Developing Methods for Prediction and Reduction of Springback using a Practical Method to Estimate E-Modulus

THESIS

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Abstract

Bending operations such as U-bending, hat bending, V-bending etc. are commonly used operations in the sheet metal forming industry. Springback is one of the most difficult and important challenges to forming good quality parts in these operations, especially for materials like Advanced High Strength Steels, Copper and Aluminum. Currently, dies are modified and recut three to five times in the industry to compensate for springback and ensure part quality. Improving the accuracy of prediction and reduction of springback would reduce the time and cost for die development and tryout. Existing mathematical models for springback prediction are complicated and require various material parameters that are difficult or expensive to obtain. This study aims to develop a simple method for accurate prediction and reduction of springback in the U-bending and Wipe bending processes.

Experiments were carried out for U-bending of AHSS and Aluminum using Shiloh die and S shaped die and wipe bending of Copper alloy using a die designed at CPF. The materials were bent to different angles. Simulations were carried out using DEFORM and PAM-STAMP for same conditions as experiments. The springback results of simulation and experiments were compared and inverse analysis was carried out to find the value of apparent E-moduli that would accurately predict the springback in different materials for the different bending angles. Experiments were conducted to investigate the effect of ram speed and ram motion on springback of AHSS and Aluminum alloys in the U-bending
process. Simulations were conducted in PAM-STAMP to study the effect of variation of pad force on springback in U-bending with crunching operation.

Inverse analysis was successfully applied to predict springback accurately in different materials with different part geometries. An apparent E-modulus vs strain curve was developed which can be input to FE software for the analysis of forming operations and springback. Ram speed and ram motion do not have significant impact on springback. The pad force was varied to successfully obtain an optimum value that would eliminate springback in the U-bending with crunching operation of AHSS.
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Chapter 1: Introduction

Stamping or sheet metal forming is a manufacturing process used to make a wide range of products such as washing machines, pressure vessels, automotive parts and even small parts such as mobile phones. Thus, the sheet metal industry is very large and a large number of companies, especially the automotive companies, are interested in the developments in this industry.

The automotive industry extensively uses materials such as Advanced High Strength Steels. AHSS are a newer generation of steel grades that provide extremely high strength while maintaining high formability which is required for manufacturing. Advanced High Strength Steels (AHSS) high are widely used in the automotive industry to meet increased specifications for strength, crash worthiness, energy absorption, part complexity, safety, efficiency, dent resistance, manufacturability, durability and quality while reducing weight and thus reducing the cost. Different type of AHSS help the different parts of the automobile meet the various performance criteria. The various types of AHSS are shown in Figure 1.
Safety regulations have increased the use of AHSS in vehicles. The National Highway Traffic Safety Administration sets various standards for vehicle safety such as impact resistance etc. Meeting these standards means addition of safety components which leads to addition of more material and thus more weight. Use of AHSS provides flexibility in design due to their high strength to weight ratio. This helps to make the automobile fuel efficient and helps it to meet the corporate average fuel economy standards.

The materials are subjected to different sheet metal processes such as drawing, blanking and bending to make the various parts in automobile industry. This study focusses on simple sheet metal operations such as U-bending and wipe bending.

The tooling for both wipe bending (shown in Figure 2) and U-bending (Figure 3) consists of three major parts: the punch, the die and the blank holder or pad. The sheet is placed on the die and held in position by the force applied by the blank holder or pad. The punch moves down to bend the sheet.
The bending processes present several challenges concerning the quality of the part manufacture.
Fracture and excessive thinning

When the strains in the part exceed the formability of the material, the part cracks as shown in Figure 4 (left). This is called fracture. Different materials can tolerate different strains depending on their formability. In some cases, the parts may not fracture, however they undergo high amounts of thinning which makes them useless.

Wrinkles

This defect as shown in Figure 4 (right) is generally found in hat bending. This is caused because of the radial drawing stresses and tangential compressive stresses acting on the blank during the drawing/bending process.

Figure 4: Fracture (left) and wrinkle (right) in sheet metal formed part

Springback

This is the deformation in the part after the unloading of the tools and results in dimensional inaccuracies in the part as shown in Figure 5. Springback occurs due to the elastic recovery of the part after unloading as shown through a schematic diagram in Figure 6. Springback causes dimensional inaccuracies in the part which leads to increase
in tolerances. In U-bending and wipe bending, springback is measured as the difference between angle under load and angle after unloading the tools.

Figure 5: Springback in hat shaped part

Springback is affected by a combination of several factors such as material properties, tool geometry, process parameters and geometry of the blank. This makes it difficult to accurately predict springback. Accurate prediction and reduction of springback are very important to reduce time and money spent in die development and try out. Currently existing methods of accurate springback prediction are complicated continuum mechanics based models which require various material parameters which makes it
difficult and expensive to use them. This study aims at developing a simple method to predict springback accurately using experiments and finite element simulations (in DEFORM and PAM-STAMP) to analyze bending and springback, so as to reduce the number of die tryouts to save time and money. This study also aims to develop a method to find the optimum pad force to eliminate springback using finite element simulations in PAM-STAMP.

**Thesis Outline**

Chapter 1 is a brief introduction to commonly used sheet metals, bending operations and springback and the need for accurate prediction and reduction of springback. Chapter 2 states the objectives of this study and the approach followed. Chapter 3 described the fundamentals and mechanics of materials, bending and springback and the previous studies on U-bending, wipe bending, prediction of springback and reduction of springback. Chapter 4 talks about experiments and simulations (in PAM-STAMP) carried out using Shiloh Die and the methodology used to reduce and accurately predict the springback in U-bending of AHSS:- DP 590 (1.4 mm) and Aluminum alloys:- Al 5182-O (1.2 mm) and Al 6014 (1.2 mm). Chapter 5 describes the design of TE Connectivity die, experiments and simulations (in DEFORM) carried out using this die and the methodology used to reduce and accurately predict the springback in wipe bending of copper alloys along with development of apparent E-modulus vs strain curve for input to simulation software. Chapter 6 describes experiments and simulations (in DEFORM for 2-D and PAM-STAMP for 3-D) carried out using an S-shaped die (S-CPF die) and the
methodology used to reduce and accurately predict the springback and twist in 2-D and 3-D U-bending of AHSS: DP 780 (1 mm) along with development of apparent E-modulus vs strain curve for input to simulation software. Chapter 7 concludes this study with an overall summary of the study and the future work.
Chapter 2: Objectives and Approach

The overall objective of this study is to develop a guideline to predict and reduce springback through experiments and finite element simulations of U-bending and wipe bending operations with different tools, materials and part geometries.

The approach used for this is described below

**Phase I:** Experiments and finite element simulations of U-bending of DP 590, Al 5182-O and Al 6014 using Shiloh die

**Phase 2:** Experiments and finite element simulations of wipe bending of copper alloy-C7026 (0.3 mm) using TE Connectivity die (designed at CPF)

**Phase 3:** Finite element simulations of U-bending of DP 780 (1 mm) using S-CPF die and comparison with experiments previously carried out at CPF [Kardes et al. 2012 and Kardes 2012]
Chapter 3: Literature Review

This section describes the preliminaries required to understand the properties of sheet metals, bending and springback. It also describes the previous studies related to U-bending, wipe bending, prediction and reduction of springback.

3.1 Material properties and characterization

The important material properties required to understand bending and formability of materials are described here:

3.1.1 Stiffness and E-modulus

Stiffness is defined as the resistance to elastic deformation. It depends on the part shape, loading conditions and elastic modulus. The value for the E-modulus or elastic modulus is given by the slope of the elastic portion of the stress-strain curve for a material. The E-modulus decreases with increasing plastic strain [Morestin and Boivin 1996]

3.1.2 Strength

The maximum strength of a material is given by ultimate tensile strength where flow stress (as obtained from tensile test) is maximum. Plastic flow or deformation occurs due to movement of dislocations present in the crystal structures. Impeding the movement of dislocations increases the strength and decreases ductility. Different mechanisms such as
solid solution strengthening (alloying), mechanical working (strain hardening), dispersion and precipitation hardening, etc. are used to increase the strength of metals. [Demeri, M., 2013]

3.1.3 Elastic-plastic properties of materials

The flow stress or true stress-strain curve for a material reflects the elastic-plastic properties of a material. This curve is one of the most important variables for calculating input data for finite element (FE) and analytical methods used to predict metal flow and defects. [Kardes et al., 2011]

3.1.4 Necking, Uniform Elongation and Formability

In a tensile test, necking is the localization of strains which occurs towards the end of the test. At this stage, strains and stresses are no longer uniform over the length of measurement or gage length. Formability is the limit of uniform elongation after which necking begins. The Considere criterion gives an estimate of the end of uniform elongation and the beginning of necking. As per the criterion, onset of necking and the end of uniform elongation occur when the true work hardening rate exactly equals the true strain. The general form of Considere Criterion states that:

\[
\frac{d\sigma}{d\varepsilon} = \sigma \quad \text{or} \quad \frac{d(\ln \sigma)}{d(\ln \varepsilon)} = \varepsilon \quad [\text{Wagoner and Chenot, 1997}] \tag{1}
\]

3.1.5 Hardening rules

As the material undergoes elasto-plastic deformation, its yield surface changes in size, shape and position. The variation of yield surface with plastic deformation is given by hardening rules.
Isotropic hardening: In the case of isotropic hardening, the shape of the yield surface does not change but it increases in size with increasing stress as can be seen in Figure 7. The shape of the yield surface is defined by the initial yield function and the change in its size depends on the change in the hardening parameter $K$. The yield function is of the following form:

$$f(\sigma_{ij}K_i) = f_0(\sigma_{ij}) - K = 0$$  \hspace{1cm} (2)

![Figure 7: Schematic of yield surface in isotropic hardening [P. Kelly]](image)

Kinematic hardening: In case of kinematic hardening, the shape and size of the yield surface remains the same but it translates in space as shown in Figure 8. This rule is useful for modeling cases such as Baushcinger effect where a hardening tension leads to softening in subsequent compression. The yield function is of the form:

$$f(\sigma_{ij}K_i) = f_0(\sigma_{ij} - \alpha_{ij}) = 0$$  \hspace{1cm} (3)
The hardening parameter is $\alpha_{ij}$. This is known as the back-stress.

Mixed hardening rules: This is a more complex type of hardening rule which combines features of both isotropic and kinematic hardening form. The general form of the loading function is given as below

$$f(\sigma_{ij} K_i) = f_0(\sigma_{ij} - \alpha_{ij}) - K = 0$$

The scalar $K$ and tensor $\alpha_{ij}$ are the hardening parameters.

[H. P. Kelly]

### 3.2 Material Characterization

The flow stress properties can be obtained from tests which measure the effect of strain and strength such as tension tests, torsion tests, compression tests, bulge tests, plane strain compression tests etc. [Hosford and Cadell, 2011] The tensile test and bulge test

$$f(\sigma_{ij} K_i) = f_0(\sigma_{ij} - \alpha_{ij}) = 0$$
are commonly used in CPF to find the elastic modulus and flow stress properties for different materials. These tests are described in this section.

3.2.1 Tensile Test

The tensile test is carried out to study the variation of stress with strain for a material. Several characteristic properties of the material can be obtained from the tensile test:

*Elastic modulus*: The elastic modulus (E-modulus), also known as the young’s modulus is the slope of the elastic part of the engineering stress-strain curve.

*Yield strength*: The value of stress at the point on the engineering stress-strain curve at which the plastic deformation begins. For some materials the yield point is not clearly defined. In such cases a line parallel to the linear elastic region is drawn at an offset of 0.2% strain. The stress at the point of intersection of this line with the stress-strain curve is the yield strength.

*Ultimate tensile strength*: This is the maximum engineering stress that the material can withstand in the tensile test before localized necking.

*Uniform elongation*: The elongation of the test sample at the maximum load is called the uniform elongation.

*Total elongation*: This is the elongation of the sample at fracture. It is the total of both uniform and post uniform elongation. [Sever et al., June 2011]

The engineering stress-strain curve as shown in Figure 9 is obtained from the load extension curve by using equations (5) and (6).

$$\sigma_e = \frac{F}{A_0} \quad (5)$$
The true stress-true strain curve as shown in Figure 9 is obtained by finding the true stress and true strain from the engineering stress and strain using the equations (7) and (8).

\[ \sigma = \sigma_f (1 + \varepsilon_e) \]  
\[ \varepsilon = \ln(1 + \varepsilon_e) \]

Figure 9: Example of engineering and true stress-strain curves [Sever et al., June 2011]

Often, material suppliers do not provide the true stress-strain data. They provide only the yield stress and ultimate tensile strength of the material. Hollomon’s power law (equation (9)) is a commonly used empirical stress-strain relationship. It is obtained by fitting an exponential curve to the experimental data points of the flow stress curve.

\[ \sigma = K \varepsilon^n \]  

where

K = strength coefficient
n = strain hardening coefficient

FE simulation input requires the full stress strain curve. Thus the values of UTS and Yield Strength (Y) are used to obtain the value of K and n. In this method [Sever et al., August 2011], there are two assumptions:

1. Effect of strain is neglected
2. Strain hardening exponent, n remains constant for all strains

Since both Y and UTS lie in the plastic region of the flow stress curve, the Hollomon power law is applicable to both points as shown in equations (10) and (11).

\[
\sigma_{UTS} = K\varepsilon_u^n \\
\sigma_Y = K\varepsilon_0^n
\]  

where

\(\varepsilon_u\) = uniform elongation

\(\varepsilon_0\) = elastic strain at yield point

Using Considere criterion, it can be shown that the total elongation equals the strain hardening exponent n as shown in equation (12):

\[
\frac{d\sigma_{UTS}}{d\varepsilon} = \sigma_{UTS}
\]

Therefore

\[nK\varepsilon_u^{n-1} = K\varepsilon_u^n\]  

Therefore

\[n = \varepsilon_u\]

The elastic strain at yield point can be found using equation (15).

\[
\varepsilon_0 = \frac{\text{yield strength}}{\text{elastic modulus}}
\]
So now we have two equations as follows:

\[ \sigma_{UTS} = Kn^n \]  \hspace{1cm} (16)
\[ \sigma_Y = K\varepsilon_0^n \]  \hspace{1cm} (17)

The values of \( K \) and \( n \) can be found from equations (16) and (17) by trial and error or iterations.

3.2.2 Viscous pressure bulge test

The tensile test has two major disadvantages:

- It is uniaxial
- It can give plastic hardening curves only up to the point of diffuse necking, which normally occurs for logarithmic strains in the range of 0.15-0.25.

Normally, the curve obtained from tensile tests is extrapolated up to the levels of plastic strains. However as per [Mattiasson 2004] this process gives quite erroneous results. Thus to get stress-strain data at higher levels of plastic strains, the viscous pressure bulge test proves to be quite useful as the necking and fracture occurs at higher levels of strains compared to uniaxial tensile test. The viscous pressure bulge test also gives biaxial properties of the material which may be required for input to FE simulations or mathematical models of forming processes.[Sigvant m, et al., 2009]

In the viscous pressure bulge test [Altan and Tekkaya, 2012(b)], a pressurizing g medium of oil/viscous fluid is used to stretch a sheet metal against a circular die, Figure 10. The sheet metal which is clamped at the edges bulges to form a hemispherical dome and then bursts. The specimen just before and after bursting is shown in Figure 11.
The membrane theory is used to determine the flow stress curve from the viscous pressure bulge test. Thus it is applicable only to thin sheets. The relationship between stresses, sheet geometry and bulge pressure is given by equation (18).

$$\frac{\sigma_1}{R_1} + \frac{\sigma_2}{R_2} = \frac{p}{t} \tag{18}$$

where:

$\sigma_1$ and $\sigma_2$ are principal stresses on the surface of the sheet

$R_1$ and $R_2$ are corresponding radii of the curved surface

$p$ is the hydraulic pressure
t is the sheet thickness

For the axisymmetric bulge test,

\[ \sigma = \sigma_1 = \sigma_2 \]  \hspace{1cm} (19)

And

\[ R_d = R_1 = R_2 \]  \hspace{1cm} (20)

Thus equation (18) now becomes

\[ \sigma = \frac{p R_d}{2 t_d} \]  \hspace{1cm} (21)

where \( t_d \) is the thickness of the sheet at the top of the dome. In hydraulic testing, the pressure acts on the inner surface and there are no normal forces on the outer surface of the sheet. Thus the average normal stress on the sheet surface is given by equation (22).

\[ \sigma_n = \frac{1}{2}(-p + 0) = -\frac{p}{2} \]  \hspace{1cm} (22)

Using the Tresca plastic flow criterion, the effective stress is given by

\[ \bar{\sigma} = \sigma_{\text{max}} - \sigma_{\text{min}} = \frac{p R_d}{2 t_d} - \frac{p}{2} \]  \hspace{1cm} (23)

or

\[ \bar{\sigma} = \frac{p}{2} \left( \frac{R_d}{t_d} + 1 \right) \]  \hspace{1cm} (24)

The effective strain is given by

\[ \bar{\varepsilon} = \ln \left( \frac{t_d}{t_0} \right) \]  \hspace{1cm} (25)

where \( t_0 \) is the initial sheet thickness. These equations are used to find the stress and strain to form the flow stress curve [Gutscher et al., 2004].
3.3 Mechanics of bending

To understand bending process, it is important to understand the mechanics of bending. The variables used in the analysis of bending mechanics are shown in Figure 12, where Ri is the inner bending radius, Ro is the outer bending radius, Rm is the radius of central fibre, Rn is the radius of neutral axis (where the elongation is zero), and R is the radius of an arbitrary layer, used in analysis.

![Figure 12: Schematic of different radii in the bent sheet [Altan and Tekkaya 2012(a)]](image)

During a bending operation, the outer fibers of the sheet metal are stretched while the inner fibers are compressed. Furthermore, during bending additional deformation mechanisms, such as tension and shear, may occur. The bending stress distribution in the bent part is shown in Figure 13. The bending strain distribution is shown in Figure 14.
Integrating the bending stress over the thickness of the sheet gives the bending moment.

In elementary bending theory, thinning of the material is zero in case of rigid plastic materials. Thus the bending moment per unit width is given by:

\[
M = M_p = \int_0^t \sigma_x y dy = \int_{-t/2}^{t/2} F\bar{\sigma} y dy = F\bar{\sigma} \frac{t^2}{4} \quad [\text{Wang 1993}] \tag{26}
\]
3.4 Mechanics of U-bending, wipe bending and V-bending

The mechanics of V-bending are described in this section. The mechanics of wipe bending and U-bending are very similar to the mechanics of V-bending. Figure 15 shows the region of the material at the bending radius where the elastic and plastic deformation take place. The piecewise subdivisions of the bent sheet are also shown.

Figure 15: Schematic of elastic and plastic deformation regions at bending region [Yang et al., 2016]

[Yang et al., 2016] suggested that for AHSS, it is more useful to calculate the loading moment piecewise over the thickness as shown in Figure 15. Here, the loading and unloading moments are assumed to be equal and are denoted as $M(S)$. This moment is calculated using the following equation:

$$M(S) = w \int_{\varepsilon(S)_{1}}^{\varepsilon(S)_{-1}} \sigma_x y dy + w \int_{\varepsilon(S)_{ln}}^{\varepsilon(S)_{-1}} \sigma_x y dy + w \int_{\varepsilon(S)_{out}}^{\varepsilon(S)_{1}} \sigma_x y dy$$  (27)
The first part on the right hand side of the equation represents the elastic part of the moment while the other two parts represent the elasto-plastic part of the moment. The different variables used in the equation are described below.

\( w = \) sheet thickness

\( \varepsilon_1 = \) elastic strain in positive direction of elastic region

\( \varepsilon_{-1} = \) elastic strain in negative direction of elastic region

\( \varepsilon_{\text{in}} = \) strain on inner extreme fiber of sheet

\( \varepsilon_{\text{out}} = \) strain on outer extreme fiber of sheet

\( \sigma_x = \) stress which is calculated by Hooke’s law for elastic deformation and Swift’s law for plastic deformation

Swift’s law is given by \( \sigma_t = K (\varepsilon_0 + \varepsilon_t)^n \)

where:

\( \sigma_t = \) true stress

\( \varepsilon_t = \) true strain

\( \varepsilon_0 = \) pre-strain

\( K = \) strength coefficient

\( n = \) strain hardening exponent

The springback angle, which is the elastic recovery of the part after unloading can thus be calculated as:

\[
\theta_{sb} = \sum_{i=1}^{n} \int_{S_n} \frac{M(S)}{E(S)^n} dS
\]

where

\[ (28) \]
$\theta_{sb}$ = springback angle

M(S) = bending moment

E(S)' = variable elastic modulus

I = moment of inertia

n = number of regions into which the calculation of elastic modulus is split up.

The strain varies at different regions on the arc. This causes the elastic modulus to vary. Hence a region wise calculation of the elastic modulus is more useful than using a constant value over the entire region. [Bader 2016]

### 3.5 Material Properties affecting springback

The important material properties that affect the springback are total strain, yield limit, E-modulus or Young’s modulus, strain hardening coefficient or flow stress curve and Bauschinger effect. The effect of these properties on springback can be seen in Figure 16.

*Bauschinger effect [F. Yoshida et al., 2002]*

According to the literatures, the numerical results of springback are strongly influenced by modeling of the Bauschinger effect. The Bauschinger effect is characterized by two distinct phenomena of stress-strain responses: One is the so-called “transient softening” which is the smooth transient stress-strain response at the early stage of stress reversal and the other is the so-called “permanent softening” appearing after the transient period, as schematically illustrated in Figure 17. The transient Bauschinger effect should be taken into account for an accurate prediction of springback. Wagoner et al. (2000) have
stressed that the permanent softening mainly affects springback, showing the results of numerical simulations and experimental data of draw-bending on aluminum alloy strips. Besdo (2000) discussed the effect of early re-yielding on springback.

Figure 16: Effect of material properties on springback [Altan and Tekkaya, 2012a]
Figure 17: Schematic illustration of stress-strain response during forward and reverse deformation [F. Yoshida et al., 2002]

3.6 Inverse Analysis

“Inverse Analysis” is a new methodology introduced by CPF for improving the accuracy of springback prediction. In this method, an average constant $E$ value for a given material, geometry, and bending process is determined by measuring springback in one experiment and comparing with simulations. This method is essentially the same method used in industry today in die development and tryout.

Procedure:

In the Inverse Analysis method, experiments are carried out and springback is measured. Then simulations are carried out using the same tooling geometry as the experiments and
using an initial E-modulus obtained from the tensile test. The simulation and experimental results are compared. Generally the E-modulus from tensile tests under predicts the springback. Since springback increases with decreasing E-modulus, further simulations are carried out with lower values of E-modulus. Using two or three different appropriate E-moduli, the curve for E-modulus vs springback is developed. The variation of E-modulus with springback is not linear. Thus it is often more useful to have an E-modulus vs springback curve obtained by using more than two values of E-modulus. Using this curve the appropriate E-modulus corresponding to springback measured from experiment can be found out. This gives the apparent E-modulus which would predict the springback accurately in FE simulations.

Figure 18 below shows a flow chart describing the algorithm followed for Inverse Analysis. Figure 19 gives an example of Inverse Analysis.

![Flow Chart](image)

**Figure 18: Algorithm for inverse analysis**
Figure 19: Example of inverse analysis

### 3.7 Previous studies on Wipe bending and U-bending

[Livatyali and Altan 2001] carried out wipe bending using AKDQ and CQ steels and AA6111 to investigate the influence of die corner radius, punch radius, punch and die clearance, pad force and material properties on springback. Wipe bending experiments were carried out on a tool designed with punch and die inserts with different radii. It was found that springback increases with increasing die corner radius, increasing punch and die clearance and decreasing pad (blank holder force). The springback increased with increasing punch radius up till a certain maximum value after which it was constant. The effect of E modulus was observed clearly as AA6111 with three times smaller E-modulus value gave larger springback.

[Mkaddem and Saidane, 2007] also carried out wipe bending tests and studied the effect of punch stroke, punch and die clearance and die radius. The springback varied non-
linearly with punch stroke. Similar to [Livatyali and Altan 2001], springback was found to increase with increasing die radius and increasing punch and die clearance. The variation was non-linear. The influence of anisotropy and the bobbing process which occurs during the rolling of sheet metal (deformation history of the sheet metal) on springback was also studied. The paper also describes RSM, a theoretical model using cubic approximations and response surfaces for springback prediction.

3.8 Previous studies on Mathematical Modeling of bending and prediction of Springback

[Chaboche and Rousselier, 1983] developed continuum mechanics based equations which used a combination of isotropic and nonlinear kinematic hardening rules. These were successful in modelling monotonic and cyclic behavior of metals and alloys and are used in commercial FE software. A uniaxial constitutive model was proposed by [Hu et al 1992] and [Hu 1994]. This was generalized to multiaxial state of plasticity by [Teodosiu et al., 1997]. These models were successful in simulating the transient Bauschinger effect and the workhardening stagnation but failed to accurately describe the small scale re-yielding which is important for modeling and simulating springback.

[Yoshida and Uemori, 2002] developed a model for large-strain cyclic plasticity to account for all aspects of the Bauschinger effect and variation of E-modulus with strain. The model introduces a backstress evolution equation for accurate representation of the reverse stress-strain curve of the transient Bauschinger deformation and a non-isotropic hardening surface to describe the workhardening stagnation. The Yoshida-Uemori model
has seven material parameters in the basic version, most of which can be determined from the stress-strain curve. The accuracy of the model was validated by comparing results of numerical simulations and experimental results for stress-strain behavior of mild steel, high strength steel and aluminum under cyclic deformation at large strain.

Studies on tensile tests of DP 780 and DP 980 with intermediate unloading cycles by (Sun and Wagoner, 2011), show that unloading and reloading are nonlinear and form hysteresis loops, Figure 20 (left). This is a challenge to accurate springback prediction. The E-modulus measured from the slope of the loop is found to be significantly different from the chord E-modulus as can be seen in Figure 20 (right) where the blue line represents the E-modulus from the slope of the curve and green line represents the chord E-modulus.

Figure 20: Four cycle load unload test on DP 980 (left) and expanded view of one loop of the test (right) [Sun and Wagoner 2011]
To account for this, a special component of strain called the quasi-plastic-elastic strain is introduced in the paper and its properties are mentioned. A constitutive model called the quasi-plastic-elastic (QPE) model is developed to represent the variation of E-modulus with strain, hysteresis loops in tensile test and hardening rules. The model is a two surface constitutive model where the inner surface account for the elastic-QPE transitions and the outer surface can be defined using any plastic constitutive model. This is used in FE software and the results of FE simulations and experiments are compared for tensile tests, reverse tension-compression tests and draw bending tests. This model significantly improved prediction of springback. This model too requires a significant number of parameters from the tensile test.

The mathematical models are successful in reasonably accurate prediction of springback but the major drawback of these models is that they require a large number of material parameters which are expensive and time consuming to obtain.

### 3.9 Previous studies in reduction of springback

[Ogawa and Yoshida 2011], carried out experiments on TS590 (1.02 mm) to investigate the effect of bottoming on springback in U-bending. Three die corner radii: 4.02, 4.07 and 4.12 mm were used in this study. FE simulations of the process were also carried out using both rigid tooling and deformable tooling (to account for elastic deflection) to study the effect on springback prediction. Effect of material hardening model on springback prediction was also investigated. The study concluded that bottoming reduced springback to a certain extent but was not successful in eliminating it. A combination of deformable
tooling and advanced kinematic hardening model: Y-U model gave most accurate springback prediction.

[Komgrit et al, 2016] introduced a new four step U-bending process for the reduction of springback. This process used a counter punch for bottoming as shown in Figure 21. The punch has a shallow hollow at the bottom with depths of 0.5 mm, 1 mm and 1.5 mm as shown in figure. The counter punch bottoms the sheet after the bending operation by pushing it into this hollow. This operation is shown in Figure 21.

[Weinschenk and Volk 2014] suggested a change in part geometry to reduce springback. This study was carried out on hat bending however it can also be applied to U bending. The paper suggests a modification of the conventional U-shaped profile. The single radius at the corner of the conventional geometry leads to springback in one direction. This can be countered by replacing the single radius with three radii. The important geometrical parameters for this were defined by radii r₁, r₂ and r₃ and related angles α, β
and $\gamma^0$ and as shown in Figure 22. The relation between these parameters is given by the following equations:

$$\alpha - \beta + \gamma = 90^\circ \quad (29)$$

$$a = r_1 - (r_1 + r_2) \cos(\alpha) + (r_2 + r_3) \sin(\gamma) \quad (30)$$

$$b = (r_1 + r_2) \sin(\alpha) - (r_2 + r_3) \cos(\gamma) + r_3 \quad (31)$$

![Figure 22: Schematic of suggested profile with multiple radii](image)

Different combinations of these parameters are evaluated to find the optimum combination for minimum springback.

The disadvantages of the methods for reduction of springback described above are that either they are not successful in eliminating springback [Ogawa and Yoshida] or the geometry of the part is changed which may not be acceptable to industry.

Tamai et al. investigated the effect of ram motion (attach-detach) on drawing and springback of TRIP 780 and DP 780. It was found that the attach-detach motion reduced springback in hat bending and increased the draw depth by 13-17%. It was also found
that for reducing springback, the ram stroke where the detachment happened was more important than the number of detachments. There was maximum reduction in springback when detachment occurred at the end of the stroke.

This study aims to develop a simple method to accurately predict springback and a method to eliminate springback without changing geometry of final part.
Chapter 4: U-bending using Shiloh Die

U-bending experiments were carried out with AHSS and Aluminum alloys, using the Shiloh Die to analyze the effect of ram motion on springback. Simulations were carried out in PAM-STAMP to compare the results of experiments and simulations and to carry out inverse analysis to find the apparent E-modulus for accurate prediction of springback.

4.1 Description of tooling and experimental set up

U-bending tests for three different materials: DP 590 (1.4 mm), Al 5182-O (1.2 mm) and Al 6014 (1.2 mm) were carried out using the Shiloh Die. The tests were conducted at AIDA-America using the AIDA 300 ton servo press with a 25 ton (max) servo cushion shown in Figure 24. The schematic of the Shiloh die is shown in Figure 23. The geometrical parameters of the Shiloh die are described in Table 1. The tooling set up and geometry is described in Table 2.
Figure 23: Schematic of Shiloh die

Table 1: Geometrical parameters of Shiloh Die

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave side radius</td>
<td>R1</td>
<td>601.6</td>
</tr>
<tr>
<td>Convex side radius</td>
<td>R2</td>
<td>598.4</td>
</tr>
<tr>
<td>Cavity corner radii</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>51.6</td>
</tr>
<tr>
<td></td>
<td>R4</td>
<td>56.6</td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td>61.6</td>
</tr>
<tr>
<td></td>
<td>R6</td>
<td>66.6</td>
</tr>
</tbody>
</table>

Table 2: Set up of tooling and geometry for Shiloh Die

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch corner radius</td>
<td>4 mm</td>
</tr>
<tr>
<td>Die corner radius</td>
<td>10 mm</td>
</tr>
<tr>
<td>Punch and die clearance</td>
<td>1.6 mm</td>
</tr>
</tbody>
</table>
4.1.1: Preliminary FE Simulations

Initial FE simulations were carried out using the full geometry model and shell elements with different blank sizes using PAM-STAMP v2015.1. The tools were meshed in Visual Environment 8.6. The coefficient of friction was 0.1. The punch, die and pad were modeled as rigid bodies. Die was assigned an imposed velocity of 0.05 m/s in the negative Z direction. The remaining five degrees of freedom were locked. The movement of punch and knockout was locked in all six degrees of freedom. The advanced implicit method was used for springback simulation. The sheet was bent to 90 degrees. The isotropic hardening law and Hill 48 yield function was used for DP 590 (1.4 mm) and Al 6014 (1.2 mm) while the Barlat 2000 model was used for Al 5182-O (1.2 mm).
The aim of the preliminary FE simulations was to find out the optimum blank size for each of the three materials used. The input for simulations and the results are shown in Table 3 and Table 4 respectively.

### Table 3: Simulation input for U-bending using Shiloh Die

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>DP 590</td>
</tr>
<tr>
<td></td>
<td>A 15182-O</td>
</tr>
<tr>
<td></td>
<td>Al 6014</td>
</tr>
<tr>
<td>Thickness</td>
<td>1.4 mm</td>
</tr>
<tr>
<td></td>
<td>1.2 mm</td>
</tr>
<tr>
<td></td>
<td>1.2 mm</td>
</tr>
<tr>
<td>E-modulus (initial from tensile test)</td>
<td>194GPa(^1)</td>
</tr>
<tr>
<td></td>
<td>70 GPa(^2)</td>
</tr>
<tr>
<td></td>
<td>70 GPa(^3)</td>
</tr>
<tr>
<td>Plasticity law (Yield function)</td>
<td>Hill 48(^1)</td>
</tr>
<tr>
<td></td>
<td>Barlat 2000(^2)</td>
</tr>
<tr>
<td></td>
<td>Hill 48(^3)</td>
</tr>
<tr>
<td>COF</td>
<td>0.1</td>
</tr>
<tr>
<td>Pad force *</td>
<td>Fixed pad, i.e. knock out is in contact with the sheet throughout the bending operation</td>
</tr>
<tr>
<td>FE Software</td>
<td>PAM-STAMP v2015.1</td>
</tr>
</tbody>
</table>

1. DP 590 (1.4mm): Tensile test was carried out at Honda America. This data was used to obtain R values and Young’s (E) modulus. The bulge test was carried out at CPF. The flow curve was obtained from the combination of tensile test and bulge test.
2. Al 5182-O: Tensile test was carried out at Honda America. This data was used to obtain Barlat coefficients and Young’s (E) modulus. Bulge test was carried out at CPF. The flow curve was obtained from combination of tensile test and bulge test.
3. Al 6014: Tensile test at was carried out at Novelis. This data was used to obtain the R-values. The flow curve was obtained from the tensile test. The Young’s (E) modulus in this case was obtained from literature.
Table 4: Results of initial FE simulations for U-bending with Shiloh Die

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Blank Geometry (mm*mm)</th>
<th>Minimum required pad force (kN)</th>
<th>Springback (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP 590</td>
<td>1.4</td>
<td>600*50</td>
<td>11.60</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600*30</td>
<td>6.80</td>
<td>3.9</td>
</tr>
<tr>
<td>Al 5182-O</td>
<td>1.2</td>
<td>600*30</td>
<td>2.75</td>
<td>4.7</td>
</tr>
<tr>
<td>Al 6014</td>
<td>1.2</td>
<td>600*30</td>
<td>4.4</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Results show that the springback is nearly equal for both the blank sizes used for DP 590 (1.4 mm). For DP 590, the minimum required pad force is smaller for blank size of 600*30 mm as compared to 600*50 mm. Thus blank size of 600*30mm is chosen as the optimum geometry. Smaller widths would reduce the pad force further however, for the smaller widths, edge effects would affect the results of the bending and springback operation and make them inaccurate. Both, the minimum required pad force and the force on the die is much less for Aluminum alloys as compared to DP 590. The orientation of the blank is shown in Figure 25. The dimensions of the blank are given in Table 5.
4.1.2: Experiments

Experiments were carried out using the optimum blank size obtained from the preliminary FE simulations Table 4 to investigate the effect of ram speed and ram motion on springback. The sheet was placed on the punch and the die moved down to bend the sheet to 90 degrees. Five different cases of ram motion were used as described below:

- Case U1: Ram speed 5 strokes per minute, no attach-detach
- Case U2: Ram speed 20 strokes per minute, no attach-detach

<table>
<thead>
<tr>
<th>Process</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₁</td>
<td>600 mm</td>
</tr>
<tr>
<td>L₂</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

Table 5: Optimum blank size for U-bending using Shiloh Die

Figure 25: Blank geometry and orientation for U-bending using Shiloh Die
• Case U3: One time attach-detach motion at 5mm with ram speed of 5 strokes per minute. The die stroke vs time graph is shown in Figure 26 and Table 6

• Case U4: One time attach detach motion at 40 mm with ram speed of 5 strokes per minute. The die stroke vs time graph is shown in Figure 26 and Table 6

• Case U5: Two times attach-detach motion. Once at 5 mm and second time at 20 mm with ram speed of 5 strokes per minute. The die stroke vs time graph is shown in Figure 27 and the parameter are described in Table 7.

Three samples each of DP 590 (1.4 mm), Al 5182-O (1.2 mm) and Al 6014 (1.2 mm) were used for cases U1 and U2 while cases U3, U4 and U5 were carried out using three samples each of DP 980 and Al5182-O. There was no lubrication. The experimental matrix is shown in Table 8.

![Stroke vs time graph for 1 time detach](image_url)

Figure 26: Stroke vs time graph for case U3 and U4 one time attach-detach at 5 SPM ram speed
Table 6: Parameters for one time attach-detach motion

<table>
<thead>
<tr>
<th>Case</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U3</td>
<td>5</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>U4</td>
<td>40</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 27: Stroke vs time graph for case U5, two times attach-detach at 5 SPM ram speed

Table 7: Parameters for two time attach-detach motion

<table>
<thead>
<tr>
<th>Case #</th>
<th>X (mm)</th>
<th>X' (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U5</td>
<td>5 mm</td>
<td>20 mm</td>
<td>10 mm</td>
<td>50 mm</td>
</tr>
</tbody>
</table>
Table 8: Experimental matrix for U-bending tests

<table>
<thead>
<tr>
<th>Case #</th>
<th>Punch/Die speed (SPM)</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>U2</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>U3*</td>
<td>5 SPM, 1 time at 5 mm (attach-detach)</td>
<td>3</td>
</tr>
<tr>
<td>U4*</td>
<td>5 SPM, 1 time at 40 mm (attach-detach)</td>
<td>3</td>
</tr>
<tr>
<td>U5*</td>
<td>5 SPM, 2 times at 5 mm and 20 mm (attach detach)</td>
<td>3</td>
</tr>
</tbody>
</table>

4.2 Effect of ram speed and ram motion on springback

As can be seen from the experimental matrix in Table 8, the effect of ram speed was observed by U-bending of 3 samples of each of the materials at speeds of 5 SPM and 20 SPM each, while the effect of ram motion was observed by U-bending of 3 samples each of DP 590 and Al 5182-O using the attach detach motion.

The effect of ram speed and ram motion on the springback in U-bending of DP 590 (1.4 mm), Al 5182-O (1.2 mm) and Al 6014 (1.2 mm) are shown in Figure 28, 29 and 30 respectively.
Figure 28: Effect of ram speed and ram motion on DP 590 (1.4 mm)

Figure 29: Effect of ram speed and ram motion on Al 5182-O (1.2 mm)
4.3 Inverse analysis for accurate prediction of springback

Inverse analysis was carried out for all the three materials by comparing the springback obtained from the bending at 5 SPM (Case U1) with the springback obtained from FE simulation using the E-modulus from tensile tests. FE simulation was also carried out for Al 5182-O (1.2 mm) using the Yoshida model to observe the effect on springback prediction.

4.3.1 Inverse analysis for DP 590 (1.4 mm)

The comparison of the experimental result and simulation result with E-modulus = 194 GPa (as obtained from tensile test) for DP 590 (1.4 mm) is shown in Figure 31 below. Since the experimental result matches with the simulation result, inverse analysis was not carried out for DP 590.
4.3.2: Inverse analysis for Al 5182-O (1.2 mm)

The inverse analysis which was carried out for Al 5182-O (1.2 mm) is shown in Figure 32. The comparison of the experimental result and simulation results with $E=70$ GPa (from tensile test), $E = 112$ GPa (from inverse analysis) and Yoshida model are shown in Figure 33.
4.3.3: Inverse analysis of Al 6014 (1.2 mm)

The inverse analysis which was carried out for Al 6014 (1.2 mm) is shown in Figure 34. The comparison of the experimental result and simulation results with $E=70$ GPa (from tensile test), $E = 111$ GPa (from inverse analysis) are shown in Figure 35.
4.4 Effect of variation of pad force on springback in U-bending with crunching

Effect of variation of pad force on springback in U-bending with crunching was analyzed through FE simulations in PAM-STAMP v2015.1 with the full geometry model. The analysis was carried out using 1.4 mm blank of DP 590 with dimensions 600 mm X 30 mm. The tooling is described in Figure 36 and Table 9. The blank geometry and properties are described in Table 10. The input to simulation is given in Table 11.
Figure 36: Schematic of the tooling for study of variation of pad force on springback

Table 9: Tooling geometry and dimensions for study of effect of variation of pad force

<table>
<thead>
<tr>
<th>Shiloh Die</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>L1</td>
<td>496 mm</td>
</tr>
<tr>
<td>L2</td>
<td>500 mm</td>
</tr>
<tr>
<td>L3</td>
<td>150 mm</td>
</tr>
<tr>
<td>R1,R2</td>
<td>4mm</td>
</tr>
</tbody>
</table>

Table 10: Blank geometries and properties for study of effect of variation of pad force

<table>
<thead>
<tr>
<th>Material</th>
<th>DP 590</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Dimensions</td>
<td>600 mm x 30 mm</td>
</tr>
</tbody>
</table>
Table 11: Simulation input for study of effect of variation of pad force

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>DP 590</td>
</tr>
<tr>
<td>Thickness</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>E-modulus (from tensile test)</td>
<td>194 GPa$^1$</td>
</tr>
<tr>
<td>Plasticity law (Yield function)</td>
<td>Hill 48 $^1$</td>
</tr>
<tr>
<td>COF</td>
<td>0.1</td>
</tr>
<tr>
<td>FE Software</td>
<td>PAM-STAMP v2015.1</td>
</tr>
</tbody>
</table>

The analysis was carried out through simulations of four different cases as shown in Figure 37, Figure 38, Figure 39 and Figure 40. The die stroke was 150 mm in all the cases. In case A, C and D, the pad is modeled to exert a force (as shown in Figure 37, 38, 39 and 40 respectively) in the negative Z direction and the rest of the degrees of freedom were locked. The minimum required pad force ($F_{min}$) to keep the sheet in contact with the punch throughout the bending operation was found to be 6.6 kN for DP 590 (1.4 mm) with blank size of 600 mm x 30 mm. The other conditions are same as the conditions used in the initial FE simulations. The results of the simulations of the four different cases are shown in Table 12. It was found out that the springback can be eliminated by using an optimum value of the pad force.
Figure 37: Case A - Pad force = Minimum required pad force to keep the sheet in contact with the punch throughout the bending operation ($F_{min} = 6.6 \text{kN}$)

Figure 38: Case B - No pad force

Figure 39: Case C - Pad force = 50% of $F_{min}$

Figure 40: Case D - Pad force = 10% of $F_{min}$
Table 12: Simulation results

<table>
<thead>
<tr>
<th>Springback Case A (Pad force=6.6kN, (F_{\text{min}})) (°)</th>
<th>Springback Case B (Pad force=0) (°)</th>
<th>Springback Case C (Pad force=3.3kN, 50% (F_{\text{min}})) (°)</th>
<th>Springback Case D (Pad force = 0.66kN, 10% (F_{\text{min}})) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>-5</td>
<td>3.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4.5 Summary and Conclusions

- The springback does not vary significantly with attach-detach motion for both DP 590 (Figure 28) and Al 5182-O (Figure 29).

- A significant reduction in springback was observed in case U2 (20 SPM) as compared to case U1 (5 SPM) (Figure 28) for DP 590 (1.4 mm). This difference is not observed for the Aluminum alloys (Figure 29 and Figure 30.).

- The force applied on pad is higher in bending of steel compared to aluminum (Table 4). Therefore, the difference observed in springback for different SPM (ram speed) in bending of DP 590 may be due to improper movement of pad and insufficient pad force at faster ram speed.

- The values of the E-modulus obtained from the inverse analysis are 194 GPa for DP 590, 112 GPa for Al 5182-O and 111 GPa for Al 6014 respectively (Figure 31, Figure 32 and Figure 34).

- For Aluminum alloys, the apparent E-modulus obtained from inverse analysis accurately predicts the springback (Figure 33 and Figure 35).
• For Al 5182-O, springback predicted using Yoshida model is similar to that predicted using E-modulus=70GPa and does not match with the experimental results (Figure 33). Thus use of Yoshida model in simulation does not improve the prediction of springback.

• Springback decreases as the pad force decreases and is almost 0 in Case D (pad force = 10% of \( F_{\text{min}} \)) (Table 12).

• Trends observed in Case C (pad force = 50% of \( F_{\text{min}} \)) and D (pad force = 10% of \( F_{\text{min}} \)) show that it may be possible to reduce or eliminate springback by selecting the appropriate pad force (Table 12).

• In this study, it was found that applying a pad force equal to 10% of \( F_{\text{min}} \) (case D) gives a springback of 0.3, thus reducing the springback by 93%. (Table 12).
Chapter 5: Wipe bending using TE Connectivity Die

The contents and results shown in this chapter will be submitted for future publishing in Stamping Journal along with some other studies. The authors for this paper are Ali Fallahiarezoodar, Aanandita Katre and Dr. Taylan Altan. My role in this paper is to carry out the experiments and simulations to obtain all the results shown in this study and which might be reprinted in the paper.

In this study, copper alloy C7026 was bent to different angles under load using the tools designed at CPF and the INSTRON machine. Inverse analysis was done for all the angles under load and apparent E-modulus vs strain curve was developed to use as input to FE software.

5.1 Design of tooling

The tooling for wipe bending was designed and modeled using SOLIDWORKS at CPF and manufactured by Jett Industries. This section describes the process of design of tooling and the final CAD model that was developed.
5.1.1 Simulation input

The tooling consists of three major components: the punch, the die and the blank holder.

FE simulations were carried out as per the simulation input shown in Table 13 and tooling geometry as shown in Figure 41 using DEFORM 2-D Ver 11.1.

Figure 41: Schematic of tooling in wipe bending
Table 13: Simulation input for wipe bending simulations

<table>
<thead>
<tr>
<th>Material</th>
<th>C7026</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank Size</td>
<td>70 mm * 40 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Die corner radius (r)</td>
<td>0.3 mm (variable)</td>
</tr>
<tr>
<td>Punch Corner radius (R)</td>
<td>1 mm (variable)</td>
</tr>
<tr>
<td>Punch and die clearance (c)</td>
<td>0.3 mm (variable)</td>
</tr>
<tr>
<td>Young’s Modulus (initial)</td>
<td>135 GPa (constant)</td>
</tr>
<tr>
<td>Punch Velocity</td>
<td>5 mm/s</td>
</tr>
<tr>
<td>Punch Stroke (total)</td>
<td>15 mm</td>
</tr>
<tr>
<td>CoF</td>
<td>0.1</td>
</tr>
<tr>
<td>Simulation software</td>
<td>DEFORM 2-D Ver 11.1</td>
</tr>
</tbody>
</table>

Simulations were carried out using plane strain condition. The sheet was meshed using brick elements. The number of elements along the thickness of sheet was five. At the bending region, the mesh was refined to have eleven elements along the sheet thickness so as to capture the small bending radius accurately. The workpiece was modeled as
elasto-plastic. The flow stress curve which was input was obtained from tensile tests at CPF and extrapolation of the curve as is shown in Figure 42.

![Flow stress curve for C7026-0.3 mm obtained from tensile tests at CPF](image)

Figure 42: Flow stress curve for C7026-0.3 mm obtained from tensile tests at CPF

The hardening law used was isotropic hardening while the yield function type was von Mises. The elastic modulus used in the initial simulation was 135 GPa which was also obtained from the tensile tests at CPF. The punch, die and blank holder were modeled as rigid bodies. The blank holder and die were locked by assigning a velocity 0. The punch was assigned a velocity of 5 mm/s in the negative Y direction (Figure 41). The Coulomb friction law with coefficient of friction equal to 0.1 was used in the simulations. The sheet was bent to 90 degrees in the initial simulation.
5.1.2 Effect of punch corner radius

The effect of punch corner radius on springback was observed through simulations for three different punch corner radii 0.3 mm, 0.7 mm and 1 mm. The results of the simulations can be seen in Figure 43.

![Figure 43: Effect of punch corner radius on springback.](image)

The variation in punch corner radius does not affect the springback. Punch corner radius of 1 mm was used for ease of manufacturing.

5.1.3 Calculation of force on punch and blank holder-experiments

The experiments were carried out using INSTRON testing machine with a capacity of 50 kN. The force on the punch was calculated from the simulations to ensure that the
INSTRON machine could provide the force necessary to bend a sample of C7026 with dimension 70 mm * 40 mm * 0.3 mm. The minimum required blank holder force to keep the sheet in contact with the die throughout the bending operation was calculated from the simulation to design the screws required to fix the blank holder. The results of the simulations are shown in Table 14.

Table 14: Punch force and blank holder force obtained from simulations.

<table>
<thead>
<tr>
<th>Minimum required punch force using DEFORM</th>
<th>1.2 kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum required blank holder force</td>
<td>2.5 kN</td>
</tr>
</tbody>
</table>

The number of screws required was calculated using the procedure described below.

Basic major (nominal) diameter of M6*1 screw: 6 mm

\[ n = \text{threads per mm}: 1 \]

Effective area for stress calculation

\[
\left( \frac{\pi \left( d_n - 0.9743 \right)^2}{n} \right) = 19.83 \text{ mm}^2
\]

Minimum Yield strength of alloy steel*: 620.53 MPa (90,000 psi)

Force for one screw = 12.305 kN

Blank holder force for C7026 (70 mm x 40 mm x 0.3 mm): 2.5 kN

Safety Factor: 4

Total force = 2.5*4 = 10 kN

Number of screws = 10/12.305 = 0.813

Thus we need minimum of 1 M6 screw.
*Minimum value of yield strength was used for calculations. In practice, screws made of alloy steel stronger than grade 8 steel (min yield strength 130 ksi) were used to hold the blank holder.

The tools were designed for 4 M6 screws to allow for stronger or thicker materials in future.

5.1.4 CAD model of the tooling

Using the results of analysis from initial FE simulations, the CAD model of the tooling was developed in SOLIDWORKS. The CAD model of the assembly is shown in Figure 44.

Figure 44: CAD model of the assembly
5.2 Analyze the wipe bending operation and determine the appropriate apparent e-modulus by “inverse analysis method”

Wipe bending experiments and FE simulations (using DEFORM 2-D) were carried out and results were compared to obtain the apparent E-modulus which can give accurate prediction of springback.

5.2.1 Experiments for different punch strokes

In the experiments it was found that the punch deflects elastically when it comes in contact with the sheet and this results in change in the punch and die clearance during the bending operation. A guide was used to prevent deflection of the punch and maintain a constant clearance during the entire bending operation. An adapter was designed to attach the punch to the INSTRON machine and maintain the alignment of the punch with the die. The setup of the tooling for experiments is shown in Figure 45 and dimensions are shown in Table 15.

Figure 45: Experimental setup
Table 15: Dimensions in tooling

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 (Punch corner radius)</td>
<td>1 mm</td>
</tr>
<tr>
<td>R2 (Die corner radius)</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Punch Die Clearance</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

The clearance between the tool and die in the experiments was measured by taking a photograph of the set up with a sample bent to 90 degrees. This is shown in Figure 46.

Figure 46: Measurement of punch and die clearance

In the experiments the 0.3 mm thick samples of C7026 with dimensions 70 mm x 40 mm were bent to different angles by adjusting the punch strokes using the settings of the INSTRON machine. 3 samples were used for each punch stroke. After each sample was
bent to the desired angle, photographs were taken before unloading the tools. These photographs were used to measure the angle under load for each punch stroke. The average angle under load was taken as the average of all the three samples for each punch stroke. Table 16 shows the experimental matrix.

Table 16: Experimental matrix for wipe bending of C7026 (0.3 mm)

<table>
<thead>
<tr>
<th>Punch stroke</th>
<th>Number of samples</th>
<th>Avg. Angle under load (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3</td>
<td>15.5</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>37.33</td>
</tr>
<tr>
<td>1.5</td>
<td>3</td>
<td>58.33</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>71.67</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>79.83</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>84</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>87.67</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>89.73</td>
</tr>
</tbody>
</table>

For each bending angle, another photograph was taken after unloading the punch. These photographs were used to measure the angle after unloading. The springback was calculated as a difference of the angle under load (Ø₁) and the angle after unloading (Ø₂). The springback is thus given by:

\[
\text{Springback} = (Ø₁ - Ø₂)
\]  

(36)

The average springback was obtained by averaging the springback for all three samples for each angle under load. The variation of average angle under load with punch stroke from experiments is shown in Figure 47 and the variation of springback with angle under load (experiments) is shown in Figure 48.
Figure 47: Experimental results-variation of angle under load with punch stroke

Figure 48: Experimental results-variation of springback with angle under load
5.2.2 Effect of punch and die clearance

Simulations were carried out in DEFORM using the same tooling and geometry as used in experiments. The effect of punch and die clearance on variation of angle under load with respect to punch stroke was observed by using 3 values of clearance-0.3 mm, 0.4 mm and 0.5 mm. The rest of the input for the simulations was same as that for the initial FE simulation as described in Section 5.1.1.

The angles under load for different punch strokes were measured from the simulations. The results of the simulations show that change in punch and die clearance can significantly affect the variation of angle under load with punch stroke Figure 49.

Figure 49: Effect of punch and die clearance on angle under load
5.2.3 Effect of die corner radius

Simulations were carried out in DEFORM using the same tooling and geometry as used in experiments. The effect of die corner radius on variation of angle under load with respect to punch stroke was observed by using 3 values of die corner radius: 0.25 mm, 0.3 mm and 0.35 mm. The rest of the input for the simulations was same as that for the initial FE simulation as described in Section 5.1.1.

The angles under load for different punch strokes were measured from the simulations. The results of the simulations show that slight variation in die corner radius does not affect the variation of angle under load with punch stroke, Figure 50.

![Figure 50: Effect of die corner radius on angle under load](image_url)
5.2.4 Effect of coefficient of friction

Simulations were carried out in DEFORM using the same tooling and geometry as used in experiments. The effect of coefficient of friction on springback was analyzed by using two different coefficients of friction: 0 and 0.1. The rest of the input for the simulations was same as that for the initial FE simulation as described in Section 5.1.1.

In the simulations, the sheet was bent to different angles under load (as obtained from experimental matrix: Table 16) and springback was simulated for each of the angles. The results of the simulation show variation of coefficient of friction does not affect springback, Figure 51.

![Figure 51: Effect of coefficient of friction](image-url)
5.2.5 Determination of apparent E-modulus for accurate springback prediction

Inverse analysis was carried out for each angle under load to find the apparent E-modulus for accurate prediction of springback. The initial FE simulation was carried out using $E=135$ GPa as obtained from the tensile test. A comparison of the springback obtained from FE simulation with E-modulus from tensile test and springback obtained from experiments is shown in Figure 53. The E-modulus from tensile test under predicted the springback. Thus lower E-moduli were used to obtain the Springback vs E-modulus curve for the different angles under load. Using these curves, the E-modulus corresponding to the experimental springback was obtained for each bending angle. The apparent E-modulus vs angle under load curve was developed as shown in Figure 52.

![Figure 52: E-modulus vs angle under load](image-url)
The springback was predicted using the apparent E-modulus obtained for each of the bending angles from Figure 52 and compared with springback obtained from experiments. This is shown in Figure 53.

![Figure 53: Comparison of springback from experiments and simulation with different E-moduli](image)

5.3 Development of a guideline for using appropriate e-modulus for better prediction of springback

The E-modulus vs bending angle curve was developed in the previous chapter. However this cannot be used for direct input to FE software for analyzing the bending operation and springback. The E-modulus vs strain curve was developed which can be used as an input to the FE software.

The maximum effective strains for various angles under load were found from the FE simulation of the bending operation from DEFORM. The strain distributions for different
bending angles under load are shown in Figure 54(a-h). The variation of apparent E-modulus with maximum effective strain is shown in Figure 55.

Figure 54(a)

![Figure 54(a)](image)

Angle under load = 15.5°
Max. Strain = 0.157

Figure 54(b)

![Figure 54(b)](image)

Angle under load = 37.2°
Max. Effective Strain = 0.386

Figure 54(c)

![Figure 54(c)](image)

Angle under load = 58.4°
Max. Effective strain = 0.531

Figure 54(d)

Figure 54(e)

Figure 54: Distribution of strain for different angles under load (from DEFORM)

(CONTINUED)
Figure 54: (CONTINUED)

Angle under bend = 71.5°  
Max. Effective Strain = 0.568

Angle under bend = 79.8°  
Max. Effective Strain = 0.571

Figure 54 (f)  
Angle under bend = 84°  
Max. Effective Strain = 0.571

Figure 54 (g)  
Angle under bend = 87.7°  
Max. Effective Strain = 0.571

Figure 54 (h)  
Angle under bend = 89.7°  
Max. Effective Strain = 0.571
5.4 Summary and conclusions

- Simulations show that the minimum required punch force is 1.2 kN for C7026 (0.3 mm) and blank size of 70 mm * 40 mm (Table 14).
- Thus the available INSTRON Testing Machine with 50 kN load capacity can provide sufficient punch force for the bending operation.
- Punch corner radius of 0.3mm, 0.7mm and 1mm predict same value of springback angle (Figure 43). Thus punch corner radius does not affect springback.
- Punch corner radius of 1 mm was selected for ease of manufacturing. Die radius of 0.3 was chosen to maintain r/t = 1.
- 1 M6*1 screw was sufficient to provide the minimum blank holder force to keep the sheet in contact with the die (35).
• 4 M6*1 screws were used to fix the blank holder to the die to account for stronger or thicker materials.

• Variation of punch and die clearance affects the variation of angle under load with respect to punch stroke (Figure 49).

• Variation of die corner radius does not significantly affect the variation of angle under load with respect to punch stroke (Figure 50).

• The variation of springback with angle under load gives similar trends in both experiments and simulations (Figure 51).

• The coefficient of friction does not affect the prediction of springback significantly (Figure 51).

• The simulations with $E = 135$ GPa under predict the springback for all the angles under load. Hence inverse analysis was carried out for each angle under load to find an E-modulus which can accurately predict the springback and curve of E-modulus vs angle under load was obtained. (Figure 52)

• Simulations with E-moduli obtained from inverse analysis provides more accurate prediction of springback compared to those obtained from the simulations with E-modulus from the tensile test (Figure 53). The apparent E-modulus for accurate prediction was seen to increase with bending angle (Figure 52).

• The apparent E-modulus vs maximum effective strain curve is developed (Figure 55). This curve can be input to different FE software for bending and springback analysis.
• The apparent E-modulus increases nearly linearly with increasing maximum effective strain (Figure 55).

• Near the maximum effective strain of 0.57, the strain does not change significantly with increasing angle under load (Figure 55).

• There is a sudden increase (as calculated) for the value of apparent E-modulus at 71.5° angle under load. This is expected to be due to increase of number of elements that are in the elastic range. However, the data near the maximum effective strain of 0.57 can be averaged for practical purposes (Figure 55).
Chapter 6: Inverse Analysis using S-CPF Die

[Kardes et al., 2011], carried out studies on effect of variation of E-modulus on springback using an S-shaped tooling. The E-modulus vs strain curve for DP 780 (1 mm) was developed by tensile-compression tests and used to simulate the springback in DEFORM. Springback was also simulated using constant E-modulus in both DEFORM and PAM-STAMP. Experiments were carried out and the data from simulation and experiments was compared. The same experimental data and tooling geometry is used for this study to carry out inverse analysis for accurate prediction of springback.

6.1 Description of tooling and experiment

U-bending was carried out in both 2-D and 3-D. The tooling and blank geometry for both 2-D and 3-D part is described.

6.1.1: 2-D U-bending

A schematic of the tooling used in the experiments is shown in Figure 56. The rubber pads provided the minimum pad pressure required to keep the sheet in contact with the punch throughout the operation. For the 2-D U-bending, the sheet geometry and orientation is shown in Figure 57. The sheets were bent to different angles by adjusting
the die stroke using shims. The press used was 40 ton hydraulic press at CPF. The experimental matrix is given in Table 17.

Figure 56: Tooling for 2-D U-bending [Kardes 2012]

Figure 57: Blank geometry and orientation for 2-D U-bending [Kardes 2012]
Table 17: Experimental matrix [Kardes 2012]

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet material</td>
<td>DP 780</td>
</tr>
<tr>
<td>Sheet dimensions (thickness, width, length)</td>
<td>1 mm x 40 mm x 185 mm</td>
</tr>
<tr>
<td>Die corner radius Rd</td>
<td>4 mm</td>
</tr>
<tr>
<td>Punch corner radius Rp</td>
<td>2 mm</td>
</tr>
<tr>
<td>Punch width, Wp</td>
<td>83.26 mm</td>
</tr>
<tr>
<td>Die width, Wd</td>
<td>85.46 mm</td>
</tr>
<tr>
<td>Approximate bending angle, B</td>
<td>$10^\circ$, $15^\circ$, $25^\circ$, $40^\circ$, $65^\circ$, $90^\circ$</td>
</tr>
<tr>
<td>Strokes for different bending angles</td>
<td>1.1, 1.4, 2.4, 3.6, 5.4, 25.3 mm</td>
</tr>
<tr>
<td># of samples per condition</td>
<td>3</td>
</tr>
</tbody>
</table>

6.1.2: 3-D U-bending

For the 3-D U-bending, a sheet of a special geometry was placed on the S-shaped punch. The schematic of the tooling is shown in Figure 58. The die moved down to bend the sheet. The formed part is shown in Figure 60. The sheet geometry and position is shown in Figure 59.

![Figure 58: Tooling for 3-D U-bending [Kardes 2012]](image-url)
6.2 Inverse analysis in 2-D U-bending

The experimental data was obtained from [Kardes 2012]. The simulations for each angle under load were carried out using half geometry and plane strain condition in DEFORM 2-D Ver 11.1. The sheet was meshed using brick elements. The number of elements along the thickness of sheet was 6. Total number of elements in the mesh was 3162. The workpiece was modeled as elasto-plastic. The flow stress curve which was input was obtained from viscous pressure bulge tests at CPF and is shown in Figure 61. The hardening law used was isotropic hardening while the yield function type was von Mises. The Elastic modulus used in the initial simulation was 207 GPa which was also obtained
from the E-modulus vs strain curve shown in Figure 62 at CPF. The movement of the sheet in the X direction was locked by applying a boundary condition along the thickness, on the edge of the sheet which was between the die and blank holder. The punch, die and blank holder were modeled as rigid bodies. The blank holder and punch were locked by assigning a velocity 0. The die was assigned a velocity of 0.05 m/s in the negative Y direction. The Coulomb friction law with coefficient of friction equal to 0.12 was used in the simulations. The sheet was bent to 90 degrees in the initial simulation.

![Flow stress data for DP 780](image)

**Figure 61: Flow stress data for DP 780 [Kardes 2012]**

The strain distribution depends on the angle under load. Thus in the simulations, the sheet was bent to the angles under load obtained from experiments and the springback was simulated for these angles. Initially, the E-modulus used was 207 GPa which was the
highest value in the E-modulus vs strain curve obtained from the tensile test. This E-modulus under-predicted the springback for all the angles under load. Thus E=150 GPa was used as this was the lowest value of E-modulus in E-modulus vs strain curve in the tensile test. The apparent E-modulus for accurate prediction of springback for each angle under load was found by inverse analysis. The results of the simulations are shown in Figure 63. The E-modulus vs angle under load curve was developed as shown in Figure 64.

![Graph showing variation of E-modulus with strain](Figure 62: Variation of E-modulus with strain [Kardes 2012])
Figure 63: Comparison of experimental and simulation results

Figure 64: E-modulus vs angle under load

E-modulus vs strain

The E-modulus vs angle under load curve cannot be used in FEA code for the analysis of bending operation and springback. Thus the strain distribution for different angles under load was studied and a curve for apparent E-modulus vs maximum effective strain was
developed. This curve can be used as an input to FEA code. The strain distributions for different angles under load is shown in Figure 65. The curve for apparent E-modulus vs maximum effective strain is shown in Figure 66.

Figure 65: Distribution of strain for different angles under load
6.3 Inverse analysis in 3-D U-bending

Simulations were carried out with $E = 207$ GPa. The full geometry model was used in PAM-STAMP v2015 11.1 with shell elements. The advanced implicit and automatic mesh refinement features were used. The punch and knockout were locked in all six degrees of freedom. The die was given an imposed velocity of 0.5 mm per millisecond in the negative Z direction and the remaining five degrees of freedom were locked. Springback from experiments and simulation was compared by analyzing the profiles of the part at 2 sections P and S. For section P, $E = 207$ GPa gave a reasonably accurate prediction of the profile obtained from experiment. For section S, the profile obtained from simulation using $E = 207$ is quite close to the experimental profile. E-modulus of 150 GPa gave a result very similar to $E = 207$ GPa. Thus a much higher value of $E = 300$
GPa and a much lower value of $E = 100$ GPa was used to study the effect of E-modulus on springback and twist.

The sections P and S are shown in Figure 67. The comparison of experimental and simulation results for section P is shown in Figure 68 and for section S in Figure 69.

Figure 67: Location of section P and section S on the S-formed part [Kardes 2012]
Figure 68: Comparison of experiment and simulation result for section P

Figure 69: Comparison of experiment and simulation result for section S
6.4 Summary and conclusions

*Inverse analysis in 2-D U-bending*

- The experimental results and simulations results follow similar trends (Figure 63).
- It can be seen that E-modulus of 207 GPa (from tensile test) under predicts the springback while E-modulus of 150 GPa over predicts the springback (Figure 63)
- Thus inverse analysis is carried out for each of the bending angles to find the apparent E-modulus that accurately predicts the springback (Figure 64)
- The range of calculated apparent E-modulus is found to between 180 GPa and 207 GPa. The E-modulus is nearly constant up till 66 degree angle under load after which it decreases by about 13% compared to initial E-modulus from tensile test (207 GPa) (Figure 64)
- The apparent E-modulus vs maximum effective strain curve is obtained. The E-modulus is nearly constant for smaller strains and decreases at a maximum strain of 0.292 (Figure 66)

*Inverse analysis for 3-D U-bending*

- For section P, the difference between simulation and experiment is negligible. E=207 GPa gives nearly accurate prediction of springback and hence inverse analysis is not required (Figure 68).
- For section S, the simulation (E=207 from tensile test) and experimental results have no significant difference (Figure 69).
• The effect of E-modulus is also negligible for section S as $E=100$ GPa, $E=207$ GPa and $E=300$ GPa all give similar results. However $E=300$ GPa gives best results when compared to experiments (Figure 69).

• An average E-modulus of 207 GPa gives reasonably accurate prediction of springback for both section P and S.
Chapter 7: Overall summary and Future Work

7.1 Summary

- Inverse analysis was successfully applied to simple 2-D bending processes such as wipe bending and U-bending to find the apparent E-modulus which gave an accurate prediction of springback for different materials and angles under load (strain distributions).

- Inverse analysis was also applied to 3-D U-bending process to find the apparent E-modulus to predict springback and twist with reasonable accuracy.

- Strain distribution across sheet thickness in C7026 (0.3 mm) and DP 780 (1 mm) for different angles under load was studied using DEFORM-2D and a curve for apparent E-modulus vs maximum effective strain was developed. This curve can be directly input to FE software for analysis of bending and springback.

- A guideline for eliminating springback, without affecting the geometry of the part, by variation of pad force in U-bending with crunching was developed through FE simulations in PAM-STAMP.
7.2 Future Work

Studies will be conducted to apply the Inverse Analysis method to ‘real’ bending operations and complicated parts for accurate prediction of springback. An example of a practical bending operation used in industry is shown in Figure 70.

![Example of practical bending operation used in industry](image)

Figure 70: Example of practical bending operation used in industry

The guideline for eliminating springback with variation of pad force should be applied to 3-D parts and also validated through experiments.
References

- Advanced High Strength Steel (AHSS) Application Guidelines Committee on Automotive Applications, “Advanced High Strength Steel (AHSS) Application Guidelines”, International Iron and Steel Institute
- AHSS 101 C. Tamarelli, “AHSS 101, The Evolving Use of Advanced High-Strength Steels for Automotive Applications” Steel Market Development Institute, Autosteel, 2011


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Appendix A: TE Connectivity Die detailed drawings

Tooling Assembly

Tool material: 4140 PH, Hardness: 28-30 RC, All dimensions in mm
Die

Perspective View

Y view

X view

Z view

Perspective View
Punch Holder

Blank holder