Visualization of the Invisible, Explanation of the Unknown, Ruggedization of the Unstable

Sensitivity Analysis, Virtual Tryout and Robust Design through Systematic Stochastic Simulation

Dr. Titus Zwickl, Dr. Bart Carleer, Dr. Waldemar Kubli

Abstract. In the past decade, sheet metal forming simulation became a well established tool to predict the formability of parts. In the automotive industry, this has enabled significant reduction in the cost and time for vehicle design and development, and has helped to improve the quality and performance of vehicle parts. However, production stoppages for troubleshooting and unplanned die maintenance, as well as production quality fluctuations continue to plague manufacturing cost and time. The focus therefore has shifted in recent times beyond mere feasibility to robustness of the product and process being engineered. Ensuring robustness is the next big challenge for the virtual tryout / simulation technology.

We introduce new methods, based on systematic stochastic simulations, to visualize the behavior of the part during the whole forming process - in simulation as well as in production. Sensitivity analysis explains the response of the part to changes in influencing parameters. Virtual tryout allows quick exploration of changed designs and conditions. Robust design and manufacturing guarantees quality and process capability for the production process. While conventional simulations helped to reduce development time and cost by ensuring feasible processes, robustness engineering tools have the potential for far greater cost and time savings.

Through examples we illustrate how expected and unexpected behavior of deep drawing parts may be tracked down, identified and assigned to the influential parameters. With this knowledge, defects can be eliminated or springback can be compensated e.g.; the response of the part to uncontrollable noise can be predicted and minimized. The newly introduced methods enable more reliable and predictable stamping processes in general.

INTRODUCTION

Validation of constrained springback and process capability prediction of a real world part with simulation tools is the aim of this work. Analysis, quantification and detailed visualization of the sensitivity of the part to changes in the tool design as well as to uncontrollable material property and process condition variations increase the predictability and robustness of the production process. A verified robust production process ensures reduced part defect rates and assembly failures in the body shop. New easy-to-use software tools enable the engineer to directly visualize the hitherto invisible response of the part to changes of design parameters, to explain unknown or ‘unexpected’ behavior of the part during production, and to thus ruggedize unstable production processes through adjustment of the corresponding process layout. Predicting and controlling springback including its fluctuations during production is a significant challenge for engineers and manufacturers. The efficacy and value of the systematic stochastic simulation technologies proposed in this article are best demonstrated and verified by application: DaimlerCrysler AG provided quality control data sets of the rear floor panel of the current Mercedes-Benz A-Class [1] for validation purposes. Process layout, tool development and production of the part were all re-enacted, accompanied and followed with the most recent AutoForm design and simulation tools [2].
Virtual and real results are compared and assessed in the following.

**THE PART**

For the purpose of validation, the currently produced rear floor panel of the actual Mercedes-Benz A-Class from Daimler Chrysler AG [1] was chosen (Figure 1). In the test rig (14 clamps, 3 pilots) the clamped part has to comply with a tolerance of ± 0.5 mm for deviations from the nominal geometry. Quality control protocols from different stages of the tool and process layout development as well as from production monitoring runs were provided for both the unclamped and the clamped part [1].

**INITIAL PROCESS LAYOUT**

At first view, the part geometry (Figure 1) looks relatively simple and easy to press. Therefore, the first attempt was to design and try out a stamping process layout with uncompensated, flat tools (i.e. no overcrown). A progressive die layout was chosen; six stations are necessary on the die:

- OP00: First cutting of the blank
- OP10: Second cutting of the blank
- OP20: Drawing with tools OP20
- OP30: Drawing with tools OP30
- OP40: Drawing with tools OP40
- OP50: Final cutting of the part and flanging with tools OP50

Parts were stamped on a tryout press with this initial layout. The stamped parts were thoroughly checked for assembly or overall clamped springback tolerance compliance (±0.5 mm) respectively.

Analysis of the clamped tryout parts showed that the part cannot be produced within the tolerances with the initial design and process layout. Severe and uncontrollable springback in the zones 3-6 of Figure 2 was observed. Both the measured and the simulated distances from the nominal geometry in z-direction were outside the tolerances to an extent that made assembly impossible (Table 1). The most stable zones 1 and 2, lying close to clamps (see Figure 7), were chosen as reference zones. The rest of the part was subject to moderate positive or negative springback deviation from nominal geometry, and were therefore of lesser interest than the critical zones 3-6.

**TABLE 1. Clamped springback of tryout parts:**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Simulated a)</th>
<th>Measured b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.0 (-0.2 .. +0.1) mm</td>
<td>-0.2 mm</td>
</tr>
<tr>
<td>2</td>
<td>-0.1 (-0.7 .. +0.0) mm</td>
<td>-0.3 mm</td>
</tr>
<tr>
<td>3</td>
<td>+3.1 (+2.4 .. +5.5) mm</td>
<td>+3.8 mm</td>
</tr>
<tr>
<td>4</td>
<td>+3.5 (+1.9 .. +3.6) mm</td>
<td>+2.0 mm</td>
</tr>
<tr>
<td>5</td>
<td>+1.6 (+0.8 .. +2.6) mm</td>
<td>+0.7 mm</td>
</tr>
<tr>
<td>6</td>
<td>-5.4 (-6.5 .. -3.6) mm</td>
<td>-3.6 mm</td>
</tr>
</tbody>
</table>

a) Simulation results for nominal material properties and friction as well as range of results to expect (in parentheses) for material properties and friction variation as specified by the suppliers (95 simulation AutoForm-Sigma result [2]).

b) Single measurement on one single tryout part [1].

Prior to tryout, no simulation based springback analysis was carried out. Subsequent to tryout, the initial process layout was re-simulated using AutoForm-Incremental [2]. Additionally, a 95-simulation AutoForm-Sigma analysis [2] was carried out to account for the uncertainty of material properties and surface roughness (affecting the frictional behavior) of the tryout blank. The
AutoForm-Sigma analysis furthermore allows robustness and sensitivity quantification (see later sections). Within the expected material property and friction variations as provided by the steel suppliers (see Table 3, section 'FINAL PROCESS LAYOUT') the simulation results for the clamped springback of the part fully agree with the measured springback of the analyzed clamped tryout part, except for zone 5, for which the measured result was slightly (0.1mm) below the range of the results predicted by simulation.

### FINAL PROCESS LAYOUT

To overcome the springback problems observed on initial trials, the edges of the OP40 tools were overbent by -10mm as shown in Figures 3 and 4:

**FIGURE 3.** Overbending edge zones of the OP40 tools indicated by the framed hatched areas on the left and right.

**FIGURE 4.** Right hand overbending zone as indicated in Figure 3: Overbending of the tools OP40 by -10mm in the denoted zones.

The overbending eliminated the severe out-of-limits springback, allowing the production of parts compliant to the ± 0.5mm tolerance necessary for assembly. Measurement and simulation results for the zones shown in Figure 2 are given in Table 2:

### TABLE 2. Clamped springback of final layout parts:  
z-distance from nominal geometry

<table>
<thead>
<tr>
<th>Zone</th>
<th>Simulated</th>
<th>Mean of 25 measurements</th>
<th>Corresponding range of results observed (in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+0.1 (-0.2..+0.2) mm</td>
<td>+0.3 (+0.0..+0.6) mm</td>
<td>(no range) (mm)</td>
</tr>
<tr>
<td>2</td>
<td>-0.1 (-0.3..+0.1) mm</td>
<td>-0.1 (-0.2..+0.0) mm</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+0.5 (+0.0..+0.6) mm</td>
<td>+0.4 (-0.1..+0.7) mm</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+1.0 (+0.6..+1.6) mm</td>
<td>+0.5 (+0.4..+0.8) mm</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>+0.3 (+0.1..+0.7) mm</td>
<td>+0.5 (+0.3..+0.7) mm</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.3 (-0.6..+0.4) mm</td>
<td>-0.5 (no range) mm</td>
<td></td>
</tr>
</tbody>
</table>

- Simulation results for nominal material properties and friction as well as range of results to expect (in parentheses) for material properties and friction variation as specified by the suppliers (85 simulation AutoForm-Sigma result [2]).
- Mean of 25 measurements on 25 different parts and corresponding range of results observed (in parentheses) for the 5 x 5 blanks feed into the press line from 5 samples cut from 4 different H340LAD coils (see Table 3) [1].
- Single measurement interpolation data [1]; no range.

Subsequent to the process layout corrections and tool adjustments, the process was re-simulated using AutoForm-Incremental. Additionally, an 85-simulation AutoForm-Sigma analysis was carried out to account for the uncertainty of material properties and surface roughness (affecting the frictional behavior) of the stamped blanks. Assuming linear dependency of the coefficient of friction on surface roughness, the corresponding friction coefficients of the individual operations of the process were varied in proportion to the observed variation in surface roughness. The AutoForm-Sigma analysis allows robustness and sensitivity analysis and quantification thereof (see later sections). The part production was monitored: 5 samples of 5 blanks each were taken from 4 different coils of the same steel (H340LAD). The 25 blanks were stamped and the springback behavior of the resulting parts was statistically analyzed. The material properties for the five 5-blank samples are shown in Table 3:

### TABLE 3. Mechanical properties of monitored 25 blanks

<table>
<thead>
<tr>
<th>Coil</th>
<th>#</th>
<th>d [mm]</th>
<th>Rp0.2 [N/mm²]</th>
<th>Rm [N/mm²]</th>
<th>Ra [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.78</td>
<td>394</td>
<td>463</td>
<td>1.72</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.78</td>
<td>394</td>
<td>463</td>
<td>1.72</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.78</td>
<td>394</td>
<td>467</td>
<td>1.81</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.84</td>
<td>389</td>
<td>463</td>
<td>1.75</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.77</td>
<td>394</td>
<td>465</td>
<td>1.70</td>
</tr>
</tbody>
</table>

- Sample, d = Thickness, Rp0.2 = Yield strength, Rm = Tensile strength, Ra = Surface roughness.

Within the expected material property and surface roughness variations (as provided by the steel suppliers), the simulation results for the clamped springback of the final parts fully agree with the measured springback of the analyzed clamped final parts for all zones.
VISUALIZATION OF SPRINGBACK RESPONSE TO OVERBENDING

AutoForm-Sigma provides new simulation tools enabling the engineer to 'visualize the invisible'; i.e. the sensitivity of the part to the change of design and/or noise parameters can be visualized directly on the sheet e.g., allowing immediate identification of sensitive zones. Sensitive zones may - depending on the context of the analysis carried out - denote either critical zones or most useful responsive zones for the improvement of the investigated design. Operating on the acquired stochastic simulation sample, ultra-fast virtual tryout methods allow checking out unlimited numbers of new designs without requiring any additional simulations.

Sensitivity Analysis And Virtual Tryout

With AutoForm-DieDesigner, the geometry change of the OP40 tools as indicated in Figures 3 and 4 was parameterized. With AutoForm-Sigma, the fully parameterized overbending was varied continuously between 0.0mm (flat initial tools OP40) and -10.0mm (overbent final tools OP40). From the sampled 25 simulations, springback sensitivity results were calculated and displayed on the sheet as shown in Figure 5:

![Figure 5](image1)

**FIGURE 5.** Sensitivity of clamped springback to -10mm overbending of the tools OP40 as indicated in Figures 3 and 4. Overbending parameterization of the tools was carried out with AutoForm-DieDesigner and automatically varied with AutoForm-Sigma. Zones with springback distance (clamped) from nominal geometry (z-direction) compensation of -1.5mm or more upon overbending of the tools by -10mm are shown in green color, zones responding with a springback change of +1.5mm or more are shown in yellow color. Intermediate colors stand for intermediate springback changes as indicated by the color scale. White areas denote zones where no statistically significant springback response to the overbending was detected. The black arrow points to the zone shown in details in Figure 6.

![Figure 6](image2)

**FIGURE 6.** Scatter plot of springback from nominal geometry in z-direction vs. tool overbending for the zone of Figure 5, labeled with the black arrow. The sensitivity of the springback behavior of the part to the overbending of the tools OP40 as indicated in Figures 3 and 4 is visualized in form of the thick grey slope line. The thick black horizontal line denotes the upper specification limit of +0.5mm. The light red spots are individual results from different simulations. It can be seen clearly how springback deviation from nominal geometry (z-direction) is reduced by overbending of the OP40 tools. For the overbent tools, springback values within the tolerance are achieved finally.

With the presented simulation tools, it can be easily estimated where and to what extent the part responds to overbending of the tools. Further virtual tryout result predictions based on the implemented sensitivity analysis, allow quick visualization and exploration of alternative design strategies. The applied methods operate in a conservative way to not overestimate the predicted results: in the present case, the sensitivity based predictions provided correct results for zones 2, 3 and 6; while the prognosis in fact showed the correct tendency, but the estimate was too conservative for zone 4. With the applied low sample size of only 25 simulations, the results were statistically not significant for zones 1 and 5.

However, sensitivity analysis and quick virtual tryout methods provide deep insight into hitherto invisible process characteristics. They allow the engineer to clearly explain even complex dependencies such as constrained springback response at the center of a part on overbending of the edges of one of the tool sets in a multi operation progressive die process layout, as demonstrated in the present example.
INVESTIGATING AND ENSURING OVERALL PROCESS ROBUSTNESS

It is most important to realize, that there is never a single and exact solution to a design in reality. In the real world, not two stamped parts are completely identical. Material properties vary from coil to coil (as indicated in Table 3), from blank to blank, even when cut from the same coil, and even within a single blank itself. Process conditions vary as well: lubrication, press forces, positioning, tool temperatures, tool wear, etc., can never be held fully constant. Therefore, a ‘cloud’ of different results (or parts with slightly different properties respectively) is the output of a real world press line. The big challenge is to estimate the range of results to expect, prior to even setting up the first tryout press. The goal is to adjust the design in such a way that keeping the result scatter within the required tolerances can be ensured and the scrap rate can be minimized. Latest specialized statistical process control (SPC) simulation tools [2] provide methods to visualize statistical process or quality control statistics (QCS) according to DIN/ISO [3-4] directly on the analyzed sheet. They allow easy and immediate identification of zones that are either within or outside the tolerances. Influence/sensitivity analysis enables tracking and elimination of the origin of instabilities and thus to ruggedize the process by compensation of the impact of unavoidable process condition variations with a more robust design.

FIGURE 7. Cp robustness analysis for the initial process layout with flat OP40 tools: Large zones in the right half of the part and on the edges are non-robust (red) and cannot be kept within the ± 0.5mm tolerance if the material properties vary as indicated in Table 3.

FIGURE 8. Cp robustness analysis for the final process layout with overbent OP40 tools: Not only the nominal or median springback (Table 2 and Figure 12) was reduced by overbending the OP40 tools, but also a more robust process was achieved (green areas are ‘robust’).

Material properties vary from coil to coil (as indicated in Table 3), from blank to blank, even when cut from the same coil, and even within a single blank itself. Process conditions vary as well: lubrication, press forces, positioning, tool temperatures, tool wear, etc., can never be held fully constant. Therefore, a ‘cloud’ of different results (or parts with slightly different properties respectively) is the output of a real world press line. The big challenge is to estimate the range of results to expect, prior to even setting up the first tryout press. The goal is to adjust the design in such a way that keeping the result scatter within the required tolerances can be ensured and the scrap rate can be minimized. Latest specialized statistical process control (SPC) simulation tools [2] provide methods to visualize statistical process or quality control statistics (QCS) according to DIN/ISO [3-4] directly on the analyzed sheet. They allow easy and immediate identification of zones that are either within or outside the tolerances. Influence/sensitivity analysis enables tracking and elimination of the origin of instabilities and thus to ruggedize the process by compensation of the impact of unavoidable process condition variations with a more robust design.

FIGURE 9. Scatter plots of the final layout results for the zones indicated in Figure 2: Simulation results for the noise variable ‘Thickness’ e.g. are shown on the left; the
horizontal black lines indicate the ± 0.5mm specification limits. The measured monitoring results of the current rear floor panel production are shown on the right with red horizontal lines indicating the ± 0.5mm specification limits. In zone 3, statistically significant sensitivity of springback to the displayed blank thickness was detected (thick gray line): less springback is expected for thicker sheets. Keeping in mind that the first 10 monitoring results were obtained with blanks from the same coil clearly points out that the real world process still depends on more noise parameters than yet considered for the simulations (see Table 3).

For the present validation example, the QCS ‘process potential’ or ‘process capability’ Cp [3-4] was evaluated for the initial process layout with flat tools OP40 and compared to the Cp for the final layout with overbent tools OP40. The AutoForm-Sigma Cp analysis for the initial process layout with flat tools OP40 is shown in Figure 7; similar analysis for the final layout with the overbent tools OP40 is shown in Figure 8. All clamps (red numbered circles), pilots (blue numbered circles) and analysis zones (gray boxes) are also visible in the figures.

The process potential or process capability Cp [3-4] indicates if a process can be potentially run within the tolerances. It measures the spread of the output scatter in relation to the given tolerance. According to DIN 55319, M4 [3], the robust non-parametric variant is calculated as \( \text{Cp} = \frac{\text{Tolerance}}{\text{Q}_{0.99865} - \text{Q}_{0.00135}} \) whereas \( \text{Q}_{0.99865} \) and \( \text{Q}_{0.00135} \) denote the corresponding quantiles. Hence, if the QCS Cp is equal to 1.0, it means that the center 99.73% of results are not spread wider than the given tolerance. Therefore, not more than 0.27% of scrap will be produced potentially. If \( \text{Cp} < 1.0 \), then the center 99.73% of results are spread wider than the tolerance; if \( \text{Cp} > 1.0 \), then the center 99.73% results are spread narrower than the given tolerance. Systematic absolute specification limit violations as assessed by additionally available Cpk measures [2-4] can often be compensated with design changes (for example through tool overbending as shown above). Keeping wide, diffuse result scatter under control is usually a much harder task.

In summary, all zone results for the initial, flat design (Figure 11) are directly compared to those for the final, overbent design (Figure 12).

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**FIGURE 10.** (a) Histogram for zone 3 of the final layout parts (see Figure 2), visualizing the compliance with the ± 0.5mm tolerance (black lines on the left and right) for the nominal as well as for the median result. While two results exceed the absolute upper limit, the whole spread of the result scatter is within the ± 0.5mm tolerance (thick black bar at the bottom) resulting in a ‘reliable’ Cp rating (green) for the zone (see Figure 8): The process can be run reliably. (b) Histogram for zone 6 of the final parts: While the bulk of results complies with the tolerance, more than 0.27% of the results are beyond tolerances, resulting in an ‘unacceptable’ Cp process rating (red) for zone 6 (see Figure 8). The blue normal-boxplots below the histograms are an alternative, condensed representation form for the information shown in the histograms.

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**FIGURE 11.** AutoForm-Sigma robustness plot, summarizing the results for zones 1-6 (see Figure 2) for the initial, flat design. The small vertical black lines indicate the ± 0.5mm specification limit bounds, the boxplots visualize position and spread of the result clouds. Cp values for the zones are displayed in the last column.

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**FIGURE 12.** AutoForm-Sigma robustness plot, summarizing the results for zones 1-6 (see Figure 2) for the final, overbent design. The small vertical black lines indicate the ± 0.5mm specification limit bounds, the boxplots visualize position and spread of the result clouds. Cp values for the zones are displayed in the last column.
Comparison of the Cp values (last column) for the initial and final process layout given in Figures 11 and 12 respectively clearly shows how the process was ruggedized by overbending the OP40 tools.

The Cp results for the final, overbent design were finally compared to the measured monitoring results from the current production of the Mercedes-Benz A-Class rear floor panel [1].

However, for comparing the process capabilities (Cp) from different samples with different sample sizes, it is important to rely on confidence intervals. For the data sets discussed, approximate confidence intervals (C.I.) for the Cp values were calculated according to equation (1):

$$ C.I_{Cp} \approx \left[ \frac{\chi^2_{\alpha/2}(df)}{df}, \frac{\chi^2_{1-\alpha/2}(df)}{df} \right] \cdot C_p \cdot \left( \frac{1}{\sqrt{n}} \right) $$

with $\chi^2$ being the Chi-Square distribution, $\alpha$ the significance level, and $df$ corresponding to the degrees of freedom ($= n - 1$) for the sample size $n$.

To assess defect rates of $\leq 0.27\%$ as measured by Cp, a significance level of $\alpha = 0.001$ is appropriate. Table 4 summarizes the simulation and monitoring Cp results for the zones 1-6 (see Figure 2) together with the corresponding calculated 99.9\% confidence intervals (in parentheses):

<table>
<thead>
<tr>
<th>Zone</th>
<th>Cp Simulations (n=85)</th>
<th>Cp Measurements (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.33 (1.76..2.94)</td>
<td>1.69 (0.94..2.52)</td>
</tr>
<tr>
<td>2</td>
<td>1.96 (1.48..2.47)</td>
<td>4.35 (2.42..6.49)</td>
</tr>
<tr>
<td>3</td>
<td>1.61 (1.21..2.03)</td>
<td>1.85 (1.03..2.76)</td>
</tr>
<tr>
<td>4</td>
<td>1.05 (0.79..1.32)</td>
<td>2.38 (1.33..3.55)</td>
</tr>
<tr>
<td>5</td>
<td>1.08 (0.81..1.36)</td>
<td>2.50 (1.39..3.73)</td>
</tr>
<tr>
<td>6</td>
<td>0.64 (0.48..0.81)</td>
<td>-</td>
</tr>
</tbody>
</table>

From Table 4 it can be seen, that the calculated and the measured Cp results agree within the error margins for zones 1-3. For zones 4 and 5, the results differ only marginally within the error margins. For zone 6 no monitoring data set was available.

**CONCLUSIONS**

With this validation study based on a real world example [1], it was shown that systematic stochastic simulation tools [2] enable the visualization of the hitherto invisible, and to accurately explain much more of the unknown than ever before. Most importantly, it is possible to correctly estimate and improve the robustness of complex multi operation processes with respect to clamped springback deviation from nominal geometry.

For the presented example, it can be stated that applying the described simulation tools at an early development phase may have avoided the fabrication of the unsuitable initial flat tryout tools for OP40. Consequently, it would have enabled the application of the optimized, tolerance compliant and more robust final process layout right from the very beginning. Cost and time savings accompanied by deeper knowledge and insight into the response behavior of deep drawn parts are the benefits of applying the systematic stochastic simulation methods of newest simulation tools like AutoForm-Sigma [2].

**ACKNOWLEDGMENTS**

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