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Determination of variable E-modulus through wipe bending test and application to springback prediction

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Abstract. Nonlinear elastic behavior and degradation of the E-modulus with increasing plastic strain in advanced high strength steels makes the springback prediction more challenging. The conventional method for determining the E-modulus degradation with plastic strain is the loading-unloading-loading tensile test. This paper proposes a new methodology to determine E-modulus variation using a wipe bending operation. During wipe bending, the sheet material experiences simultaneous tension and compression loading through the sheet thickness, so the test data closely emulates actual metal forming conditions. Wipe bending tests for 1.2 mm MP980 steel sheet samples were conducted using different bending angles and springback was measured for each sample. Finite element model of this bending process were also developed. A constant apparent E-modulus was determined for each bending angle by comparing the springback predicted by the simulation model with the springback measured during the wipe bending test. Average effective strain was also calculated for each bending angle using FE simulations. A curve relating the E-modulus variation to effective strain was developed by correlating the apparent E-modulus and the average effective strain at each bending angle. Inputting this curve into the FE simulation revealed that springback prediction improved significantly compared to the case of using a constant E-modulus.

1. Introduction

Elastic recovery (also called springback) is a stress driven problem. Because of their high strength, Advanced High Strength Steels (AHSS) produce a large amount of elastic recovery after forming, which results in dimensional inaccuracy and limits the application of these materials. Stamping tools must be designed to compensate for springback and produce the part geometry within required tolerances. Therefore, for more accurate die design, it is important to accurately predict the springback.

An accurate prediction of residual stresses in simulation through appropriate material modeling increases the accuracy of springback prediction. Many studies have been conducted to characterize material properties and develop advanced constitutive models with objective of improving

springback prediction. Among the material properties, the yield function, the hardening law, and the unloading elastic modulus significantly affect the springback prediction [1,2]. In classic plasticity theory, the elastic recovery of material after plastic deformation is assumed to be linear with stiffness equal to Young's modulus. However, several studies have shown that the assumption of a constant unloading elastic modulus is not correct and the unloading elastic modulus decreases with increase of the plastic strain [1,3,4]. Up to 25% decrease in the unloading elastic modulus for advanced high strength steels is reported [1,5,6]. This phenomenon has a considerable effect on springback.

In the past decade, to create a material constitutive description of elasto-plasticity, the chord modulus has been used to account for degradation of the unloading elastic modulus with plastic strain. To model the unloading behavior of materials, they described the experimental observations with mathematical expressions. Several different expressions have been proposed [2,6,7]. In this work, the analytical expression, Y-U model, proposed by Yoshida et al. [6] is used:

$$E_{av} = E_0 - (E_0 - E_a)[1 - \exp(-\xi \varepsilon_0^p)] \quad (1)$$

where E_0 and E_a are the E-modulus for virgin and approximately large pre-strained materials, respectively, and ξ is a material constant.

In addition to degradation of the unloading elastic modulus, Yoshida et al. [6] and Cleveland and Ghosh [3] observed that the elastic unloading curve normally falls below the reloading curve, forming a hysteresis loop. This indicates that the unloading elastic behavior of material is not linear and therefore, the chord line method does not represent the actual material behavior in the unloading stage. To capture the nonlinear elastic behavior of the material, Sun and Wagoner [8] proposed the Quasi-Plastic-Elastic (QPE) model to more accurately predict the nonlinear unloading behavior of material. However, this is complex and not convenient for engineering applications.

The effect of the nonlinear elastic behavior of material and degradation of elastic modulus with plastic strain on springback has been ignored in most industrial forming applications, i.e., the elastic modulus has usually been assumed constant. Also, despite considerable research on explanation and constitutive description of nonlinear elastic behavior of material, there are not many studies that investigate the appropriate technique for measuring the unloading elastic modulus. The conventional method for determining the unloading elastic modulus is the uniaxial Loading-Unloading-Loading (LUL) test.

Xue et al [5] experimentally observed that the unloading elastic modulus of material can be strain path dependent. Thus, the data obtained from the uniaxial loading-unloading-loading test may not be sufficient to simulate a real forming process in which the sheet material is in a multiaxial loading state.

The objective of this work is to introduce a practical method for calculating the unloading elastic modulus degradation with plastic strain using a wipe bending test.

2. Experiments

Wipe bending tests were performed using a 5500 series Instron machine. Schematic of the tool geometry and dimensions are shown in Figure 1. A MP980 steel sheet with 1.2 mm thickness was considered and its basic mechanical properties were provided by General Motors. The flow stress data obtained from the tensile test was fitted by Swift law, $\bar{\sigma} = K(\epsilon_0 + \bar{\epsilon})^n$. The degradation of unloading elastic modulus with plastic strain was initially determined by the uniaxial loading-unloading-loading test. The experimental data was fitted by Y-U model ($E_0 = 207$ GPa, $E_a = 156$ GPa, $\xi = 15$).

The bending specimens were waterjet cut to 70×100 mm rectangular geometry with two extra flange areas which allows measuring the bending angle under load using a digital protractor. Blank holder force was applied by four M10 screws and it was carefully controlled during the test that the blank holder does not move upward due to reaction force. No lubricant was applied on the specimen surfaces. Specimens were subjected to wipe bending with a punch speed of 10 mm/min. A clearance of 1.85 mm (54% of sheet thickness) was present between the punch and the die.

Due to the nature of the wipe bending operation, during the deformation, a horizontal reaction force is applied to the punch. Therefore, a punch guide was designed to eliminate the elastic deflection of the punch and keep the clearance between the die and the punch constant throughout the deformation. The elastic deflections of the tools were measured using dial indicators and it was confirmed that the elastic deflection of the tools is small enough to be neglected in the computer simulation. Seven different punch displacement strokes i.e. 3 mm, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm were considered to provide seven different bending angles. Bending angle versus punch stroke data obtained from the experiment is shown in Figure 2. The maximum punch stroke considered in the test was 30 mm which provides 90 degree bending angle. Any punch stroke more than 30 mm does not increase the bending angle. After each test, the springback was calculated as the difference between the bending angle under load and angle after unloading. Three tests were repeated for each punch stroke and it was confirmed that the results were reproducible.

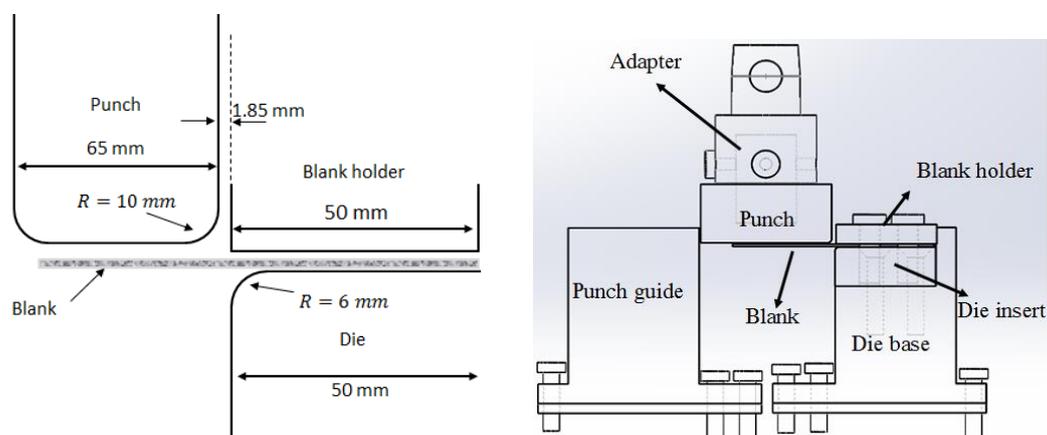


Figure 1. A schematic view of tools and dimensions used in the wipe bending tests

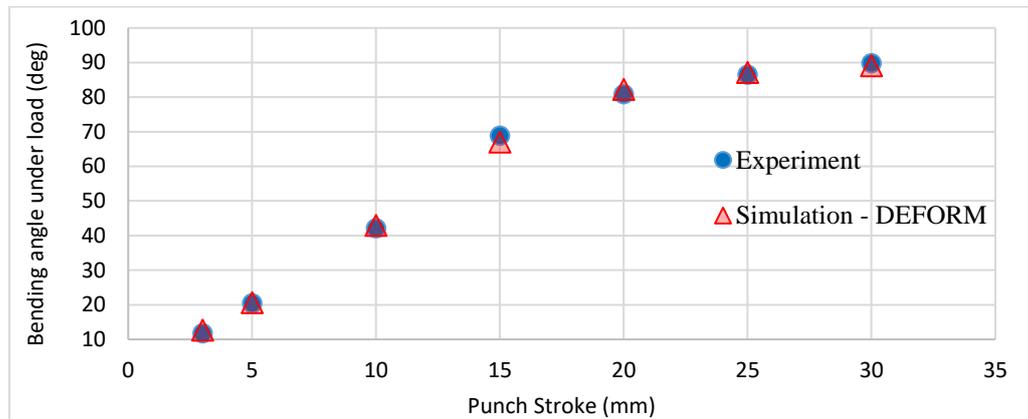


Figure 2. Bending angle under load for seven different punch strokes considered in this study

3. FE simulations of springback and inverse analysis

3.1. Simulation setup

A FE model for wipe bending was constructed in DEFORM, following the geometry shown in Figure 1. The blank was modeled using 4-node solid elements with 12 elements through the thickness direction. The tools were modeled using rigid analytical surfaces. In order to reduce the computational cost, the plane strain condition was imposed which means strain in the transverse direction was eliminated. The effect of material anisotropy was neglected and the von Mises yield criterion was used. A constant E-modulus measured from the tensile test was used as the initial value in the simulation. The Coulomb friction law was used with a coefficient of 0.1 for all contacts between tool and blank. The flow stress data of material were defined using the Swift law. No movement was allowed to the die and blank holder. A constant speed was input for the punch to move downward and form the part. Simulations were stopped at punch strokes similar to the experiment and springback was predicted at each punch stroke. The predicted bending angle under load at each punch stroke was compared with the experimental measurement to validate the simulation model, Figure 2. Results showed that the simulation model predicted the bending angle underload with less than ± 2 degree variation.

In addition to the simulation model with constant E-modulus, two other simulation models were also conducted with variable E-modulus as a function of plastic strain. One model is based on the data obtained from the loading-unloading-loading tensile test and the other model is based on the data obtained from the inverse analysis method described in next section. Results of springback predicted by these three simulation models are compared with experimental measurements for all seven different punch strokes.

3.2. Inverse analysis method

The inverse analysis method is used to determine an apparent E-modulus for a given punch stroke which can provide accurate springback prediction, Figure 3. In this method, the springback predicted from the simulation model with the constant E-modulus, was compared with experimental

measurement. Based on the comparison result, the E-modulus in the simulation was adjusted to predict the springback more accurately. The value of the E-modulus which can provide accurate springback prediction for a certain punch stroke / bending angle under load was considered as the apparent E-modulus for that punch stroke.

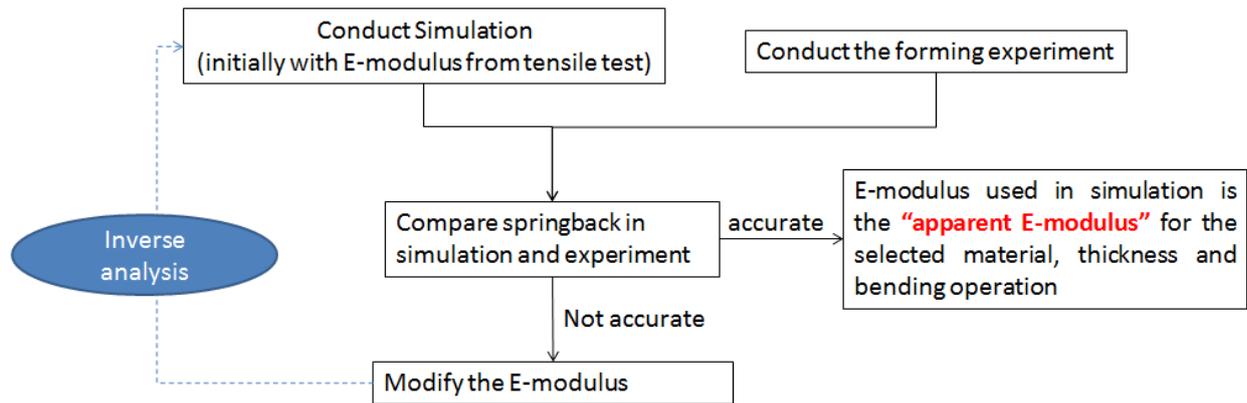


Figure 3. Inverse analysis method used to determine the apparent E-modulus for each punch stroke / bending angle under load.

3.3. Calculation of the E-modulus variation through the Inverse analysis method

The inverse analysis method was used to determine an apparent E-modulus for each punch stroke. To correlate the punch stroke to strain, and determine the variation of E-modulus as a function of strain, average strain in the part at each punch stroke was calculated as:

$$\bar{\epsilon}_{av} = \frac{\sum \bar{\epsilon}_i}{n} \quad (i = 1 - n) \quad (2)$$

where $\bar{\epsilon}_i$ is the effective strain of the i^{th} element and n is the total number of the elements which have strain value more than zero. The average strain in the part rose up until the punch strokes reaches to 20 mm and then by continuing the punch movement, the average strain is reduced.

4. Results and discussion

4.1. Elastic modulus degradation with plastic strain

Figure 4 shows the selected apparent E-modulus for each punch stroke. In general, by increasing the punch stroke the apparent E-modulus decreases and reaches a saturation value. This is consistent with the results of the LUL tensile test. The reduction of E-modulus by increasing the punch stroke is due to increase of plastic strain. The minimum calculated apparent E-modulus, 155 GPa, was considered as the saturation value E_a in the Y-U model.

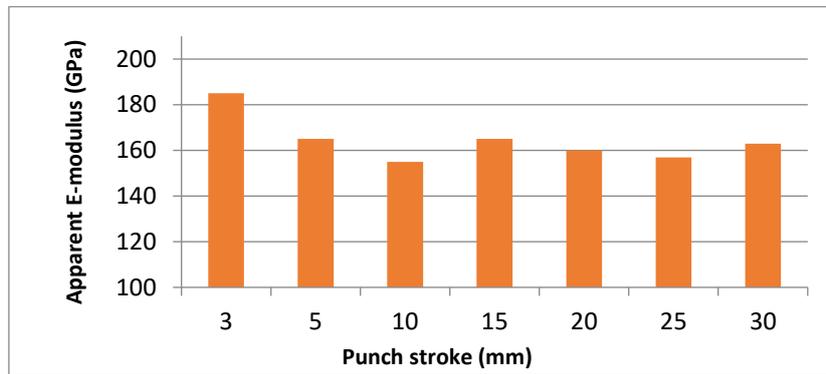
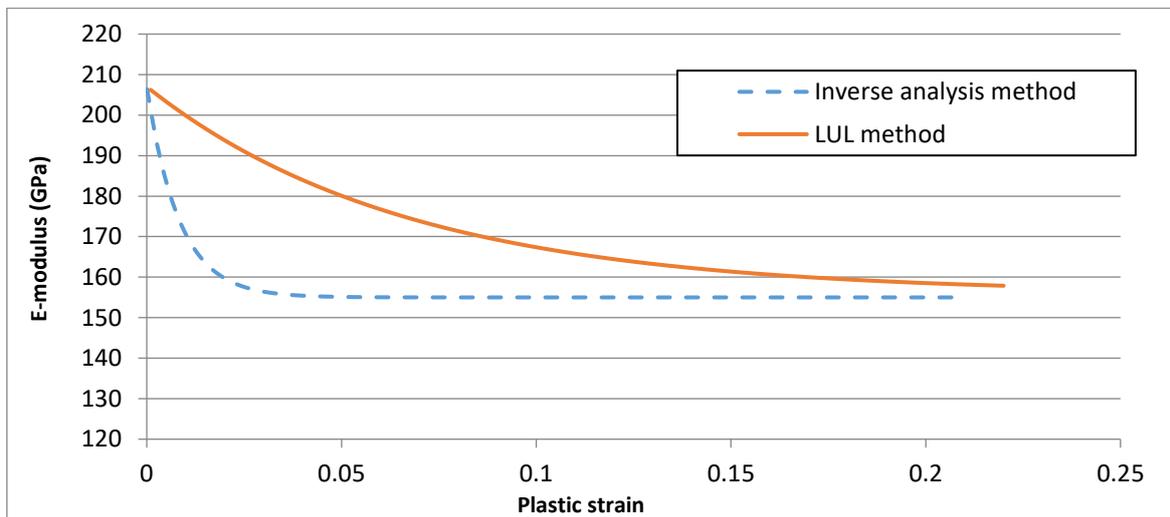


Figure 4. Selected apparent E-modulus through the inverse analysis at each punch stroke

The apparent E-modulus calculated for each punch stroke, Figure 4, was used to create the variable E-modulus versus strain curve. Since the average strain at the part starts to decrease after about 20 mm punch stroke, the apparent E-modulus for the strokes more than 20 mm is eliminated from the data. Figure 5 shows the comparison between the Y-U curve obtained from the wipe bending test and the inverse analysis method and the curve obtained from the LUL tensile test. The saturated value of the E-modulus (E_a) was about 155 GPa in both methods. However, the reduction rate of the E-modulus with strain (ξ) is more abrupt in the model obtained from the inverse analysis method than the model obtained from the LUL tensile test. In order to investigate the improvement in springback prediction using the variable E-modulus, the calculated curves from the inverse analysis method and the LUL method were applied in the simulations and results were compared with experimental measurements.



Test method	E_0 (GPa)	E_a (GPa)	ξ
LUL Method	207	156	15
Inverse analysis method	207	155	120

Figure 5. Comparison of the E-modulus versus plastic strain calculated from the inverse analysis method and the LUL method

4.2. Improvement in springback prediction using the variable E-modulus

Figure 6 shows the springback prediction at each punch stroke from three simulation models i.e. with constant E-modulus, with variable E-modulus that is obtained from the LUL method, and with variable E-modulus that is obtained from the inverse analysis method. In all three simulation models, springback increases by increasing the punch stroke similar to the experimental results. The most accurate prediction results were obtained when the variable E-modulus from the inverse analysis method was used. Using the variable E-modulus from the LUL test improved the prediction results compared to the case of using the constant E-modulus.

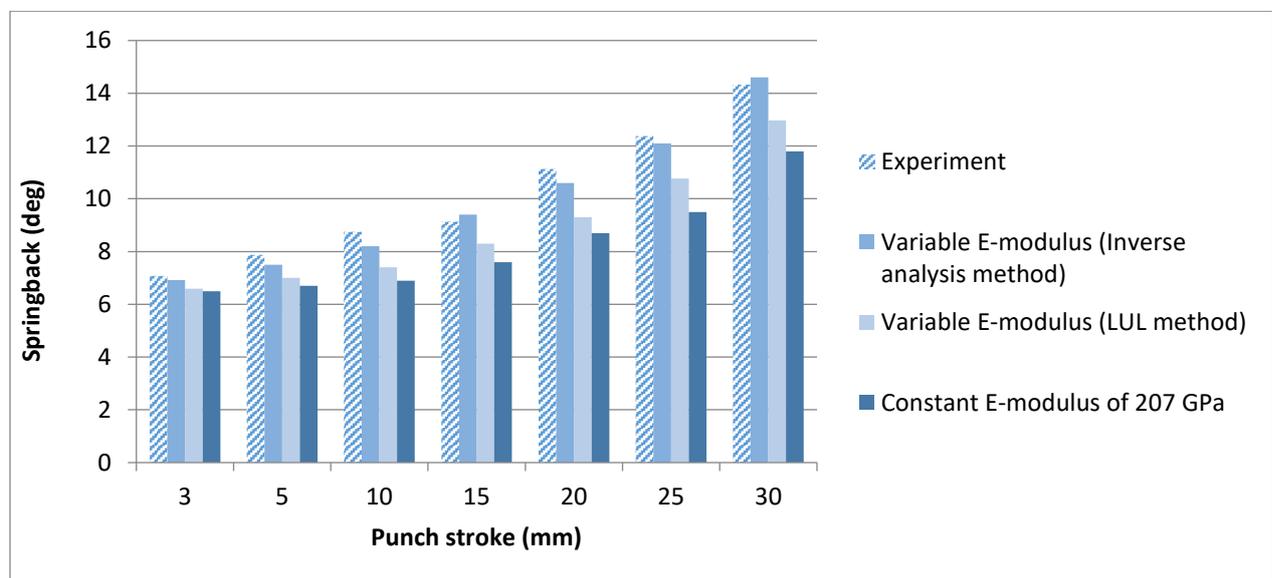


Figure 6: comparison of springback prediction results obtained from simulation models with different E-modulus and experimental measurement

5. Conclusions

E-modulus determines the stiffness of the material and the amount of elastic strain during the deformation. Therefore, it is one of the most important material properties affecting the springback prediction. The elastic deformation of some steel materials is not linear and this makes determination of the E-modulus difficult. Also, researchers have shown that the E-modulus is strain path dependent and an E-modulus obtained from uniaxial test may not accurately represent the material stiffness in multiaxial forming process.

In the current study, the inverse analysis method was used to determine the variation of E-modulus with plastic strain. The wipe bending test was considered as the experiment which provide plane strain condition. Results showed that using the variable E-modulus versus plastic strain obtained

from the inverse analysis method significantly improves the springback prediction compared to the case of using the constant E-modulus, or variable E-modulus from the LUL test.

Calculation of strain in the wipe bending test was performed by averaging the strain values of all elements of the part. Since the strain distribution in the part during the wipe bending operation is not uniform, taking the average of strains reduces the accuracy of the inverse analysis method for prediction of springback. Determination of E-modulus degradation with plastic strain through a bending operation which can provide a pure bending condition at the part can increase the accuracy of the method.

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