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Sheet Forming Simulation and Springback Prediction for AHSS Automotive Components

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Keywords: Finite element simulation, Sheet metal forming, Springback, Sensitivity, Advanced high strength steel, Dual-Phase, TRIP, Automotive application

Abstract

Understanding the accuracy of Finite Element (FE) springback predictions has become increasingly important in the automotive industry, due to recent trends towards the use of Advanced High Strength Steels (AHSS). This paper investigates the accuracy and sensitivity of FE tools in predicting the forming behavior and post-formed geometric shape of conventional steel and AHSS grades for a practical automotive case study. The steel grades examined include Hot Rolled Low Carbon (HRLC), Dual-Phase (DP) and TRansformation-Induced Plasticity (TRIP); the characteristics of which were determined from tensile tests. To model the complete forming process of the complex automotive component, AutoForm Incremental, a commercially available sheet metal forming software package, was employed. An investigation into the differences in predictions between the new version (v4.0) and the older version (v3.2) of the software is also presented. To ensure the validity of the springback predictions, calculated strains, thicknesses and flange lengths were first correlated with experimental measurements of components stamped at the industrial production line. Measured final part geometries were then compared to FE springback predictions. Accuracies and sensitivities in the numerical prediction of both formability and final part shape are presented and discussed.

Introduction

Steady advancements in technology, combined with shortened product cycle times and continual demand to reduce costs, has resulted in the dependence on FE codes for the simulation of sheet metal forming processes in the automotive industry. It is generally accepted that commercially available FE programs can be successfully utilized to predict formability, and the likelihood of splits and wrinkles, even for complex part geometry. It has been shown, in an industrial setting, that such software packages are able to predict strain and thickness distributions with accuracies of up to 90%, or more [1].

However, the phenomenon of springback, which relates to the inherent post-formed elastic recovery, remains a challenge. This is particularly evident in an industrial setting, where springback has often been reported as difficult to simulate [2]. In recent years, the automotive industry has also seen a growing trend towards the application of AHSS, allowing possible down-gauging of blank material, which each result in a tendency for larger springback. Furthermore, parts constructed from AHSS generally require high dimensional accuracy, due to their rigidity in the assembly line. These factors have placed increasing significance on springback predictions, prompting the need for a clear assessment of the accuracy of commercial springback predictions.
This paper investigates the accuracy and sensitivity of FE tools in predicting the forming behavior and post-formed geometric shape of a conventional steel and AHSS grades, for a practical industrial case study. The sensitivity analysis examined direct partial derivatives of model outputs with respect to key input parameters, such as friction, blank holder force, and material model characteristics. The material grades examined include HRLC, Dual-Phase and TRIP steels, having a nominal strength range from approximately 350 MPa to 800 MPa. AutoForm Incremental was employed to model the complete forming process of the complex automotive component. An investigation into the differences between v4.0 and v3.2, and the accuracy of results predicted, is also examined. It is appreciated that the accuracy of the springback predictions are principally dependant on the accuracy of the manufacturing operations simulated prior to springback (i.e. forming and trimming). Hence, predicted strains, thicknesses and flange lengths were first correlated with experimental measurements prior to investigating springback.

**Advanced High Strength Steels**

The principal difference between AHSS and conventional steels is due to their microstructure. To achieve a higher strength, conventional steels are typically manufactured using solid-solution strengthening, grain refinement, precipitation-strengthening, or a combination of these mechanisms. Therefore by selecting higher strength steel grades, reduced formability and elongation is generally expected. In contrast, AHSS typically develop their higher strength by transformation-strengthening, in which a significant proportion (up to 20%) of hard transformation products, such as martensite, bainite and/or retained austenite, are contained in a matrix of soft fine ferrite grains [3]. For this reason, AHSS grades can provide an excellent combination of strength and formability.

The term “dual-phase” refers to the presence of two phases, ferrite and martensite, but small amounts of other phases may also be present (bainite, pearlite, retained austenite). Dual-Phase steels have a number of unique properties, which include: a low 0.2% offset yield strength; a high tensile strength; a high work hardening rate; and a high uniform and total elongation [4]. This favorable combination of strength and ductility is primarily due to the distribution of a substantial amount of the hard phases throughout the soft ferrite matrix.

The microstructure of TRIP steels also consists of a continuous ferrite matrix containing a dispersion of hard second phases – martensite and/or bainite. However, TRIP steels also contain retained austenite in volume fractions in the range of 5% to 20% [5]. Upon straining, the dispersion of hard phases in soft ferrite creates a high work hardening rate, as observed with Dual-Phase steels. As the material plastically deforms, the retained austenite also progressively transforms to martensite, with increasing strain [6]. This phenomenon is responsible for the increased work hardening rate at higher strain levels, when compared to Dual-Phase steels, thus providing improved formability.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HRLC</th>
<th>DP</th>
<th>TRIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Offset Yield Strength (MPa)</td>
<td>241</td>
<td>486</td>
<td>542</td>
</tr>
<tr>
<td>Tensile Strength – Engineering (MPa)</td>
<td>344</td>
<td>636</td>
<td>794</td>
</tr>
<tr>
<td>Tensile to Yield Strength Ratio</td>
<td>1.43</td>
<td>1.31</td>
<td>1.47</td>
</tr>
<tr>
<td>n-Value (5-15% Strain)</td>
<td>0.17</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>Average r-Value</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Blank Thickness (mm)</td>
<td>2.2</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The mechanical properties of the three steel grades used in this study were determined from conventional tensile tests conducted at Deakin University. The key properties obtained are summarized
in Table I, and the average stress strain curves obtained are shown in Figure 1. The average r-values shown have been obtained from the manufacturer's specifications. The curves in Figure 1 show the trends outlined in the preceding discussion. The stress strain curve of DP steel shows that, for strains less than 5%, the strain hardening rate is high, and is comparable with TRIP steel in this region. However, the n-value obtained for DP is only 0.14, when calculated for 5 to 15% strain range (Table I). Hence, it is evident that the power law is not an accurate indication of material behavior at the initial ranges of strain.

![Stress-strain curves for HRLC, DP, and TRIP steels.](image)

Figure 1: Experimental true stress - true strain curves for HRLC, DP and TRIP steels.

Due to these unique characteristics of AHSS grades, direct substitution of conventional steels with AHSS is not a straightforward task. Increased springback, excessive tool wear caused by higher forming forces, and parts with poor dimensional tolerances are some of the challenges that AHSS grades introduce to design, process and product engineers. Hence, an initial step towards improving the part, tool and process design of components made out of AHSS is to understand the accuracy and reliability of current numerical tools.

**Experimental Setup**

The first part of this investigation was to conduct plant trials, where the components to be simulated were stamped in the industrial production line. The component selected for this study was an automotive front cross-member, which has a relatively complex geometry (Figure 2). Figure 2(a) shows the 'drawn part', which was removed from the process prior to the final trimming stage, with the 'final part' shown in Figure 2(b). These drawn and final parts were stamped for each material grade examined.

![Component investigated.](image)

Figure 2: Component investigated. (a) Drawn and (b) final component stamped at the production line. Importantly, the press settings remained unaltered throughout the trial, so that a direct comparison between each of the material grades could be made. Strain and thickness measurements were conducted using a circle grid pattern analyzer and an ultrasonic thickness gauge, respectively. For the springback analysis, point cloud data, constructed from FARO arm measurements, was used to determine the post-formed part geometry of each of the final parts.

To assess the amount of draw-in, flange lengths on the drawn parts were determined. Measurements were taken at several locations, but the amount of draw-in at the part centre was of primary interest, as
this proved to be representative of the draw-in over the complete component. The locations of these primary flange length measurements are indicated by length F1-F2 and length F3-F4 in Figure 3.

![Figure 3: Position of primary flange length measurements on drawn part.](image)

**Numerical Setup**

Primarily, forming simulations were performed using AutoForm Incremental v3.2 (AF v3.2). AutoForm is a specialized software package that is optimized for the simulation of sheet metal forming processes, using a specific implicit FE formulation. The mesh for all tools and blank was generated in AutoForm using imported IGES geometry files. An Intel platform PC (2.0GHz) was used for all simulations.

The material characteristics determined from tensile tests (Table 1 and Figure 1), were used to define the material behavior. To avoid the error typically associated with using a power law approximation, as highlighted earlier, the flow curve was defined using the tabulated stress-strain data.

After preliminary analysis of the experimental and numerical results, several cross-sections along the components were chosen for critical analysis (Figure 4(a)). The position of these sections were chosen to ensure that: a variety of forming modes were examined; the blank experienced significant forming strains in these regions to permit a useful comparison; and the springback trend over the entire part could be sufficiently represented. All experimental strain, thickness and geometric shape measurements were compared to numerical outputs at these locations. The values of springback, for both simulation and experimentation, were reported at the ends of the trimmed flanges at each of these cross-sections, as indicated by points A1 through to E2 in Figure 4(b).

![Figure 4: (a) Cross-sections and (b) points selected for detailed analysis of results.](image)

AF v3.2 simulation predictions for the HRLC steel were first correlated with the corresponding experimental measurements. Comparisons were primarily focused on Section C and Section D, due to the different forming modes and comparatively large strains experienced at these regions. Figure 5
shows the strain signatures at these cross-sections, obtained from simulation predictions. It is evident that Section C experiences primarily a plane strain forming mode, whereas a drawing deformation mode is predominant in Section D. Experimental results also show the same trends at these regions.

Figure 5: Strain signatures; (a) plane strain forming mode predominant at Section C, (b) drawing forming mode present at Section D.

In addition to correlating strains and thicknesses at Sections C and D, the flange lengths measured from the simulation of HRCLC steel were also compared to the experimental results, to ensure a good correlation was achieved. The primary simulation input parameters that were adjusted during the correlation process are listed in Table II, along with the final values used.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Blank Holder Pressure</td>
<td>3.0 MPa</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>0.1</td>
</tr>
<tr>
<td>Initial Blank Position</td>
<td>0 mm</td>
</tr>
<tr>
<td>Tool Offset</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>Tool Stiffness Parameter</td>
<td>25 N/mm³</td>
</tr>
</tbody>
</table>

The initial blank holder pressure, referred to in Table II, is specified in AutoForm, with the required force exerted by the blank holder to generate this pressure calculated automatically. This force, which equates to approximately 500kN in this case, is then held constant throughout the forming process. The initial blank position describes the x-location of the blank, as referenced from the final correlated blank position (refer to axis shown in Figure 4). As such, the final blank position used is 0mm. The tool offset refers to the clearance between the punch and the die. This was set to the blank thickness (2.2mm) of the original HRCLC material used in production. Finally, the tool stiffness parameter is used to represent the influence of the configuration and geometry of the tool, the stiffness of the press, and the behavior of the tool steels. Large values (i.e. up to 1000N/mm³) may be used to characterize smaller tools, and small values (i.e. down to 1N/mm³) may be more appropriate for larger tools [7].

Once a satisfactory level of correlation with the predicted forming behavior of the HRCLC steel was achieved, the DP and TRIP material definitions were directly substituted, with initially no other changes made. Hence, the DP and TRIP models realistically simulated the experimental scenario.

In order to achieve a good correlation with the measured flange lengths, the initial blank position had to be modified slightly for each steel grade (no more than ±3mm). It was believed that this small change in blank position was a result of the part-to-part variation in the industrial press, which affects the flange size, strain and thickness distributions, and final part shape, but has not been studied here.

It is appreciated that the accuracy of the springback predictions are principally dependant on the accuracy of the manufacturing operations simulated prior to springback (i.e. forming and trimming). Of
particular importance is the accurate prediction of strain distributions across the part and through the thickness of the material. Hence, much effort was spent ensuring that predicted strains, thicknesses and flange lengths were first correlated with experimental measurements prior to investigating springback.

**AutoForm Version 4.0 Simulations**

One of the primary differences of AF v4.0 is the use of an implicit shell element formulation, instead of the bending enhanced membrane of v3.2. It is expected that this will provide more precise simulation of bending effects and therefore improve springback predictions. Other changes include an improved adaptive mesh refinement scheme, new material laws, and an increased number of integration points over the sheet thickness [8]. Each of these improvements are anticipated to contribute to an increased accuracy in predicted forming and post-formed behavior.

In order to make a direct comparison between the two AutoForm versions, the same simulations were performed in AutoForm v4.0 (AF v4.0). Values for all input parameters discussed above were maintained from the original correlated AF v3.2 models. The only alteration in the setup of the AF v4.0 models are the simulation-specific parameters arising from the above differences. Therefore, for all forming and springback steps, the type of element was set to ‘elastic plastic shell’ (instead of bending enhanced membrane) and number of integration points set to 11 (instead of 7 in v3.2).

**Sensitivity Analysis**

To complement the investigation into the accuracy of commercial FE tools, a brief analysis into the sensitivity of forming and springback predictions was conducted. The sensitivity analysis examined direct partial derivatives of model outputs with respect to key input parameters, and is based on a single scenario – the correlated HRLC model, using AF v3.2. The outcomes of this analysis are aimed at benefiting the users of such FE packages by identifying the most influential input parameters. This will ensure that appropriate resources are devoted to obtaining precise values for these key parameters, with less attention/resources spent on those parameters which have minimal effect. Further details of the sensitivity analysis are discussed with the results in the subsequent sections.

**Results and Discussion**

The results of this investigation will be presented and discussed in three specific sections. The first two sections examine the accuracy of forming behavior predictions (thickness and strain) and post-formed predictions (springback). The third section focuses on the results of the sensitivity analysis.

**Forming Behavior**

As previously mentioned, strains and thicknesses were primarily examined at Section C and Section D due to the magnitude of strain and modes of deformation experienced in these regions. Figure 6 displays the comparison between experimentally measured and numerically predicted major strain and change in thickness at Section C and Section D, for the correlated HRLC steel model. Change in thickness was plotted, instead of the actual thickness, to allow a direct comparison with other steel grades, which have differing initial blank thicknesses (Table I).

In Figure 6, the regions of approximately 35 to 60mm along the sections correspond to the sidewall of the part closest to points C2 and D2, respectively (refer to Figure 4(b)). The peak strain / minimum thickness occurs at the top of the sidewall (55mm along section), as expected. The region of approximately 10 to 30mm refers to the tight radius bend area, in which no accurate strain measurements are possible, due to the size of the grid pattern analyzer camera lens.

Figure 6 shows that an excellent correlation between experimental measurements and the simulation results is achieved for these regions of the part. However, it is evident that AF v4.0 predicts the forming
behavior with greater accuracy than AF v3.2. In particular, AF v4.0 seems to have an improved ability to predict the rapid change in thickness and peak strains along the sections associated with localized strains. This phenomenon is not captured as accurately with AF v3.2.

![Graphs showing major strain and change in thickness comparison](image)

(a) Section C - HRLC  
(b) Section D - HRLC

Figure 6: Major strain and change in thickness comparison along (a) Section C, and (b) Section D.

Similar graphs for DP and TRIP were constructed, but are not presented here for reasons of conciseness. However, the correlation achieved for all three steel grades at Section C and Section D, using both simulation versions, is summarized in Figure 7. This correlation is based on a calculated statistical R-squared value, for the change in thickness predictions compared to the experimental measurements. Change in thickness was used for the correlation instead of major strain for numerous reasons. Firstly, the thickness predictions provide more information than major strain alone, since it is related to both the major and minor strain. Secondly, the experimental thickness measurements could be determined at a greater number of points, since the small radii did not present a problem for the ultrasonic thickness probe. Finally, the thickness results could be determined with a much greater accuracy than the major strain, as indicated by the error bars in Figure 6.

![Correlation charts for Section C and Section D](image)

(a) Section C  
(b) Section D

Figure 7: Change in thickness correlation for all 3 steel grades along (a) Section C, and (b) Section D.

Figure 7 shows that for all cross-sections examined, a correlation of above 90% is achieved. Furthermore, there is no perceivable trend showing a decrease (or increase) in accuracy when the AHSS grades are substituted. Hence, it is evident that the FE software is able to accurately predict the forming behavior for the conventional and AHSS grades. However, it is worth noting that AF v4.0 consistently produced improved accuracy in thickness predictions, when compared to AF v3.2. However, in some cases, this improvement was only marginal.
**Springback**

Based on the above correlated forming predictions, the post-formed behavior was examined. The first step in comparing the springback results was to construct the appropriate cross-sections of: the final mesh (for the simulations), the scan data (for the experimental final part), and the IGES part data (for the pre-springback reference). Next, these cross-sections were superimposed in 3D-space, to produce a similar plot to that shown in Figure 8.

![Section Diagram](image)

**Figure 8: Post-formed shape of all cross-sections for experimental Dual-Phase final part. For clarity, the x- and y-locations have been modified to aid visual comparison.**

This process of positioning the cross-sections is not a trivial task, as the experimental data, simulation data and original part data are all at different locations in space. Firstly, all cross-sections were translated such that Point G on each part, shown in Figure 8, was located at the same point in space. This point was then constrained in all translational degrees of freedom (DOF). Through an optimization-type process, each part was then rotated, using all rotational DOFs, in order to minimize the error between the sprung and unsprung cross-sections.

The graph shown in Figure 8 provides a qualitative representation of the overall post-formed shape. However, for this investigation quantitative values of springback are required in order to correctly assess the accuracy of the springback predictions. For this investigation, the value of springback has been defined as the vertical distance (z-direction) between the examined point on the reference cross-section, and the corresponding point on the post-formed cross-section. Furthermore, a positive value indicates that the post-formed shape is above the reference shape. From this, the actual values of predicted and measured springback at points A1 to E2 have been plotted in Figure 9 for each of the steel grades. (Refer to Figure 4(b) for the location of points A1 to E2.)

Observing the overall trend in the experimental springback results in Figure 9(a)-(c), it can be seen that the higher the strength of the steel, the more it tends to springback. This trend is expected, and seems to be captured by both AutoForm versions. However, when examining the actual magnitude of the springback predictions, it is evident that the AF v4.0 predictions are significantly more accurate than those of AF v3.2. This difference in accuracy between the two versions is summarized by Figure 9(d), which shows the average percentage error between the predicted and actual values of springback. Inspection of the springback error for each of the steel grades indicates that springback predictions for AHSS grades can be equally accurate as those for conventional steel grades.

When comparing the error of the springback predictions shown in Figure 9(d), to the correlation of the thickness predictions in Figure 7, it is evident that the forming behavior is predicted with greater accuracy than the post-formed behavior. Also, there is a much larger discrepancy in accuracy between AF v3.2 and AF v4.0 for the springback predictions than for the thickness predictions. This fact indicates that the bending enhanced membrane element used in AF v3.2 should be sufficient for most
stretch-drawing forming simulations, where secondary forming operations or post-formed springback predictions are not required.

Figure 9: Springback results for (a) HRLC, (b) DP, and (c) TRIP. (d) Average percentage error of springback predictions for AF v3.2 and v4.0.

It is worth noting that the improvement in accuracy of springback and forming predictions in AF v4.0 is not solely due to the use of the shell element formulation. Closer examination shows that there is a substantial increase in the number of elements at the end of the simulation for AF v4.0. The maximum number of elements in the AF v3.2 model was approximately 35,000, while this was approximately 66,000 for AF v4.0. However, for both versions, the same value for the Radius Penetration parameter, which determines mesh refinement, was used. This substantial increase is a result of the improved adaptive mesh refinement scheme, which ensures that adequately refined elements are available in areas with the likelihood of significant bending and plastic strains, before they are actually needed [8]. As such, the large increase in number of elements in AF v4.0 may be partly responsible for the increase in accuracy of the springback predictions. Furthermore, the increased number of integration points through the thickness and the claimed improved material laws may have also contributed to the improved accuracy, but this effect has not been quantified at this stage.

Finally, the increased accuracy in AF v4.0 comes at the expense of computational time, which increased from approximately 45 minutes (AF v3.2) to almost 4.5 hours. However, in cases where accurate springback predictions are of prime importance, this trade-off may be easily justifiable.

**Sensitivity Analysis**

For the sensitivity analysis, each of the parameters examined were varied individually, and the effect on model outputs at critical locations were examined. Since this analysis is aimed at benefiting the user, the input parameters chosen for investigation are those which typically may be unknown during the product development/engineering design stage (Table III).
The sensitivity of the simulation predictions to material properties such as n-value, tensile strength, yield strength, etc. have not been examined. It is expected that each of these will have a considerable effect on the results, but have been ignored due to the relative ease that this data can be obtained. However, the effect of the average r-value is examined, as this data may not be readily available.

Process parameters such as initial blank holder pressure, friction coefficient and blank position, were examined as the sensitivity of the simulation results to these parameters is of particular interest.

Simulation-specific values relating to mesh density, number of integration points, time step size, etc. were not examined. Although it is expected that these will have a considerable effect on the results produced, it is obvious that these should be set to the values which will produce the most accurate simulation predictions. For example, the number of integration points through the thickness should be set to the maximum value permitted by the simulation, in order to achieve the best accuracy. However, simulation-specific values such as the tool stiffness parameter and the location of the blank holder force were examined, as the effect of these on the simulation predictions may not be known.

Finally, the sensitivity of the predicted results to the tooling geometry was also disregarded, since the actual tooling geometry must be accurately represented in order to construct a useful simulation. However, the effect of the tool offset was examined; given that other sheet metal forming FE packages suggest using a tool offset of sheet thickness plus 10% [9].

Table III: Input parameters examined in sensitivity analysis and range of values used.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Minimum Value</th>
<th>Intermediate Value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-value</td>
<td>0.9</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Initial Blank Holder Pressure (MPa)</td>
<td>1.0</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Tool Stiffness Parameter (N/mm³)</td>
<td>5</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>Blank Position (mm)</td>
<td>-10</td>
<td>0</td>
<td>+10</td>
</tr>
<tr>
<td>Tool Offset (mm)</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Blank Holder Force Location (mm)</td>
<td>-50</td>
<td>tool centre</td>
<td>+50</td>
</tr>
</tbody>
</table>

Considering the above discussion, the selected input parameters were individually adjusted to three specific settings (Table III). The minimum and maximum values were chosen based on an estimation of a realistic range that could be encountered for these parameters. The intermediate value was chosen as either the default value, the value used in the correlated model, or a value which is approximately in the middle of the maximum and minimum range.

In order to represent the effect that each parameter had on the predicted forming behavior, the range of the maximum thinning values for both sidewalls in Section C was determined. The range is defined as the difference between the highest and lowest values predicted for the three cases. This range is represented as a percentage of maximum thinning experienced in Section C of the experimental part to allow comparison with the sensitivity of springback predictions (Figure 10(a)). It is worth noting that the range of maximum thinning values in Section D produced very similar results, and as such will not be plotted. Similarly, the effect of the input parameters on the springback predictions was represented by determining the predicted springback range at Section C (i.e. points C1 and C2), as a percentage of the experimental springback experienced (Figure 10(b)).

Figure 10 shows some noteworthy results. Firstly, it is evident that the thinning predictions show particular sensitivity to the material r-value. This result is reasonable, considering that the regions
examined experience mainly plane strain deformation. Consequently, the r-value should be determined from experimental tests, or obtained from a reliable source, due to the large errors that may result from using inaccurate data. Merely using the r-values obtained for similar material grades can prove to be very inaccurate, as results in the literature indicate that for materials with the same grade designation, the r-value can vary by over 25% [10].

Figure 10: Effect of input variables on (a) thickness prediction, and (b) springback prediction.

As expected, thinning also shows high sensitivity to the blank holder force and friction coefficient. Both of these parameters directly affect the amount of draw-in under the blank holder, which affects the strains and consequently thickness. Hence, accurate values for these process parameters should be used. Wherever possible, comparison of the flange lengths can provide an insight into how accurately the values of blank holder force and friction coefficient are represented.

The other input parameters had considerably less effect. However, the affect of parameters such as blank position and tool force location are greater than what would be typically expected. It is believed that this is primarily due to process configuration, where there is considerably less binder surface area on one side of the part than the other (see Figure 2 and Figure 4). Hence, by moving the x-location of the of the blank and blank holder force, the amount of draw-in will be considerably affected.

In general, the springback predictions show less sensitivity to the input variables examined (Figure 10(b)). This indicates that the post-formed shape of this part is quite robust, and has obvious advantages from a manufacturing point of view. However, the sensitivity to the tool offset is unusually high, due the effect that it has on the geometry of the tooling. In this case, the punch is the reference geometry, and the die is constructed by offsetting the punch surface outwards. Hence, by increasing the tool offset, the already small die radii become even smaller. This will have considerable affect on the springback results, as the material is now drawn over smaller radii. Therefore, the tool offset in the simulation should be defined to accurately represent the geometry of the actual process.

Conclusion

Results indicate that AutoForm Incremental can be utilized to accurately simulate the forming behavior of a complex automotive component. In the regions examined, an accuracy of over 90% for thickness predictions was achieved with no noticeable reduction in accuracy for AHSS grades, when compared to the conventional steel grade. These results indicate that this FE software can be utilized to accurately simulate the forming behavior of AHSS grades, provided that accurate material data is used. AutoForm v4.0 showed a small improvement in accuracy for thickness predictions, with the improvement particular evident at regions of peak strains and large strain gradients.
Post-formed behavior was not predicted with this same level of accuracy. It was found that AutoForm v3.2 had an average springback error of approximately 50%. However, this was significantly improved for AutoForm v4.0, with average errors in the range of 23% to 35%. The improved springback predictions in AutoForm v4.0 were mainly attributed to the use of a new full shell element, instead of the previously used bending enhanced membrane, and the revised adaptive mesh refinement scheme.

The sensitivity analysis showed that for parts formed by predominantly plane strain deformation modes (cross-members, channels), the material r-value will have a significant effect on thickness and strain predictions. Blank holder force and friction coefficient also had significant influence on the forming predictions. Springback predictions showed some similar trends, but it was found that the springback in this part was not particularly sensitive to the input parameters examined.

Acknowledgements

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