Springback Prediction on Slit-Ring Test

Xiao Ming Chen¹, Ming F. Shi¹, Feng Ren² and Z. Cedric Xia²

¹United States Steel Corporation
²Ford Motor Company

Abstract. Advanced high strength steels (AHSS) are increasingly being used in the automotive industry to reduce vehicle weight while improving vehicle crash performance. One of the concerns in manufacturing is springback control after stamping. Although computer simulation technologies have been successfully applied to predict stamping formability, they still face major challenges in springback prediction, particularly for AHSS. Springback analysis is very complicated and involves large deformation problems in the forming stage and mechanical multiplying effect during the elastic recovery after releasing a part from the die. Therefore, the predictions are very sensitive to the simulation parameters used. It is very critical in springback simulation to choose an appropriate material model, element formulation and contact algorithm. In this study, a springback benchmark test, the slit ring cup, is used in the springback simulation with commercially available finite element analysis (FEA) software, LS-DYNA. The sensitivity of seven simulation variables on springback predictions was investigated, and a set of parameters with stable simulation results was identified. Final simulations using the selected set of parameters were conducted on six different materials including two AHSS steels, two conventional high strength steels, one mild steel and an aluminum alloy. The simulation results are compared with experimental measurements for all six materials and a favorable result is achieved. Simulation errors as compared against test results falls within 10%.

INTRODUCTION

The dimensional control of stamped AHSS parts is more challenging due to the high strength nature of these alloys as compared with milder steels. Some traditional techniques for springback control such as multiple-stage forming and re-striking may not be suitable for AHSS due to their rapid strain hardening behavior. Some successes in springback control for AHSS have been reported with process control and tool compensation approaches. Various process control methods have been used including optimizing die gaps, using variable blank holding force, flowing draw bead by increasing the part stretch at the last drawing stroke, using step flange to increase side wall stretch, and adding stiffening beads, etc. [1-4]. One of the common features found in these approaches is to increase panel stretch to obtain a more uniform residual stress distribution through the sheet thickness. However, most of those process control methods still involve trial-and-error, which is very time and cost consuming. Therefore, it is very desirable to develop computer simulation technology for springback prediction and control similar to that used in formability assessment.

The FEA has been widely used in automotive design and manufacturing feasibility evaluation. A high level of confidence has been built in predicting cracking and wrinkling in metal forming processes. However, it remains a very challenging task to accurately predict springback, particularly for those parts with twist and sidewall curl. The prediction accuracies are case dependent. They can be satisfactory for some cases, but highly deviated for others. For example, 30% prediction error was reported for a channel type analysis when using a DP980 steel [2]. Springback prediction is a complicated process since it involves large, non-uniform deformation in the forming stages and follows with elastic unloading for residual stress redistribution. Numerous studies have been carried out to understand the root causes of prediction errors [5-9]. It has been shown that material behaviors such as anisotropy, the Bauschinger effect and non-linearity during unloading need to be considered in the material model. For tight radii or complex parts, fine meshes need to be used to adequately model
geometry details. Existing shell elements may introduce error when characteristic lengths such as die radii are comparable to metal thickness, and new formulations need to be developed. A better contact algorithm is necessary to improve the accuracy during forming processes simulations. During the last decade, FEA software developers and users have been putting great effort into solving springback prediction problems. The computational prediction capability and methodology have been steadily improving. Some successes have been realized for parts with moderate radii and low twist.

Many previous studies indicated that springback results were also sensitive to simulation parameters such as mesh size, the number of through thickness integration points, simulation speed, contact penalty factor, etc.[5-8]. In this study, the slit ring benchmark test [10-11] is used to assess the capability of current simulation technology using the commercial FEA package of LS-DYNA. The slit ring test uses a circular blank to form a deep drawn cup, followed by cutting a ring from the cup, and then slitting the ring to open and measure the springback. The simulation technique used in this study follows the current common practice: using the dynamic explicit method for the forming simulation and the static implicit method for the springback analysis. Parameter sensitivity studies were carried out for six simulation variables using deep drawing quality and special killed (DQSK) steel, and the influence of these parameters on springback prediction is then identified. A satisfactory result was achieved with a maximum prediction error around 10% for six materials.

**EXPERIMENT AND MATERIALS**

**Deep Draw Cup and Slit Ring Test**

The experiments were conducted on a “Slit-Ring” Test, which consists of four steps: (a). Deep draw a cylindrical cup from a circular blank with a constant blankholder force; (b). Cut a circular ring from the mid-section of the drawn cup; (c). Slit the ring along certain direction to release residual stresses introduced from drawing operation, and (d). Measure the opening of the ring (springback). The experimental setup and tool dimensions for the cup drawing are shown in Figure 1. The blankholder force used was 88.9 kN and the maximum punch travel was set at 56 mm. An oil lubricant is applied to both sides of blanks, and dry film is also applied to the die side of blank to further reduce friction. The illustration of a drawn cup and slit-ring is shown in Figure 2. The final cup diameter is 110 mm with 56 mm height, drawn from a circular blank of 195 mm in diameter. A circular ring of 15 mm width is cut from the formed cup as shown in Figure 2a. Then the ring is slit for springback measurements as shown in Figure 2b. The detailed experimental procedures and results are well documented in reference [12].

**Materials**

Six different automotive sheet metals were selected for the study, with one DQSK mild steel, one bake hardenable (BH) medium strength steel, a conventional high-strength low-alloy (HSLA) steel, one dual-phase (DP) steel, one transformation induced plasticity (TRIP) steel and one aluminum alloy (6022-T4). Their respective coatings and gauges are listed in Table 1. The tensile properties of those materials were tested along three orientations, namely the rolling direction (0°), the diagonal direction (45°), and the transverse direction (90°). They are listed in Table 1. The stress – plastic strain curves in rolling direction are plotted in Figure 3. The curves are extended after uniform elongation.
with the power law for simulation purpose. It can be seen that DP and TRIP steels have much higher tensile strength. This capability makes them better in crashworthiness and structural performance, but also causes higher springback after forming.

Table 1. Test Materials and Mechanical Properties

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DQSK</th>
<th>BH33</th>
<th>HSLA50</th>
<th>TRIP600</th>
<th>DP600</th>
<th>AA6022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>1.01</td>
<td>0.783</td>
<td>1.54</td>
<td>1.58</td>
<td>1.6</td>
<td>0.93</td>
</tr>
<tr>
<td>YS (Mpa)</td>
<td>153</td>
<td>248</td>
<td>441</td>
<td>407</td>
<td>340</td>
<td>180</td>
</tr>
<tr>
<td>UTS (Mpa)</td>
<td>307</td>
<td>370</td>
<td>496</td>
<td>623</td>
<td>563</td>
<td>300</td>
</tr>
<tr>
<td>n – value</td>
<td>0.253</td>
<td>0.195</td>
<td>0.146</td>
<td>0.225</td>
<td>0.166</td>
<td>0.247</td>
</tr>
<tr>
<td>Re</td>
<td>1.734</td>
<td>1.48</td>
<td>0.907</td>
<td>0.916</td>
<td>0.843</td>
<td>0.758</td>
</tr>
<tr>
<td>R45</td>
<td>1.515</td>
<td>1.349</td>
<td>1.064</td>
<td>0.833</td>
<td>0.912</td>
<td>0.426</td>
</tr>
<tr>
<td>R90</td>
<td>2.085</td>
<td>2.173</td>
<td>0.68</td>
<td>0.967</td>
<td>1.018</td>
<td>0.475</td>
</tr>
<tr>
<td>R-bar</td>
<td>1.712</td>
<td>1.588</td>
<td>0.929</td>
<td>0.887</td>
<td>0.921</td>
<td>0.521</td>
</tr>
</tbody>
</table>

Figure 3. Stress - Strain Curves for Tested Materials

SIMULATION SET UP

The FEA simulations consisted of cup drawing, ring trimming and springback simulation after the ring slitting. The commercial code of LS-DYNA version 970 was used for all simulations. A dynamic explicit method was used for cup drawing and a static implicit one was used for springback simulations.

Figure 4 depicts the FEA model during cup drawing. Due to the symmetry of the part, the half model was used in this study and the full model was used only for the verification purpose. The slit ring model and its rigid body motion constraints for springback simulations are illustrated in Figure 5. A set of baseline parameters was selected and is summarized as follows:

- Punch speed: 2500 mm/sec
- Element size: 1.25 mm without adaptive mesh
- Material model: Transversely anisotropic elastic-plastic model (Mat 37)
- Element: Fully integrated shell element (#16)
- Integration points through thickness: 7
- Friction Blank – Blank hold, Punch: 0.10
- Friction Blank - die: 0.05
- Blank holder Pressure: 88.9 kN
- Contact penalty factor: 0.1
- Hold time after the bottom of stroke: 0.0

Figure 4. Deep Draw Cup Forming Model Set up

In the parametric sensitivity study, six variables were selected: mesh size/adaptive level, model size (half and full), number of integration points through thickness, contact penalty factor, simulation speed and hold time (settle down time). In each case study, only one parameter was changed while the others remained the same as the baseline values.

Figure 5. Slit Ring Springback model set up

RESULTS AND COMPARISONS

Forming

The drawn cups from the experiment are shown in Figure 6 for all six materials. The peripheries of the cup flanges were also measured and are presented in Figure 7. These data are used to check the accuracy of forming simulations. Circular cup
drawing is a well-studied case in metal forming analysis. The simulation result can be verified by strain distribution and final blank diameter comparisons. Figure 8 depicts the strain distribution pattern (signature) of DQSK steel, which shows a typical shape of circular cup drawing. All other materials have a similar strain signature, which indicates that the simulation results are valid. The comparison of final blank diameters also indicates a good correlation as shown in Figure 9. The maximum deviation between simulations and tests is less than 5%.

Figure 6. Formed Deep Draw Cups

Figure 7. Measured Peripheries of Cup Flanges

Parameters Sensitivity Study

The sensitivity study was performed on forming simulation and the variables have less effect on forming results (measured by strains). However, they affect more significantly on the consequent results of springback simulations. The simulation matrix of the six parameters selected is listed in Table 2 (shown in the last page). The DQSK material is selected for this sensitivity study.

Figure 8. Strain Signatures of the Deep Draw Cup from the Simulation

Figure 9. Comparison in Flange Diameters

Figure 10 (shown in the last page) depicts results of all the simulation cases based on the matrix in Table 2. The simulation predictions are also compared to the experimental results. Three horizontal lines are shown in the figure in which the center one is the average value from experiments, and the upper and lower ones are ±10% from the average experimental data. Looking at the simulation results only, the variation of results is within 10%, which indicates that the simulation results are reasonably stable within the variable ranges selected. When compared to the experiment results, the springback results are higher, but the deviations for most cases are less than 10%, which is considered to be satisfactory for springback simulation.

Some sensitivity trends can be seen from Figure 10. Reducing the number of integration points through the thickness increases the springback slightly. The predicted springback increases as the simulation speed decreases. However, the settle down time has little effect on the springback prediction results, which indicates that the dynamic effect is negligible for the simulation speed used. Contact forces have minor effect on the results. It can be also seen that the simulated results are not
affected when the initial element size is 2.5 mm or smaller. However, when the element size is 20 mm (about 20 times of shell thickness), the blank deviates from circular shape considerably and the adaptive mode becomes non-symmetrical, as shown in Figure 11. In this case, the simulation results are not stable. The simulation results are similar between the full model and the half model.

**Figure 11.** Element size is too large

### Springback Prediction

As shown in the parameter sensitivity study, the parameters listed in the base line set up resulted in a satisfactory result for DQSK steel. Therefore, these parameters were used in the simulation for all other five materials. The summary of simulation results along with experimental data is shown in Figure 12 for all six materials listed in Table 1. Again, the three data points from the experimental measurements are given for all materials, i.e., the average value and 10% above and below the average value. It is shown from the Figure 12 that the simulation under-predicts springback for all materials except for the DQSK, in which it is about 10% over predicted. Results for both BH33 and HSLA are about 10% under-prediction and that for DP600 is 5% under-predicted. For TRIP600, the prediction is about 12% lower than the mean experimental value. For AA6022, the prediction is 9.6% lower than measured mean value.

**Figure 12.** Predicted Springback Results vs. Experimental Results

### CONCLUSIONS

- The variation of springback simulation results is within 10% in the general parameter ranges.
- Six different materials were simulated and compared to experiments. The maximum deviation of outer diameter from forming predictions is less than 3%.
- The computer simulation can predict the springback within 10% for most materials except for the TRIP600 where the deviation is 12%.
- The simulation results under-predict the springback for most of materials except for the DQSK, where the simulation over-predicts the springback.

### REFERENCES

ACKNOWLEDGEMENTS

The authors would like to acknowledge the United States Steel Corporation and Ford Motor Company for approving the publication of current work and Mr. Kalyan Palanisamy for assisting with the simulations work.

Table 2. Simulation Parameter Sensitivity Study Matrix

<table>
<thead>
<tr>
<th>Uniform</th>
<th>Model</th>
<th>Integration Points</th>
<th>Contact</th>
<th>Acceleration</th>
<th>Settle Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.25mm 5 mm 10 mm 20 mm</td>
<td>Half</td>
<td>Full</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Level 4 Level 5 Level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

DISCLAIMERS

The material in this paper is intended for general information only. Any use of it in relation to specific applications should be based on independent examination and verification of its unrestricted availability for such use, and determination of suitability for the application by professionally qualified personnel. No license under any United States Steel Corporation patents or other proprietary interest is implied by the publication of this paper. Those making use of or relying upon this material assume all risks and liabilities arising from such use or reliance.

Table 2. Simulation Parameter Sensitivity Study Matrix

Figure 10. Springback Simulation Results from Parameters Set up Matrix