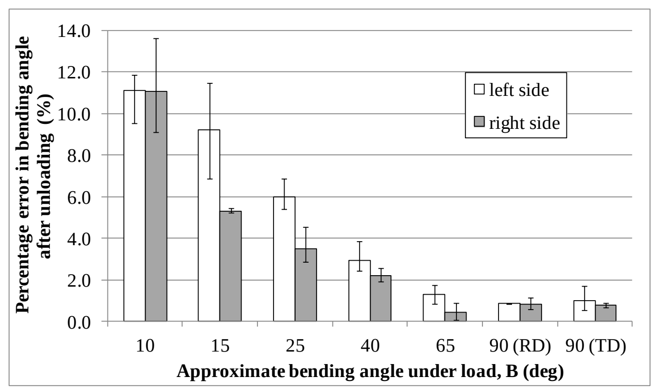


Figure 15. Percentage error in bending angle after unloading.

U-Bending Test without Stretching Experimental Results

The variation of springback angle with punch stroke is shown in Figure 16. The springback angle was calculated considering the photos taken from both legs. Moreover, for 90° bending angle, 3 additional specimens were cut parallel to transverse direction (TD) to investigate the effect of anisotropy. It should be noted that at 90° bending angle, only for the 2nd sample (RD) photos could be taken for both legs of the bent specimen.

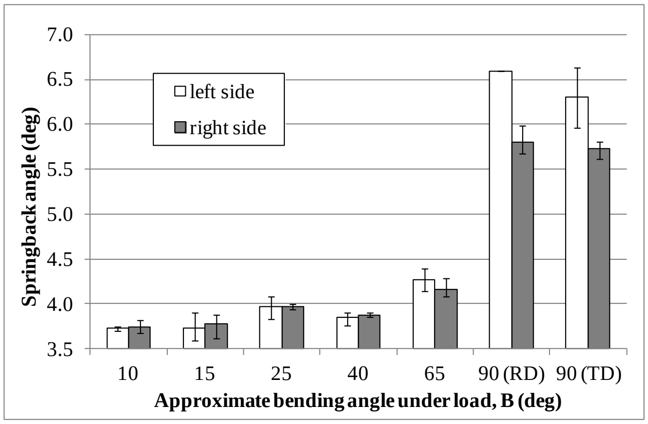


Figure 16. Springback angle vs. bending angle under load.

FE Simulation of U-Bending Test without Stretching

The main objective of FEA is to predict springback for U-bending tests. The second objective is to compare the results obtained from different FE codes, DEFORM 2D and PAMSTAMP. In these simulations, the springback angle was calculated considering the coordinates of two nodes. The first node is the node at the edge (N_1) and the second node (N_2) is selected ~45 mm away from the first one as shown in Figure 17. Half and quarter models were utilized in the FE analysis with DEFORM 2D and PAMSTAMP respectively. In DEFORM 2D, solid elements were used and shell elements in PAMSTAMP. The effect of anisotropy was investigated in the FE simulations done by using PAMSTAMP. Bauschinger effect is neglected for simplicity.

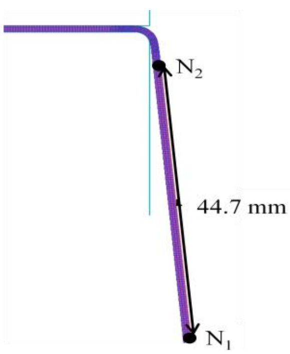


Figure 17. Selected nodes in FE code (DEFORM 2D given as an example) to calculate springback.

FE Simulation Results for U-Bending Test without Stretching

Comparison of springback angles obtained by DEFORM 2D, PAMSTAMP and experiments (only for samples in RD direction) is given in Figure 18.

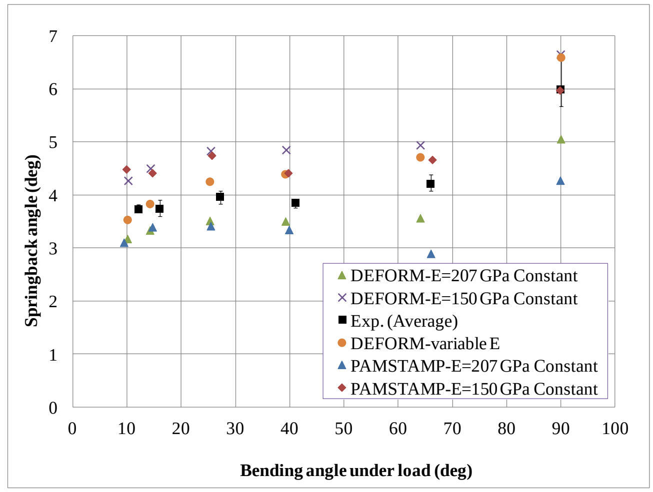


Figure18. Comparison of springback angles obtained by DEFORM 2D, PAMSTAMP and experiments.

U-Bending Test with Stretching Experimental Set-up

The sheet material was bent under tension by using the blank holder (BH), Figure 11b. Different BH forces (2tons/20kN and 8tons/80kN) created different stress and strain distributions in side wall of the specimen. The die stroke was 25.3 mm (90° bending angle). The effect of anisotropy on springback was also investigated.

U-Bending Test with Stretching Experimental Results

CMM was used for measuring the bent specimens after springback. A 0.984 mm round tip probe was used for scanning on the CMM. To measure the coordinates of the specimen, it was placed on CMM table on its flat surface. Three sections (A, B, C) were designated on specimen as illustrated on Figure 19. For each specimen, K and L trajectory was followed for left side and M and N trajectory was followed for right side for CMM measurement.

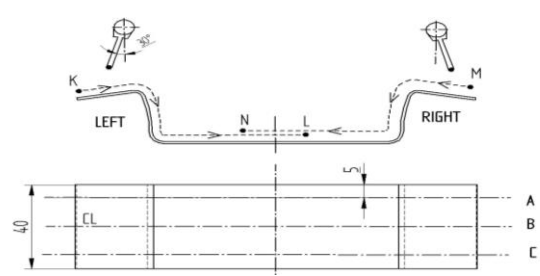


Figure 19. Front view (above) and top view (below) of the specimen.

There were twelve specimens for U-bending with stretching tests. A and C sections were measured for each specimen and section B was only measured for three samples (1, 2 and 7). The angles shown in Figure 20 (θ, α, β) were calculated from the slopes of the fitted straight lines by using Ms Excel from CMM data. θ and β angles are listed in Tables 3 and 4 for different blank holder forces and sheet directions.

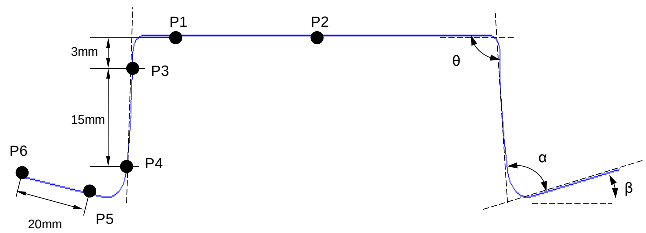


Figure 20. Angles after springback on one of the sections of the specimen.

Table 3. Average angles after springback for BHF 2T/20kN.

Angle	BHF: 2T/20kN (average springback)			
	RD		TD	
	Left	Right	Left	Right
θ	99.38	98.55	99.65	100.35
β	10.12	8.88	11.19	11.58

Table 4. Average angles after springback for BHF 8T/80kN.

Angle	BHF: 8T/80kN (average springback)			
	RD		TD	
	Left	Right	Left	Right
θ	97.04	96.63	97.02	95.65
β	8.74	7.61	8.8	6.69

It should be noted that the second sample (RD) has significantly different springback than the other two samples (RD).

FE Simulation of U-Bending Test with Stretching

Half and quarter models were utilized in the FE analysis with DEFORM 2D and PAMSTAMP respectively. Solid elements were used in DEFORM 2D where as shell elements were used in PAMSTAMP. Sheet is elastic-plastic and punch, pressure pad and die are rigid in both FE analysis. Minimum and maximum values of E-modulus were input. The effect of anisotropy was investigated in the FE simulations done by using PAMSTAMP. Bauschinger effect is neglected for simplicity.

FE Simulation Results for U-Bending Test with Stretching

Comparison of angles after springback obtained by DEFORM 2D and PAMSTAMP are given in Tables 5 and 6.

Table 5. Angles after springback for BHF 2T/20kN obtained by using DEFORM 2D and PAMSTAMP.

Angle	BHF: 2T/20kN – DEFORM 2D		BHF: 2T/20kN – PAMSTAMP			
	E=207 GPa	E=150 GPa	E=207 GPa		E=150 GPa	
			RD	TD	RD	TD
θ	96.7	99.8	100.1	100.4	103.1	103.4
β	12.2	16	17.4	17.8	21.5	21.8

Table 6. Angles after springback for BHF 8T/80kN obtained by using DEFORM 2D and PAMSTAMP.

Angle	BHF: 8T/80kN – DEFORM 2D		BHF: 8T/80kN – PAMSTAMP			
	E=207 GPa	E=150 GPa	E=207 GPa		E=150 GPa	
			RD	TD	RD	TD
θ	92.2	92.3	100.6	100.9	104.3	104.6
β	5.5	6.5	15.5	15.9	20.5	20.8

SUMMARY AND CONCLUSIONS

Summary

- Load-unload tensile tests were performed to obtain variation of unloading apparent modulus with strain.
- V-die bending and U-bending tests were conducted to investigate the effect of unloading apparent modulus variation and anisotropy on springback.
- Compression tests were conducted to select the type of rubbers to be used in U-bending tests.
- Different methods such as taking pictures, digital protractor and CMM were used to determine inner bending angle under load and after unloading.
- FE codes DEFORM 2D and PAMSTAMP were used to predict springback considering the unloading apparent modulus variation.
- Minimum and maximum values of unloading apparent modulus were input to FE analysis to investigate the effect of unloading apparent modulus. Unloading apparent modulus was assumed to be constant in PAMSTAMP and DEFORM 2D simulations.

- Later a user subroutine was utilized to input the unloading apparent modulus as a variable in DEFORM 2D simulations.

Conclusions

The major conclusions drawn from the study for V-die bending test are:

- As shown in Figure 4, the unloading apparent modulus decreased about 28% as true strain increased up to 0.11. The non-linear curve can be used in either tabular form or equation form for the elastic properties of DP 780 to predict springback.
- V-die bending of DP 780 is possible without cracking and rubbing of the sheet with the 75° V-bending punch and die pair.
- In V-die bending experiments, it is found that anisotropy has a small effect on springback. The difference between springback angles for RD and TD samples increased with a decrease in inner bending angle under load. The maximum difference in average springback angles was 1.51° which corresponds to 90° bending angle.
- FE simulations that were performed by using PAMSTAMP and DEFORM 2D with maximum value of unloading apparent modulus showed better agreement with experiments than the predictions with minimum value of unloading apparent modulus obtained using DEFORM 2D.
- When the variation of unloading apparent modulus was considered in FE simulations by using DEFORM 2D, no improvement in predictions was observed. However, considering variable unloading apparent modulus in FE simulations may improve the springback predictions for different sheet materials and bending angles
- Using the flow stress data obtained from tensile test and VPB test gave similar results in FE simulations since the max. effective strain (~0.07) in the bending area with the existing tool geometry was smaller than the maximum strain (~0.12) obtained from tensile test.

The major conclusions drawn from the study for U-bending test without stretching are:

- Bending angle after unloading could be calculated with maximum ~14% error (at 10° bending angle under load). The angle under load was measured by a digital camera. After unloading the angle (after springback) was measured by i) digital camera and ii) a digital protractor. We considered the protractor data to be more reliable. The samples bent at 90° were measured (after unloading) in a CMM. The data was the same as that obtained from protractor measurements. As bending angle under load increased, the percentage error decreased. It should be noted that when CMM was used to measure the section on the actual samples, the tip of the probe traveled until it reaches a point which is couple millimeters away from the flange edge. Therefore, there are a few millimeter differences in flange length between the actual samples and the simulated sample/blank.
- In U-bending without stretching experiments, it was found that anisotropy has a small effect on springback. The difference in springback angle of specimens that were bent 90° parallel and perpendicular to rolling direction was ~0.3° as shown in Figure 17.
- Initially constant pressure pad force of 10kN was used in FE simulations done by using DEFORM 2D. Later, pressure pad force was input as a function of die stroke as in actual tests. There was a maximum difference of ~0.22° in springback angle between the two cases.
- In FE simulations done by using PAMSTAMP, three different constant pressure pad forces (3, 5 and 7 kN) were input to investigate the effect of pressure pad force on springback. There was a maximum difference of ~0.19° in springback angle between the three cases. The sheet is always in contact with the top of the punch for all pressure pad forces.
- For U-bending without stretching, springback angles obtained from experiments fell in between the springback angles obtained from FE simulations that considers the maximum and the minimum values of E-modulus (Figure 19). Thus, considering variable apparent modulus (E-modulus) should improve the FE simulation results. It was proved with the FE simulations conducted by using DEFORM 2D.

The major conclusions drawn from the study for U-bending test with stretching are:

- In U-bending with stretching experiments at 2T/20kN and 8T/80kN BHF, it was found that anisotropy also has small effect on springback. The difference in springback angle of specimens that were bent 90° parallel and perpendicular to rolling direction was ~1° as given in Tables 3 and 4. It should be noted 1 out of 3 samples (sample # 2) resulted in significantly different springback (~6° difference in flange opening angle, β) in U-bending with stretching experiments at 2T/20kN BHF in rolling direction. It can be measurement or experimental error so this sample was ignored when the difference in springback angles between the specimens bent in parallel and perpendicular to rolling direction was calculated.
- FE simulation of U-bending with stretching at 2T/20kN BHF by using DEFORM 2D considering the maximum and minimum values of E-modulus (Table 5) showed good agreement with the U-bending with stretching at 2T/20kN BHF test results. When the maximum value of E-modulus was considered the flange opening angle, β was predicted accurately (less than 1° error) but the

side wall opening angle, θ was underestimated by ~4°. On the other hand, when the minimum value of E-modulus was considered side wall opening angle, θ was predicted accurately (less than 1° error) but the flange opening angle, β was overestimated by ~5°.

- FE simulation of U-bending with stretching at 8T/80kN BHF by using DEFORM 2D considering the maximum and minimum values of E-modulus (Table 6) underestimated the springback in the flange and the sidewall by ~3° and ~5° respectively. (See Table 2-13)
- When the maximum value of E-modulus was considered in FE simulation of U-bending with stretching at 2T/20kN BHF by using PAMSTAMP (Table 5), the sidewall angle, θ, was predicted accurately (less than 1° error) but the flange opening angle, β was overestimated by ~5°. On the other hand, when the minimum value of E-modulus was considered, the springback was overestimated in the flange and the sidewall by ~10° and ~3° respectively. (Table 5)
- When the maximum value of E-modulus was considered in FE simulation of U-bending with stretching at 8T/80kN BHF by using PAMSTAMP (Table 6), the springback was overestimated in the flange and the sidewall by ~8° and ~4° respectively. When the minimum value of E-modulus was considered, the springback was overestimated in the flange and the sidewall by ~13° and ~8° respectively. (Table 6)
- FE simulations considering the variation of apparent modulus with strain may bring some improvement. Since there is bending and unbending, considering Bauschinger effect may improve the results in FE simulations by using PAMSTAMP.
- Increasing the applied blank holder force is one of the methods to reduce springback in industry. Thus, U-bending with stretching tests were done at two different blank holder forces (2T/20kN and 8T/80kN) to demonstrate the reduction in springback with increasing blank holder force. As shown in Tables 3 and 4, as the blank holder increases springback (or sidewall and flange angles) decreases in the experiments. The same trend was also observed in FE simulations with DEFORM 2D both for springback in sidewall and flange angles. However, FE simulations with PAMSTAMP only shows decreasing springback with increasing blank holder force for the flange angle not for the sidewall angle.

ACKNOWLEDGEMENTS

We would like to thank Edison Welding Institute for conducting load-unload tensile tests to obtain unloading apparent modulus variation and Cincinnati Inc. for allowing us to run V-die bending tests in their facility. We would like to thank Mr. Gautham Sukumaran for his help in the experiments.

REFERENCES

[1] Yanagimoto J., Oyamada, K. and Nakagawa T., 2005, Springback of High-Strength Steel after Hot and Warm Sheet Formings, CIRP Annals-Manufacturing Technology, 54/1:213-216.

[2] Cleveland, R. and Ghosh, A., 2002, Inelastic Effects on Springback in Metals, International Journal of Plasticity, 18:769-785.

[3] Cobo, R., Pla, M., Hernandez, R. and Benito, J. A., 2009, Analysis of the Decrease of The Apparent Young’s Modulus of Advanced High Strength Steels and Its Effect in Bending Simulations, IDDRG, 1-3 June 2009, Golden, CO, USA, 109-117.

[4] Fei, D. and Hodgson, P., 2006, Experimental and Numerical Studies of Springback in Air V-bending Process for Cold Rolled TRIP Steels, Nuclear Engineering and Design, 236:1847-1851.

[5] Morestin, F. and Boivin, M., 1996, On the Necessity of Taking into Account the Variation in the Young’s Modulus with Plastic Strain in Elastic-Plastic Software, Nuclear Engineering and Design, 162:107-116.

[6] Thibaud, S., Boudeau, N. and Gelin, J., 2002, On the Influence of the Young Modulus Evolution on the Dynamic Behavior and Springback of a Sheet Metal Forming Component, NUMISHEET 2002, 149-153.

[7] Yu, H. Y., 2009, Variation of Elastic Modulus during Plastic Deformation and Its Influence on Springback, Materials and Design, 30:846-850.

[8] Palaniswamy, H. and Altan, T., 2007, Determination of Elastic Modulus for Loading Unloading in Sheet Materials, CPF report no: CPF/1.4/07/02, The Ohio State University.

[9] Micari, F., Forcellese, A., Fratini, L., Gabrielli, F. and Alberti, N., 1997, Springback evaluation in fully 3-D sheet metal forming processes, CIRP Annals-Manufacturing Technology, 46/1: 167-170.

[10] Gutscher, G., Wu, H., Ngaile, G., and Altan, T., 2004, Determination of Flow Stress for Sheet Metal Forming Using the Viscous Pressure Bulge (VPB) Test, Journal of Materials Processing Technology, 146/1:1-7.