Analysis and prediction of springback – 3 point bending and U-bending

THESIS

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By

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Abstract

This thesis studies the phenomenon of springback in the bending operation of sheet metal. Two types of bending operations: 3 point bending and U- bending are studied in this thesis. Copper alloy, advanced high strength steels and Aluminum are the materials that are considered for this study.

This thesis describes the experimental parameters used to study these bending processes along with the FE simulations conducted using two commercially available software packages (PAMSTAMP and DEFORM 2D).

Using both experimental data and FE simulations, the most important factors influencing the springback predictions by the FEA software for each of the bending operations under consideration are determined. Inverse analysis methodology to determine accurate material data is also described.
Acknowledgements

I would like to thank the department of Integrated Systems Engineering, the graduate school and The Ohio State University for giving me the opportunity and the necessary resources to hone my skills as an engineer and to complete a Master’s degree in my chosen field. I would like to thank Dr Taylan Altan for his guidance, patience and kindness in helping me to mold myself into a better engineer and for giving me the opportunity to work at the prestigious Center for Precision Forming. I would like to thank Ali Fallahiarezoodar who’s insights and advice guided me throughout my graduate school work, Ruzgar Peker, for her support in conducting experiments and analyses. I would like to extend special thanks also to Adam Groseclose, Siddhart Kishore and Ganapathy Srinivasan for all their guidance. I would also like to thank all the students and members of CPF with whom I have had the pleasure to work with.

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Major Field: Industrial and Systems Engineering
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CHAPTER 1 Introduction

1.1 Bending Operations and Springback Problem

Bending is a manufacturing process that produces a V-shape, U-shape, or channel shape along a straight axis in ductile materials, most commonly sheet metal. In this process, a work piece is positioned over the die block and the die block presses the sheet to form a shape [1]. When sheet metal is bent, it stretches in length. The bend deduction is the amount the sheet metal will stretch when bent as measured from the outside edges of the bend. The bend radius refers to the inside radius. The formed bend radius is dependent upon the dies used, the material properties, and the material thickness.

In the U-bending process the blank is placed on a die such that when the bending occurs the sides have a straight edge and the final shape of the part resembles a “U” shape [2]. Figures 1 – 3 illustrate the U bending operation.
Figure 1 Schematic of the U bending operation

Figure 2 Final U bending Part

Figure 3 Section view of final U-bending Part
In the 3 point bending operation, the sheet metal is bent to a V-Shape using a stationary die and a downward moving punch. Figures 4 and 5 illustrate the 3 point bending operation.

![Figure 4 Schematic of the 3 point bending operation](image1)

![Figure 5 Section view of the final 3 point bending part](image2)

One of the biggest problems in stamping of metals is that of Springback. Spring back occurs because when a metal is being formed, the material is deliberately over-stressed
beyond the yield strength in order to induce a permanent deformation. When the load is removed, the stress will return to zero along a path parallel to the elastic modulus (Figure 6). Therefore, with some exceptions, the permanent deformation will usually be less than the designer-intended deformation of the strip. The springback will be equal to the amount of elastic strain recovered when the die is removed [3].

![Forming Operation](image)

**Figure 6 Stress and strain response during forming [3]**

Accurate prediction of springback in FE simulations is extremely important because it enables for better tooling design and saves a significant amount of testing time and expense. This thesis aims to determine the significant factors that affect springback prediction and to determine methods to improve FE simulation prediction of springback in the U bending and 3 point bending processes.
1.2 Copper Alloy (C7026)

This alloy is widely used in the industry for making connector because of its high conductivity, high strength, bend formability and stress relaxation stability [4]. Figure 7 describes the properties of this alloy.

![Figure 7 Properties of Copper C7026](image-url)
1.3 Advanced High Strength Steels (DP980 and TRIP 780) 

Note: ALL of the information seen in this section (1.3 and all sub-sections of 1.3) was obtained from literature (reference #5).

Steels in automotive applications are generally classified based on strength as Low strength steel, High Strength Steel (HSS), and Advanced High Strength Steel (AHSS) / Ultra High strength steel (UHSS). The relative strength and the formability of the automotive steels is well illustrated by the so called total elongation vs. ultimate tensile strength (Banana curve) (Figure 8). It could be observed that there is an overlap in terms of classification of steels between the HSS steels and AHSS based on the strength and therefore classification based on strength is not complete [5].

![Figure 8 Strength versus formability relationship for automotive steel](image)

The fundamental difference between HSS steels and AHSS steels lies in the microstructure. HSS steels are single-phase ferrite microstructure steels while AHSS
steels are multiphase steels comprising of ferrite, bainite, restrained austenite and martensite in sufficient quantities to produce unique material properties. Initially, AHSS steels comprised of Dual Phase (DP) steel, Complex Phase (CP) steel, Transformation Induced Plasticity (TRIP) steel and Martensite Steel. New developments such as Twinning Induced Plasticity (TWIP) and Hot Forming (HF) steel are also part of AHSS steel. In this chapter, constituents of AHSS steels are explained in terms of their metallurgy and the mechanical properties relevant to forming [5].

1.3.1 Dual Phase (DP) Steels

The microstructure of DP steel consists of a soft phase ferrite, contributing to the good formability, and a hard martensitic phase, contributing to the strength as seen in Figure 9. Strength of the DP steels are varied by changing the amount of martensite in the steel. The amount of martensite in the steel is influenced by a) the carbon content of the steel, b) the temperature cycle at which the steel is processed in hot rolling process for hot rolled coils, and c) the temperature cycle in continuous annealing process for cold rolled products. During forming, the microstructure of DP steels may experience three stages of deformations [5].

a) Both the ferrite matrix and the martensite particles deform elastically.

b) Ductile ferrite phase deforms plastically first while the martensite phase continues to deform elastically. There is stress concentration in the boundary areas of ferrite contacting the hard phase, martensite, which stimulates more plastic deformation of ferrite in this region, resulting in high strain hardening exponent (n-value) in low strain level.
c) Both ferrite and martensite phases deform plastically, which makes the n-value decrease at higher strains.

![SEM image of DP steel and schematic of DP steel](image)

**Figure 9** (a) SEM image of DP steel, (b) Schematic of DP steel

### 1.3.2 Transformation Induced Plasticity (TRIP) Steels.

The microstructure of TRIP steels consists of a ferrite matrix containing the dispersion of hard second phases—martensite, bainite and minimum of 5% of retained austenite in volume fractions as seen in Figure 10. The various levels of these phases give TRIP steels their unique balance of properties. The phase transformation of TRIP steel can be described in three stages [5].

a) At a critical strain, retained austenite transforms irreversibly to martensite in strain concentration areas.
b) Strain-induced martensitic transformation is accompanied by a volume expansion of the transforming region, which leads to additional plastic accommodation and work hardening of the surrounding microstructure.

c) This phase transformation would result in a delay of macroscopic necking and ultimately leads to higher uniform and total elongations. Therefore, the stabilization of austenite has to be well balanced in order to prevent the formation of martensite during cooling and allow the continuous martensite formation over a large strain range.

Figure 10 (a) SEM image of TRIP steel, (b) Schematic of TRIP steel [5].

TRIP steel requires higher carbon content compared to DP steels to stabilize the retained austenite at ambient temperature.
1.3.3 Properties of DP and TRIP Steels

1.3.3.1 Flow Stress

The flow stress of conventional sheet materials at room temperature can be expressed as a simple function of strain: \( \sigma = K \varepsilon^n \), where strain-hardening exponent (n-value) is assumed to be constant over the entire plastic strain. The n-value is generally expressed as an average of instantaneous n-value (d \( \ln \sigma \) / d \( \ln \varepsilon \)) over a strain range usually from 10 % up to uniform elongation. In case of HSS steels and low strength steel, the instantaneous n-value slightly decreases with strain as shown in figure 12 [5].

Figure 11 Transformation Induced Plasticity Effect [5].
In DP steels, it could be observed that it has a very high n value at smaller strain, as the initial deformation is concentrated in the low strength ferrite region surrounding martensite. However at higher strains, both martensite and the ferrite microstructure deform plastically resulting in decrease in n-value. In TRIP steels, similar to DP steels, initial deformation is concentrated on ferrite structure followed by deformation of retained austenite resulting in irreversible transformation to martensite at higher strains thereby maintaining approximately constant n value as shown in Figure 12. However, if the retained austenite is less in the TRIP sheet due to improper cooling or due to less carbon content, there is not enough retained austenite to deform at higher strains resulting in deformation of martensite. This results in the decrease in instantaneous n value for TRIP steels at higher strain similar to DP steels leading to early fracture (Figure 13) [5].
Figure 13 Comparison of instantaneous n-value for typical HSS steel, DP steels, TRIP steels and TWIP (X-IP) steels [5].

1.3.3.2 Elastic Modulus

Elastic modulus comprises of both loading (Young’s) and unloading modulus. It is conventionally assumed that elastic modulus for loading and unloading is same and it is a constant value irrespective of the plastic strain.

Figure 14 (a) Non-linear unloading behavior leading to change in Young’s modulus, (b) Decrease in Young’s modulus with plastic strain [5,6].
It is known from various studies [5, 7, 6, 8, 9, 10, 11, and 12] that the loading modulus and unloading modulus are different for AHSS steels and unloading modulus decreases with the plastic strain. [5,6] indicated the unloading behavior is non-linear for AHSS steels in tensile test and explained this nonlinearity could be due to some micro plastic strain recovery along with elastic recovery (Figure 14). Also [6] observed that both loading and unloading modulus decreases with plastic strain for AHSS steels (Figure 14). Variation of loading and unloading modulus for TRIP steels using tensile test was also studied in [10]. It was observed that the loading modulus did not change with plastic strain while unloading modulus decreased with plastic strain (Figure 15).

![Figure 15 Variation of Young's modulus with plastic strain during loading, (b) Variation of Young's modulus with plastic strain during loading [5,10].](image)

The observed decrease in unloading modulus with plastic strain was explained as elastic deformation of martensite microstructure in the sheet during unloading. The martensitic microstructure has low unloading modulus compared to ferrite commonly seen in
It should be noted that the observations from [6] and [10] based on tensile test were contradicting with respect to variation of Young’s modulus during loading with plastic strain. Considering the difficulties and potential inaccuracies in measuring Young’s modulus from tensile test, [8] determined the variation of Young’s modulus with plastic deformation for TRIP steels by using vibrometric identification method that uses plate vibration theories. The Young’s modulus decreased with plastic strain in his observations as well.

Table 1: Young’s modulus change at various plastic strains [5,9]

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Gauge (mm)</th>
<th>E (GPa)</th>
<th>Eu (GPa, Unloading)</th>
<th>Decreasing percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>DQSK</td>
<td>1.19</td>
<td>205</td>
<td>188</td>
<td>187</td>
</tr>
<tr>
<td>BH 280</td>
<td>1.04</td>
<td>209</td>
<td>184</td>
<td>171</td>
</tr>
<tr>
<td>BH 340</td>
<td>1.02</td>
<td>211</td>
<td>187</td>
<td>181</td>
</tr>
<tr>
<td>HSLA350</td>
<td>1.52</td>
<td>209</td>
<td>185</td>
<td>182</td>
</tr>
<tr>
<td>HSLA440</td>
<td>1.58</td>
<td>205</td>
<td>181</td>
<td>174</td>
</tr>
<tr>
<td>DP500</td>
<td>0.81</td>
<td>203</td>
<td>172</td>
<td>157</td>
</tr>
<tr>
<td>DP500</td>
<td>1.54</td>
<td>212</td>
<td>181</td>
<td>177</td>
</tr>
<tr>
<td>DP980</td>
<td>1.52</td>
<td>207</td>
<td>173</td>
<td>154</td>
</tr>
<tr>
<td>TRIP500</td>
<td>1.5</td>
<td>198</td>
<td>179</td>
<td>157</td>
</tr>
<tr>
<td>MART190</td>
<td>1.03</td>
<td>203</td>
<td>188</td>
<td>178</td>
</tr>
</tbody>
</table>
[9] determined the Young’s modulus variation for 12 different steels from low alloy steel to AHSS steel using the indentation test. The sheet materials were subjected to different strains in tensile test and the Young’s modulus after unloading was measured using the indentation test (see table 1). The unloading modulus for DP980 steel decreased around 25% at the engineering strain of 5%, while TRIP500 decreased around 17%. This indicates that it is necessary to consider the Young’s modulus variation with strain for accurate prediction of springback in parts manufactured especially from DP and TRIP steel. Also, the current trend of under estimation of springback for TRIP and DP steel in simulations compared to experiments indicates that the lower Young’s modulus observed in experiments would compensate for it. The data on the variation of Young’s modulus is available for smaller range of strain due to limitation in the tensile test. However, strains in stamped parts especially in load bearing members are higher than strains in tensile test. Therefore, there is need for a method to estimate the variation of unloading modulus over a larger strain range.

1.4 Aluminum (Al 5182 –O)

This is a 5000 series Aluminum alloy which has both Magnesium and Manganese as alloying elements. This series of Aluminum has very good corrosion resistance, formability and weldability. It is used extensively in automotive body parts and in the manufacture of Aluminum cans [13]. Figure 16 shows the various properties of this alloy.
<table>
<thead>
<tr>
<th>Element</th>
<th>Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum, Al</td>
<td>95.2</td>
</tr>
<tr>
<td>Magnesium, Mg</td>
<td>4.5</td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.35</td>
</tr>
</tbody>
</table>

### Physical Properties

The physical properties of aluminium/aluminum 5182 alloy are outlined in the following table.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.65 g/cm³</td>
<td>0.0957 lb/in³</td>
</tr>
<tr>
<td>Melting point</td>
<td>577 - 638 °C</td>
<td>1070 - 1180 °F</td>
</tr>
</tbody>
</table>

### Mechanical Properties

The mechanical properties of aluminium / aluminum 5182-O alloy are tabulated below.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>275 MPa</td>
<td>39900 psi</td>
</tr>
<tr>
<td>Yield strength</td>
<td>130 MPa</td>
<td>18900 psi</td>
</tr>
<tr>
<td>Elongation at break (@thickness 1.60 mm/0.0630 in)</td>
<td>21%</td>
<td>21%</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>69.6 GPa</td>
<td>10100 ksi</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>26 GPa</td>
<td>3770 ksi</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>Hardness, Knoop (converted from Brinell hardness value)</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>Hardness, Vickers (converted from Brinell hardness value)</td>
<td>84</td>
<td>84</td>
</tr>
</tbody>
</table>

### Thermal Properties

The thermal properties of aluminium / aluminum 5182 alloy are tabulated below.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>T (°C)</td>
</tr>
<tr>
<td></td>
<td>123 W/mK</td>
</tr>
</tbody>
</table>

Figure 16 Properties of Al 5182 –O [14]
CHAPTER 2 Objectives

2.1 Three Point Bending

The 3 point bending process, as explained, makes use of a downward moving press which deforms the blank into a V shape. This process was selected in this study because of the ease of set up and study and because it represents one of the simplest forms of bending. The ease of set up enables us to make a wide array of modifications to this process and study the effects of these modifications to the bending process. For this thesis, our primary concern is with springback.

2.2 U bending

In the U bending process, a downward moving die bends a sheet of metal placed on a stationary punch in order to deform the sheet into a U – Shape. This process is one of the most common bending operations seen in the industry and was selected to be studied as part of this thesis because of its wide spread use. Any conclusions and findings obtained from studying the U bending process would contribute immensely to the industry and could be effective immediately.
2.3 Objectives

The high level objectives for both these projects is as follows

- To accurately predict springback for the 3 point bending and U bending experiments using FE simulations
- To ultimately come out with suggestions to reduce springback

Time and cost constraints meant that this thesis could not cover the entire scope of these projects. As a result the following goals (which were determined to be achievable in the given time frame) were established as the objectives of this thesis

- To determine a material model which can be used as input to FE simulation software package (DEFORM 2D) in order to obtain accurate springback predictions for 3 point bending
- To determine the factors which influence the accuracy of the springback prediction by an FE simulation software package (PAMSTAMP) for U bending
CHAPTER 3 Tooling

3.1 Three Point Bending tooling

Experimental data is paramount in order to obtain reliable and accurate results. The tooling required to perform the experiments for 3 point bending was manufactured by a member company at CPF and the experiments were run in using the extensometer available at the department of integrated systems engineering. The extensometer allows for precise control of the punch and automatically records load-stroke date. This data is extremely important to this project. The exact methodology in which this data was used will be explained in the upcoming sections.

The 3 point bending process has a tooling that consists of 2 parts: bottom die and punch. Both the die and punch are manufactured using standard tool steel (exact designation unknown) by a member company at CPF. The bottom die consists of two identical halves whose dimensions are shown in figure 17. The bottom die halves consist of a curved edge on top which the blank rests. The die half also contains a 10mm*5mm rectangular protrusion on the entire length of the bottom surface which fits into the groove of the extensometer thereby locking the die in place. Because the bottom die is made as two separate halves, the span (see figure 19) can easily be varied and this enables the project to study the effect of changing span in the future.
The punch consists of a 10mm diameter hole on the top surface into which the screw from the extensometer fits in. This is how the punch is secured on to the extensometer. The dimensions of the punch is shown in Figure 18.
Figure 18 Design of Punch [15]

The experimental schematic for the 3 point bending experiment is shown in figure 19 and 20. By using the computer controls to move the extensometer arm, the punch is made to move vertically downward and when the punch comes in contact with the blank and moves further down, it deforms the blank into the V-shape.
Figure 19 Schematic of the 3 point bending experiment [15]

Figure 20 Schematic illustrating the stroke of the 3 point bending experiment [15]
3.2 CPF/Shilo Die

Note: ALL of the information seen in this section (section 3.2) was obtained from literature (reference #2).

An existing die design, originally done for a 160 ton hydraulic press, was modified by CPF, and manufactured by Shiloh, to be used on a 300 ton Aida servo press. This die will be called the “CPF/Shiloh die” or simply the “die” in the rest of this report. Figure 21 shows the front view of the die-set.

The die-set was designed such that the punch and die are built in two pieces: a base and an insert. This is done so as to facilitate the use of different corner-radii in the punch and die. The section-view of the die-set is shown in Figure 21 [2].

Figure 21 CPF/Shiloh die-set used in the experiment (Front View) [2].
The die insert is split into 7 parts, as shown in figure 23. The current study focuses on the bending of DP980, TRIP 780 and Al 5182-O steel using the CPF/Shiloh die [2].

Figure 22 CPF/Shiloh die-set (Section View) [2]

Figure 23 Die insert layout (labels described in Table 2) [2]
Table 2  Earmarking of die inserts (shown in Figure 23) for specific operations [2]

<table>
<thead>
<tr>
<th>Operation</th>
<th>Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Straight Flanging (Wipe Bending)</td>
<td>A</td>
</tr>
<tr>
<td>2 U-Bending</td>
<td>A</td>
</tr>
<tr>
<td>3 U-Drawing</td>
<td>A</td>
</tr>
<tr>
<td>4 Shrink Flanging</td>
<td>B</td>
</tr>
<tr>
<td>5 Stretch Flanging</td>
<td>C</td>
</tr>
<tr>
<td>6 U- Flanging</td>
<td>B and C</td>
</tr>
<tr>
<td>7 Deep Drawing</td>
<td>A, B, C, and D</td>
</tr>
</tbody>
</table>

The die consists of a concave side, a convex side and two straight sides, as shown in Figure 24. As seen in figure 23 and figure 24, the straight sides of the die will be used for U-bending
Figure 24 Die schematics (Top View) (notations are described in table 3)[2]

Table 3: Description of notations shown in Figure 24[2]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave side radius</td>
<td>R₁</td>
<td>601.6 mm</td>
</tr>
<tr>
<td>Convex side radius</td>
<td>R₂</td>
<td>598.4 mm</td>
</tr>
<tr>
<td>Cavity corner radii</td>
<td>R₃</td>
<td>51.6 mm</td>
</tr>
<tr>
<td></td>
<td>R₄</td>
<td>56.6 mm</td>
</tr>
<tr>
<td></td>
<td>R₅</td>
<td>61.6 mm</td>
</tr>
<tr>
<td></td>
<td>R₆</td>
<td>66.6 mm</td>
</tr>
<tr>
<td>Die cavity width</td>
<td>LD₁</td>
<td>500 mm</td>
</tr>
<tr>
<td>Die cavity length</td>
<td>LD₂</td>
<td>273.3 mm</td>
</tr>
</tbody>
</table>
The section view of the die is shown in Figure 25.

![Figure 25 Die schematics (Section View) (notations are described in Table 4).](image)

**Table 4: Description of notations shown in figure 25.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die-corner radius</td>
<td>$R_7$</td>
<td>10 mm</td>
</tr>
<tr>
<td>Punch-corner radius</td>
<td>$R_8$</td>
<td>10 mm</td>
</tr>
</tbody>
</table>
3.3 Aida Press

Note: ALL of the information seen in this section (section 3.3) was obtained from literature (reference #2).

Electro-mechanical servo-drive presses are used in many forming machine tools, but in recent years the technology advances have allowed for them to be applied in even press drives. Originally limited to high-speed and low-torque meant that these drives could only be used in small presses. Now there is development of low-speed and high-torque motors, which allows the use if these motors in the drive for presses of up to 3000 tons. [15]

Servo presses also have advanced control over mechanical and hydraulic presses and can be fine-tuned to optimize a given stamping process. As a result these presses can be used for new applications for optimizing deep drawing and blanking operations and for combining forming and assembly in a single press [15]. The press that was used for this project is shown in figure 26. The press is a 300 ton servo press built and operated at AIDA America (Dayton, Ohio).
Figure 26: 300 Ton Aida Servo Press
CHAPTER 4 Preliminary Simulations and Experiments

4.1 Three Point Bending

4.1.1 Simulation Parameters

In order to obtain preliminary simulation data, FE simulations were conducted in accordance with the experimental schematic and tooling data described in section 3.1. The model was made using DEFORM 2D commercial FE simulation software package. In order to get input data, tensile test was conducted at The Ohio State University [15]. In order to obtain accurate tensile test data, the tensile test was conducted by using material that was cut in three different directions i.e., rolling direction, transverse direction and diagonal direction. The flow stress data obtained is shown in figure 27.

![Flow Stress obtained from tensile test for C7026 (0.3mm) [16]](image)

Figure 27 Flow Stress obtained from tensile test for C7026 (0.3mm) [16]
This was the flow stress data that was used input flow stress data into the FE Simulation model. The other material properties which were obtained from the same tensile tests and used as input into the preliminary FE Simulations are shown in Figure 28. The Simulation model setup using DEFORM 2D is shown in figure 29.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Yield Strength (Mpa)</th>
<th>Strain at yield</th>
<th>UTS (Mpa)</th>
<th>Uniform elongation</th>
<th>E-modulus (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D13</td>
<td>575</td>
<td>0.0065</td>
<td>621</td>
<td>0.042</td>
<td>125</td>
</tr>
<tr>
<td>D14</td>
<td>574</td>
<td>0.0065</td>
<td>618</td>
<td>0.043</td>
<td>126</td>
</tr>
<tr>
<td>Av D</td>
<td>574.5</td>
<td>0.0065</td>
<td>619.5</td>
<td>0.0425</td>
<td>125.5</td>
</tr>
<tr>
<td>R13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R14</td>
<td>649</td>
<td>0.007</td>
<td>666</td>
<td>0.042</td>
<td>131</td>
</tr>
<tr>
<td>Av R</td>
<td>649</td>
<td>0.007</td>
<td>666</td>
<td>0.042</td>
<td>131</td>
</tr>
<tr>
<td>T13</td>
<td>617</td>
<td>0.006</td>
<td>645</td>
<td>0.043</td>
<td>143</td>
</tr>
<tr>
<td>T14</td>
<td>616</td>
<td>0.006</td>
<td>645</td>
<td>0.042</td>
<td>144</td>
</tr>
<tr>
<td>Av T</td>
<td>616.5</td>
<td>0.006</td>
<td>645</td>
<td>0.0425</td>
<td>143.5</td>
</tr>
<tr>
<td>Av overall</td>
<td>606.2</td>
<td>0.0064</td>
<td>639</td>
<td>0.0424</td>
<td>133.8</td>
</tr>
</tbody>
</table>

**Note:** R indicates samples cut in rolling direction, T indicates samples cut in transverse direction; D indicates samples cut in diagonal direction and Av indicated average. Also, sample R13 was a bad sample, and hence data is not recorded.

Figure 28 Properties for C7026 Obtained from tensile test at OSU/CPF [16].
Since this study is concerned with only determining an accurate material model in order to improve FE simulation predictions, the preliminary simulations were run with only one span and 2 stroke values as shown in Table 5. Different spans and stroke values will be investigated at a later stage. The results from these simulations were then compared with the experimental data.

Figure 29 FE Simulation model used in DEFORM 2D.
Table 5 Simulation Matrix for preliminary Simulations.

<table>
<thead>
<tr>
<th>Material/thickness</th>
<th>Span</th>
<th>Stroke</th>
<th>Input Flow Stress curve and material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>C7026(0.3mm)</td>
<td>14mm</td>
<td>5mm</td>
<td>From Tensile Test conducted at OSU/COF (figure 27 and 29)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7mm</td>
<td></td>
</tr>
</tbody>
</table>

4.1.2 Experiments

The experiments for the 3 point bending operation were run to get data on the springback of the material. This springback data was then compared with the springback results obtained from the preliminary simulations. The experiments were conducted at the department of Industrial Systems Engineering at the Ohio State University using the tooling and process described in section 3.1. 40mm*30mm samples were used to conduct the experiments. Figure 30 describes the experimental progression.
Figure 30 Experimental Progression of 3 point bending, (a) First step where punch makes contact with the blank (b) the tooling at the end of the punch stroke (c) blank after springback.
NOTE: The numbers on each picture in figure 30 represents the experimental parameters as Span (mm)-punch stroke (mm)-sample number.

Previous experience at CPF [16] has shown that it is important to measure both the angle under load/Loaded Angle (at the end of the punch stroke) and the springback angle (unloaded angle) to ensure accuracy of results. All angles were measured using photos of each sample taken by a camera mounted on a tripod such that only the edge of the sample was visible (as shown in Figure 30). The edge of the samples was marked with a marker for better visibility. These images were digitized using software to obtain co-ordinates of 2 points on each line of the sheet edge as shown in Figure 31. The co-ordinates of these 4 points are used to determine the angle by vector analysis. Different ways of picking these 4 points were tried; however changing that resulted in the same angle measurement when rounded off to an integer value [16]. The angles so measured are show in Table 6.

Figure 31 Points picked on the edge of the samples to measure springback [15].
Table 6 Experimental Results of 3 point bending operation for C7026 (0.3mm)

<table>
<thead>
<tr>
<th>Span</th>
<th>Stroke</th>
<th>Sample #</th>
<th>Loaded Angle</th>
<th>Unloaded Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>14mm</td>
<td>5mm</td>
<td>1</td>
<td>95</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>96</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>95</td>
<td>115</td>
</tr>
<tr>
<td>7mm</td>
<td></td>
<td>1</td>
<td>69</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>68</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>68</td>
<td>91</td>
</tr>
</tbody>
</table>

4.1.3 Comparison of experimental and preliminary simulation data

In order to determine the factors that need to be analyzed further, the experimental springback angles were compared with the springback angles predicted by the FE Simulations, this comparison is shown in figure 32. Experimental Load Stroke data was also compared with springback predictions as shown in figure 33.
Figure 32 Comparison of Bending Angles obtained from experiments and Simulations (a) for 5mm stroke (b) for 7mm Stroke
4.1.4 Conclusions

- As can be seen in figure 32 (a) and (b) the FE Simulations predictions of the sprigback angle are close to experimental results. However, the objective of this thesis is to reduce the discrepancy between experimental and simulation results to lesser than 10%, thus the current results are not acceptable.

- The load stroke data from experiments and simulations don’t agree with each other. It is theorized that this was because of the use of “improper” flow stress data in the preliminary simulations.

- The flow stress data that is used as input for the FE simulations is obtained from the tensile test. However tensile test represents stress only in tension. During bending, the material undergoes both tension and compression (figure 34). We
make the assumption that tensile and compressive stresses are the same but this may be wrong.

![Figure 34 Stresses in Bending](image)

- Also, the tensile test provides data only up to strains of 0.04, but the sample in the 3 point bending experiment undergoes strains of up to 0.2

- Thus, it was theorized that by using the “inverse analysis” methodology to obtain flow stress data directly from the load stroke data, a flow stress curve that yields better springback results might be obtained. This was the next step in determining a material model that would yield an accurate springback prediction through FE Simulation. This methodology has been explained in section 5.1.
4.2 U bending

4.2.1 Simulation Parameters

In order to obtain preliminary simulation data, FE simulations were conducted in accordance with the tooling data described in section 3.2. The experimental schematic that was used to run these simulations is shown in figure 35. The blank placement and dimensions are explained in figure 36 (where L1 = 600mm and L2 = 100mm).

![Experimental Schematic](image)

**Figure 35** Experimental Schematic for U bending Process.
The preliminary data that was used as input for these experiments in obtained from the bulge test which was conducted at EWI. In the bulge test, a viscous fluid which is pressurized by a hydraulic mechanism, acts as a punch to deform the sheet metal blank. A system of lasers measures the height of the blank at failure and by using a code developed at CPF, the biaxial flow stress data is obtained for a given material. The data obtained from this data is considered to be generally more reliable than the data obtained by using the standard tensile test because the bulge test gives results up to a larger strain value (typically ~0.2 strain) while the tensile test typically gives results only up to small values of strain (~0.04) and the rest of the data needs to be extrapolated. It is because of this reason that for the U bending process it was safe to make the assumption that the flow stress data was reliable and that only the other factors (such as Emodulus, r-values etc) needed to be studied in order to improve springback predictions. The Flow Stress data and material properties used to run the preliminary simulations are shown in Figure 37 and 38 respectively. The preliminary simulation matrix is shown in figure 39.
Flow Stress Curves used in Simulations (from EWI)

Figure 37 Flow Stress curves used in preliminary U Bending simulations

<table>
<thead>
<tr>
<th>Material Property used in Simulations</th>
<th>Value</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP980</td>
<td>TRIP780</td>
<td>Al 5182-O</td>
</tr>
<tr>
<td>(E_{modulus})</td>
<td>210 Gpa</td>
<td>210 Gpa</td>
<td>66.19 Gpa</td>
</tr>
<tr>
<td>R0</td>
<td>0.689</td>
<td>0.615</td>
<td>0.79</td>
</tr>
<tr>
<td>R45</td>
<td>0.878</td>
<td>0.93</td>
<td>0.99</td>
</tr>
<tr>
<td>R90</td>
<td>0.973</td>
<td>0.705</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Figure 38 Material Properties used as input in preliminary U Bending Simulations
4.2.2 Experiments

Experiments were run at AIDA using the 300 ton servo press in order to validate preliminary simulations. It is seen that for the U-Bending operation the experimental samples have a uniform area of cross section and so measuring the spring back using the profile of these samples would give an accurate and convenient method to measure spring back. Once the experimental samples were formed both the right and left corner profile of the samples were traced onto a white sheet of paper (figure 40). This trace was then photographed and uploaded onto the online tool “WEBPLOTDIGITIZER” in order to get the digital co-ordinates for these parts and using these digitized co-ordinates and basic geometric formula’s the spring back was measured as shown in figure 41 using the formula:

<table>
<thead>
<tr>
<th>Material / Nominal Thickness</th>
<th>Process</th>
<th>BHF (kN)</th>
<th>Stroke</th>
<th>#Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. TRIP 780 (1.4mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. DP980 (1mm)</td>
<td>U bending</td>
<td>0</td>
<td>65 mm</td>
<td>3 – Longitudinal (L)</td>
</tr>
<tr>
<td>3. AL 5182-O (1mm)</td>
<td></td>
<td></td>
<td></td>
<td>3 – Transverse (T)</td>
</tr>
</tbody>
</table>

Figure 39 Preliminary U Bending Simulations Matrix
Spring back angle \(= \alpha_s - \alpha_o\)

Where \(\alpha_s\) = Measured angle/Final bending angle and \(\alpha_o\) = Initial angle (assumed to be 90 degrees).

The measurements show that both the left and right hand profile of the parts show the same spring back angle. This is expected because of the symmetry of the die and blank placement. The spring back angles for the simulations were obtained similarly and the results for both the simulation and experimental measurements were then compared.

Figure 40 (a) Left and (b) right profile of the bent part
Figure 41: (a) Final Profile of the part (b) spring back angle \( \alpha_s \)

4.2.3 Comparison of experimental and preliminary simulation data

For the U bending process, the springback angles from the experiments was compared with that of the FE Simulation predictions and the results are shown in figures 42.
Figure 42 Comparison of springback angles obtained from experiments and simulations.

4.2.4 Conclusions

- Previous Experience at CPF [16] has shown that the 3 most important factors in obtaining an accurate FE Simulation prediction of springback are accurate values of
  - Flow Stress Curves
  - Emmodulus
  - r-values

- The discrepancies in the results can be attributed to inaccurate values of r and Emmodulus and possibly flow stress curve (although this report has already established in earlier sections that the bulge test data for flow stress is the best available)
• As a result, post experimental simulations were carried out (explained in chapter 6) to determine the effect of r-values and flow stress curves on springback predictions.

• This was then followed by an inverse methodology to determine the correct value of Emodulus to improve springback predictions.
CHAPTER 5 Inverse Analysis and post experimental simulations

5.1 Inverse Analysis for 3 point bending

As established in section 4.1, in order to obtain better springback predictions in FE simulations, an inverse analysis method to obtain the flow stress curve of the material from the load stroke data was implemented. This methodology has been adopted from the methodology described in [17].

Flow stress data is usually represented by the Hollomon law: \( \sigma = K\varepsilon^n \), where \( \sigma \) is true stress, \( \varepsilon \) is true strain, \( K \) is the strength coefficient, and \( n \) is the strain-hardening exponent. However, there are many materials that don’t necessarily follow this curve and it was theorized that sticking to this material model may not yield the optimal results. The following methodology was then implemented in order to obtain a flow stress curve which doesn’t necessarily follow the hollomon law (thereby making this methodology applicable to a large range of materials).

The first step was to conduct FE simulation of the 3 point bending test using the flow stress data obtained from the tensile test. The tensile test gives data only up to the strains of 0.04 but it is extrapolated up to \( \varepsilon=0.2 \) based on last two points (\( \varepsilon=0.038 \) and \( \varepsilon=0.04 \)) by
using power law. Using this extrapolation, we have values of stress ($\sigma_t$) up to the strain of 0.2. Load vs stroke data was then extracted from this simulation.

Next, the average effective strain vs stroke data was obtained from the FE simulation and this is shown in figure 43. Figure 44 illustrates how the average effective strain was calculated from the simulation. 22 points were marked across the thickness (centerline) of the blank in the 3 point bending FE simulation and the effective strain (throughout the simulation) for each of these 22 points was obtained. The total strain in the blank during the bending operation was then calculated as the average strain across these 22 points and this was used to plot the strain vs stroke data. The value of the effective strain was averaged out over these 22 points as using the average strain yielded a closer fit in the load stroke predictions of the simulations and experiments as compared to when using only the maximum strain values. It is seen that the average effective strain becomes constant around 4mm stroke even though deformation continues, this is because of the incomplete method used in averaging the strain (strain is averaged only across the middle section). In future iterations, a better methodology to average out the strain values is needed.
Figure 43 Average Effective strain obtained from FE Simulation

Figure 44 Calculation of Average effective strain.

The load stroke data was then divided into multiple points [each point was at about 0.3mm intervals of the total stroke], and at each point the experimental load value ($F_e$)
was compared with the simulation prediction ($F_s$), this is seen in figure 45. At each point the factor $F_e/F_s$ was then calculated.

![Load vs Stroke Curve](image)

**Figure 45 Calculation of factor $F_e/F_s$**

Thus at each point, we now know

- The factor ($F_e/F_s$)
- Approximate average Strain (since we already know the stroke)
- Stress value from tensile data ($\sigma_t$)

Hence modified stress at each point ($\sigma_{\text{new}}$) = $\sigma_t$ * ($F_e/F_s$). The $\sigma_{\text{new}}$ obtained at each of the points of interest is nothing but the stress value which corresponds to a strain value (strain value at each stroke value is known as shown in figure 43). Thus we can now draw a $\sigma_{\text{new}}$ vs strain curve which is nothing but the modified flow stress of the material. Figure 46 shows the modified flow stress curve obtained from inverse analysis.
5.1.1 Inverse Analysis Results

FE Simulations were then run with the flow stress curve obtained from inverse analysis and the load stroke data was compared with the preliminary simulations (run using tensile test flow stress data) and experimental results (Figure 47). Springback angles from the new simulations were also compared with the preliminary simulations and experimental results and the results are shown in Figure 48.

Figure 46: Modified flow stress curve obtained from inverse analysis for C7026 (0.3mm)
Figure 47 Load vs Stroke comparison between experimental results, preliminary simulations (run using tensile test data) and new simulations (run using modified flow stress data)

<table>
<thead>
<tr>
<th></th>
<th>Loaded Angle</th>
<th>Unloaded Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>94</td>
<td>114</td>
</tr>
<tr>
<td>Tensile data</td>
<td>91</td>
<td>113</td>
</tr>
<tr>
<td>Modified Curve</td>
<td>88</td>
<td>109</td>
</tr>
</tbody>
</table>

Figure 48 Springback angles comparison between experimental results, preliminary simulations (run using tensile test data) and new simulations (run using modified flow stress data)
5.1.2 Conclusions

- Modified flow stress curve obtained from inverse analysis was found to give FE simulation prediction of load stroke data which matched experimental results significantly better than FE simulation prediction of load stroke data obtained by using the flow stress curve obtained from the tensile test.

- The modified flow stress curve gives springback predictions that are still very different from experimental results.

- Hence, apart from flow stress curve, there are other factors that affect springback predictions which we proceeded to study by conducting some more simulations.

5.2 Post Experimental Simulations for 3 point bending

As explained in the previous section, there are factors apart from the flow stress curve which influences springback predictions. In order to study these factors, simulations were conducted according to the matrix shown in Figure 49. Tensile data was chosen as the nominal data. Effect of E modulus, Yield stress and flow stress on the springback predictions were studied. All other simulation parameters were the same as those described in section 4.1.1.
Figure 49 Simulation matrix to study the factors that affect springback predictions.

* nominal data – tensile test data in the rolling direction.

<table>
<thead>
<tr>
<th></th>
<th>E modulus</th>
<th>Yield Stress</th>
<th>Plastic portion of the stress/strain curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects of the E modulus on the springback predictions</td>
<td>1.1 128GPa (5% less)</td>
<td>685MPa*</td>
<td>Tensile test</td>
</tr>
<tr>
<td></td>
<td>1.2 135GPa*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3 142GPa (5% more)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effects of the Yield Stress on the springback predictions</td>
<td>2.1 135GPa*</td>
<td>685MPa*</td>
<td>Tensile test</td>
</tr>
<tr>
<td></td>
<td>2.2 135GPa*</td>
<td>650MPa (5% less)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>616MPa (10% less)</td>
<td></td>
</tr>
<tr>
<td>Effects of the Plastic portion of the stress strain curve on the springback predictions</td>
<td>3.1 135Gpa*</td>
<td>655MPa*</td>
<td>Figure 5.8</td>
</tr>
<tr>
<td></td>
<td>3.2*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 50 Different flow stress curves that were input in figure 48 case 3. Case 3.2 was nominal data and was obtained from tensile test in the rolling direction.
5.2.1 Results

- It was seen from the post experimental simulations that an increasing E modulus reduces springback (as shown in figure 51). This is along expected lines as an increasing E modulus increases the amount of elastic recovery; as a result, springback is reduced.

![The effect of E modulus on springback](image)

Figure 51 Effect of E modulus on springback prediction

- 5 to 10% reduction in the yield stress does not change the springback prediction value in the simulations.

- Small change in the plastic portion of the stress/strain curve changes (figure 52) the prediction for springback by about 10%.
5.3 Conclusions for 3 Point bending of C7026 (0.3mm)

- The inverse methodology described gives good predictions of load-stroke data but springback predictions are off.
  - One primary reason for this maybe because as shown in figure 43, the averaging of strains leads to a constant strain after stroke of 4mm. This is not correct and the points chosen to average the strains need to be spread all around the sample and not only along the central line.

- It has also been shown that
  - By increasing $E_{\text{modulus}}$, springback angle decreases but the relationship is not linear. (figure 51)
  - 5 to 10% reduction in the yield stress does not change the springback value in the simulations.
- Small change in the plastic portion of the stress/strain curve changes (figure 52) the prediction for springback about 10%.
6.1 Post experimental simulations for U bending

As explained in section 4.2.4 E modulus, r value and flow stress curve are the most important factors that affect an accurate prediction of springback by FE simulations. In order to test these factors post experimental simulations were run. Apart from the factors being studied, all other dimensions and inputs were the same as that described in section 4.2

6.1.1 Simulations to study the effect of flow stress data source

In order to study the effect of the flow stress data on springback predictions, simulations were run using the following 3 different cases for all the materials

- Case 1: Bulge test data: figure 53. The flow stress data for this case was obtained from the bulge test conducted at EWI.
- Case 2: Extrapolated tensile test data: figure 54. The flow stress data for this case was obtained from EWI which consisted of the flow stress data obtained from the tensile test and extrapolated to s train of 1. The method used to
extrapolate this data is not known but the extrapolation method may have an effect on the results.

- Case 3: Modified Bulge test data: figure 55. The modified bulge test data is obtained by combining the yield stress from the tensile test data with the bulge test data [18]. First the yield point from the tensile test is converted into biaxial stress using the formula

\[
\sigma_{\text{biaxial}} = \frac{\sigma_{\text{uniaxial}}}{\sqrt{\frac{R_9 + R_0}{R_9(R_0 + 1)}}}
\]

The biaxial yield point is then combined with the bulge test data and the final modified bulge test data is obtained.

![Bulge Test data (from EWI)](image)

Figure 53 Bulge test data obtained from EWI
6.1.2 Simulations to study the effect of \( r - \) values

In order to study the effect of different \( R (r_0, r_{45}, r_{90}) \) values on springback predictions, simulations were run using the following 2 different cases for all the materials. The different cases and simulation matrix used has been shown in figure 56.
Table 56 Simulation matrix used to study the effect of \( r \)-values on springback predictions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Material (Thickness)</th>
<th>E Modulus</th>
<th>( r_0 )</th>
<th>( r_{45} )</th>
<th>( r_{90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case 1</strong></td>
<td>DP 980 (1mm)</td>
<td>210 Gpa</td>
<td>0.689</td>
<td>0.615</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>TRIP 780 (1mm)</td>
<td>210 Gpa</td>
<td>0.878</td>
<td>0.93</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Al 5182-O (1mm)</td>
<td>66.19 Gpa</td>
<td>0.973</td>
<td>0.705</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Case 2</strong></td>
<td>DP 980 (1mm)</td>
<td>210 Gpa</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>TRIP 780 (1mm)</td>
<td>210 Gpa</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Al 5182-O (1mm)</td>
<td>66.19 Gpa</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**6.1.3 Results and conclusions**

Figures 57, 58 and 59 show the effect of flow stress source on the springback predictions and figures 60, 61 and 62 shows the effect of \( r \)-values on springback predictions.

![Figure 57 Effect of flow stress source on springback prediction for DP980 (1mm)](image-url)

Case 1: Bulge test data: Figure 53
Case 2: Tensile test data: Figure 54
Case 3: Modified Bulge test data: Figure 55
Figure 58 Effect of flow stress source on springback prediction for TRIP 7890 (1.4mm)

Figure 59 Effect of flow stress source on springback prediction for Al 5182-O (1mm)

Figure 60 Effect of r-values on springback prediction for DP 980 (1mm)
Figure 61 Effect of r-values on springback prediction for TRIP 780 (1.4mm)

Figure 62 Effect of r-values on springback prediction for Al5182-O (1mm)
- It can be see that flow stress curves from different sources do not have any conclusive effect on the measured angles (figures 57, 58 and 59).
- R-values affect the springback predictions differently for different materials. For TRIP 780 and DP 980 simulations show a difference in the springback angles in longitudinal and transverse directions while this difference is not seen in the experiments. However, for Al5182-0 there is a difference in springback for rolling and transverse directions (figures 60, 61 and 62).
- Previous experience has shown that the r-values \( r_{0}, r_{45}, r_{90} \) obtained from 2 different companies is not the same; this maybe an important factor that needs to be looked into in the future.
- It can be tentatively concluded from that “correct” Emodulus and a reasonably accurate flow stress curve are paramount in obtaining an accurate springback angle prediction.
- These results further justify the need to conduct an inverse analysis to obtain the right value of Emodulus as we see the importance of using the “correct” Emodulus value in order to obtain accurate springback predictions.

6.2 Inverse Analysis for U bending

In order to obtain better U bending results, an inverse methodology was tried. Previous slides and experience at CPF has shown how important flow stress curve and Emodulus values are in predicting springback[16]. By using the modified bulge test data, reliable flow stress data has been obtained for all materials used in this project. The discrepancies in the springback predictions of preliminary simulations and experimental results are thus
attributed to improper Emodulus value as the current methodology used to determine Emodulus is riddled with a lot of inconsistencies. In the inverse methodology, E modulus of each of the materials in the simulations was varied, and the Emodulus value that gave the springback prediction that best matched the experimental results, was chosen as the “correct” Emodulus value for the material.

The Inverse analysis methodology will be explained as it was applied for TRIP780. The same was applied to DP980 and Al 5182-O as well to get the final results. First two Emodulus values (10 % lesser and 10 % more than current value) were plugged into the FE simulation. Springback angle was then calculated for each of these 2 simulations (figure 63).

<table>
<thead>
<tr>
<th>Material</th>
<th>Simulation Number</th>
<th>Emodulus value used (Gpa)</th>
<th>Springback Angle</th>
<th>Difference with experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIP780 (1.4mm) Rolling Direction</td>
<td>1</td>
<td>189</td>
<td>9.5</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>210 (Current value obtained from EWI)</td>
<td>9.8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>231</td>
<td>12.23</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Figure 63 Simulation matrix in the first step for inverse analysis of U Bending

As expected, reducing E modulus value, lead to increasing springback. Hence E modulus value was reduced until an agreeable result was obtained (figure 64)
Figure 64 Effect of reducing E modulus on springback predictions

For TRIP 780 and DP980 simulations r – values were considered = 1 as anisotropy doesn’t make a difference in springback for experiments (as explained in section 6.1). The Same methodology was applied to DP980 and Al 5182-O and the results shown in figures 65, 66 and 67 were obtained.

Figure 65 Corrected E modulus value obtained through inverse analysis for TRIP 780 (1.4mm)
Figure 66 Corrected E modulus value obtained through inverse analysis for DP 980 (1mm)

Figure 67 Corrected E modulus value obtained through inverse analysis for Al 5182-O (1mm)
• As explained in section 4.2, for DP 980 and TRIP 780, anisotropy does not make a difference in terms of springback results for experiments.

• Hence for the Inverse methodology all r-values \((r_0, r_{45}, r_{90}) = 1\) were chosen to run the simulations for AHSS and r-values \((r_0, r_{45}, r_{90})\) obtained from EWI was used for Aluminum as anisotropy does make a difference for springback angles in aluminum

• The Inverse methodology yields a good springback prediction for all the materials used in the U bending operation

• It was found that the most important factors that effect springback predictions are
  - E modulus
  - Flow stress curve
  - Anisotropy (extent of effect needs to be further analyzed)
References


3. “Elastic Springback”, retrieved from:


13. “Alu-selectApplications”, Retrieved from: 
http://aluminium.matter.org.uk/aluselect/01_applications.asp?alloyid=33

14. “Aluminum 5182 Alloy”, Retrieved from:
http://www.azom.com/article.aspx?ArticleID=8652


17. Subramonian, S.; “Investigation of Blanking as a test to obtain flow stress data at high strain and strain rates”, CPF -5.2/13/01, Center For Precision Forming, The Ohio State University, 2013.