Predicting springback variation and process-reliable tolerance limits of outer car-body panels by stochastic sheet metal forming simulation

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Abstract. Modern car-body design entails increasing requirements for the dimensional accuracy of outer car-body panels. However, tolerance limits to be met in this regard are based on specifications from component engineering aimed at ensuring dimensional accuracy of the product, less on real structural springback behaviour of outer car-body panels. Process-reliable tolerance limits for outer car-body panels can be characterized by a bandwidth in springback variation caused by fluctuations in material characteristics and process parameters during production. Differences between assumptions from component engineering and real structural springback behaviour of outer car-body panels thus leads to avoidable iterative corrections in die manufacturing and following processes. Therefore, the goal of this research work presented in this paper is to predict springback variation potentially occurring during production already in the virtual design stage of a car-body and hence set process-reliable tolerance limits. Stochastic sheet metal forming simulation is used for prediction of springback variation. Here, deterministic multi-stage springback simulation of a sidewall panel is extended by stochastic variation of material properties and process parameters. Simulation results are validated by measurement reports from series production. Results presented show strong fit in characteristics of springback variation between stochastic simulation and series measurement reports. In future, stochastic simulation results can be fed back into component engineering, making die manufacturing and following joining and assembly processes more effective.

1. Introduction

Automotive industry is challenged by shortened product development times and simultaneously increasing demands for high quality products. In terms of modern car-body design, this claim entails increasing requirements for the dimensional accuracy of outer car-body panels. Regarding the manufacturing process of outer car-body panels, springback is the main factor for dimensional part deviations. Here, springback is the change of geometry which occurs in stamped parts during opening of the tools as a result of the release of elastic energy [1]. In production, springback is affected by process-related variations in material properties such as yield strength and blank thickness as well as process parameters like blank holder force, friction or blank positioning. These variations lead to different part deviations resulting in a bandwidth of springback variation in production.

As a consequence of this springback variation, parts tolerance limits that can be realized with sufficient process reliability are restricted. Methods of geometrical springback compensation do provide approaches in this respect but they may only work effectively if the process-related springback variation...
remains within a certain tolerance range. Figure 1 shows the effect of springback variation on the tolerance limits.

![Image of Frequency distribution and Geometrical springback compensation](image)

**Figure 1.** Effect of potential springback variation on tolerance limits

Tolerance limits to be met are initially based on specifications from component engineering aimed at ensuring functionality of the complete car body, but less on part variations to be expected in real production [2]. This is due to the fact that the real part variation is unidentified in the virtual design stage. Differences between assumption about the part variation and the real part variation of a sheet metal part thus can lead to avoidable iterative corrections in the ramp-up process. Especially the die manufacturing process for outer car-body panels is affected by these iterative corrections when trying to achieve tolerances resulting from such assumptions. But also the body-in-white assembly process could be affected by this difference between assumption and reality as e.g. the developed fixture layouts might not be sufficient.

One approach to predict the real part variation was introduced by Bohn [3]. Here, the local stiffness of a body part was associated to the occurring part variation in production. In further work, this correlation was also quantified for parts made of high strength steels [4] and a body-in-white part deep drawn of aluminum alloy [2]. Sheet metal forming simulation for prediction of part variation was introduced by Stockinger [5] for a cup-shaped part and by Lindau et al. [6] for an automotive wheel house part. However, sheet metal forming simulation used has not been validated via real dimensional part data.

The prediction of the real part variation of outer car-body panels has not been addressed in any previous research work, although iterative corrections in die manufacturing of the production of such parts can be rather cost and time consuming.

The goal of the research work presented in this paper therefore is to predict springback variation of an outer car-body panel by stochastic sheet metal forming simulation. Consequently, based on the simulation results, process-reliable tolerance limits for the outer car-body panel will be set. To prove the applicability of the simulation method, calculated simulation results were validated by series measurements.

After validation, future digital manufacturing information can be fed back into component engineering to improve the tolerance specifications and fixture layouts for the manufacturing process of outer car-body panels. This will result in saving time and money in the ramp-up process.

2. **Approach for determination of springback variation and process-reliable tolerance limits**

The main factor for geometrical part variation in sheet metal forming processes is springback variation caused by variations in material properties and process parameters during production. As this study focuses on springback variation and does not consider mean shift, process capability index $C_p$ was used to set process reliable tolerance limits regarding springback variation. The equation for $C_p$ is [7]:

$$C_p = \frac{UTL - LTL}{6\sigma}$$ (1)
UTL and LTL are the lower and upper tolerance limits and \( \sigma \) represents the standard deviation. Figure 2 left illustrates the process capability index.

The tolerance limits must reflect what a forming process can achieve. In this respect, process-reliable tolerance limits for sheet metal parts can be set when the standard deviation of springback is known in the virtual design stage by rearrangement of the equation given above.

In general, determination of standard deviation requires a certain sample size since the standard deviation of a single sample is not in general equal to the standard deviation of the total population. In this regard, the confidence interval describes the correlation between these standard deviations. Figure 2 right shows the confidence interval with a probability \( \alpha = 5\% \) and a standard deviation \( \sigma = 0,15 \) which equals a tolerance range of \( \pm 0,45 \text{ mm} \) \( (C_p = 1,0) \). The figure indicates that a sample size of at least 200 is necessary to minimize statistical error in determination of standard deviation. The best effort-to-benefit ratio in practice should include a sample size of approximately 50 resulting in a statistical error of \( \pm 15\%-20\% \) [8].

![Figure 2. Illustration of process capability Cp (left) and confidence interval (right)](image)

The objective of the research work presented in this paper was to predict springback variation in terms of standard deviation for an outer car-body panel by stochastic sheet metal forming simulation. For this purpose, deterministic multistage springback simulation of a sidewall panel was extended by stochastic variations of material properties and process parameters. Subsequently, based on the predicted standard deviation, process-reliable tolerance limits were set as described above. For validation of this stochastic simulation method, standard deviation of springback measured in the series production of the investigated sidewall panel was evaluated and compared to corresponding simulation results. Due to the fact that presented method will be used to evaluate springback variation in the virtual design stage, corresponding forming simulation runs were performed with uncompensated die surfaces. The approach of the research work is presented in Figure 3.

![Figure 3. Variations in material properties and process parameters leading to springback variation that will be evaluated by stochastic forming simulation and series measurements](image)
3. Outer car-body panel use case
In this section, the considered outer car-body panel, the conditions specified in the stochastic sheet metal forming simulation and the series measurements performed are described.

3.1. Investigated outer car-body panel
Typical features of outer car-body panels are large portions of Class-A surfaces and low structural part stiffness. Therefore, to measure the springback of an outer car-body panel, a constrained clamp support is required to avoid elastically deformation due to gravity. Thus, not the free springback and springback variation of the sheet metal part is measured, but its constrained springback is evaluated.

In the study presented in this paper, a sidewall panel is chosen as the part to be investigated. This sheet metal part shows a relatively high complexity level with regard to the forming process resulting into multiple springback sensitive areas. The sidewall panel is formed of mild steel DC06 with initial sheet thickness of 0.70 mm. The sheet is electrolytically coated with zinc with a minimum weight of 53 g/m² per side. The constrained clamp support, the sidewall panel itself and the investigated areas are displayed in Figure 4. Area 1 and area 2 represent large areas of the outer surface of the sidewall panel and area 3 represents a joining flange potentially affecting the assembly process.

![Figure 4. Investigated sidewall panel and areas with clamping support system](image)

3.2. Springback variation: stochastic sheet metal forming simulation
The input for the stochastic simulation performed consisted of stochastic noise in material properties and process parameters. The parameters were set according to the values as summarized in Table 1. These values show a good agreement to literature [9]. Yield strength and tensile strength were varied with a correlation factor of 0.85 since they depend on each other. As information on the standard deviation of the input parameters is not easily accessible, advices from the AutoForm simulation guideline and in-house experiences were used here.

| Table 1. Stochastic sheet metal forming simulation input parameters |
|---------------------------------------------------------------|
| **Material properties (DC06)** | Nominal | Minimum | Maximum | Standard Deviation |
| Yield Strength       | 142 MPa | 110 MPa | 180 MPa | 11.67 MPa |
| Tensile Strength    | 293 MPa | 260 MPa | 330 MPa | 11.67 MPa |
| Average r-value      | 2.11    | 1.8     | 2.6     | 0.1405     |
| Blank thickness     | 0.70 mm | 0.66 mm | 0.74 mm | 0.02 mm     |
| **Process parameters** | Nominal | Minimum | Maximum | Standard Deviation |
| Blank holder force  | 3000 kN | 2700 kN | 3300 kN | 100 kN     |
| Lubrication amount (uniform) | 1 g/m² | 0.8 g/m² | 1.2 g/m² | 0.03 g/m² |
| X-position blank    | 0 mm    | -1 mm  | +1 mm   | 0.33 mm    |
| Y-position blank    | 0 mm    | -1 mm  | +1 mm   | 0.33 mm    |
For performing the stochastic sheet metal forming simulation, simulation software *AutoForm Sigma R8* was used. Sampling was done automatically by the *AutoForm Sigma* software using the *Latin-Hypercube-Sampling*. To provide a suitable output response, at least 16 simulations were carried out for each independent noise parameter. For the presented parameter-set, this resulted in 128 simulation runs. 

After simulation, the *AutoForm* software built a metamodel on the results which considers the distribution of the input parameters. Based on the metamodel, springback variation in terms of standard deviation at the same measuring points as in the series measurement was evaluated. Simulation results obtained in this way are described later on in section 4. The complete simulation process is depicted in Figure 5 and the numerical models used are summarized in Table 2.

![Simulation Process Diagram](image_url)

**Figure 5.** Illustration of the stochastic simulation process for the forming process of the sidewall panel

**Table 2.** Numerical models

| Hardening Curve | Hockett-Sherby | Bead model | Constant line bead |
|-----------------|----------------|------------|--------------------|
| Yield Surface   | Barlat (M = 2) | Friction model | TriboForm |

Forming simulation comprised six operations (OP) including drawing, cutting, trimming and forming processes. The drawing operation was simulated using the constant line bead model to decrease simulation time. In the simulation environment, a locating-step prior each operation and a free springback step after each operation was performed. As the last operation, springback measurement was carried out using the *Real Measurement* concept. The constrained support clamps in the springback measurement operation were specified according to those from the series measurements.

3.3. Springback variation: series measurements

Original equipment manufacturers gain many data concerning manufacturing processes like stamping. These data were used in the present study for evaluating springback variation of the sidewall panel and for validating the results of the stochastic sheet metal forming simulation. Therefore, standard deviation of springback was determined from series measurements. Here, the deviation from the nominal geometry was measured for each measuring point in order to subsequently determine the standard deviation of springback. The considered measuring points and gained results are depicted later on in section 4.

The measured sidewall panels were taken from multiple production runs covering variation in material properties and process parameter and therefore representing maximum variation in springback. For a time period of 3 years, sets of sidewall panels of a particular passenger car were taken from the beginning, middle and end of every production run, representing long-term springback variation. Measurements were performed using a tactile ZEISS 3D coordinate measuring machine.

According to section 2, a sample size of at least 50 was considered in order to keep the measured standard deviation within the confidence interval of approximately ±15-20%. In order to keep the production conditions as constant as possible, only those series measurement reports where minimum maintenance has been done on the tools were considered. To obtain two independent samples and thus to increase quality of the results, measurement data were taken from both the left and right sidewall panel. Table 3 summarizes the sample information.
4. Results and discussion
In the following section, springback variation results from the stochastic sheet metal forming simulation and the series measurements are presented and compared. Here, springback variation is displayed in six standard deviations directly representing process-reliable tolerance limits (Cp = 1.0). Further, the results are normalized for protecting true internal production data.

4.1. Validation of springback variation
Figure 6 shows springback variation obtained from series measurement of the left and right sidewall panels as well as from the stochastic sheet metal forming simulation for each measuring point along area 1. The results show that the forming simulation predicts the characteristic of springback variation - the relative amount of springback variation along the area - in strong agreement to the series measurements. Small differences between simulation and series measurement can be seen at measuring point 8, 9 and 10. A reduction of springback variation can be observed at the measuring points 15 and 25, where referring to Figure 4 - clamping support is located. Regarding the total amount of springback variation, simulation results do range slightly below the series measurement results. Differences in-between the series measurements can also be observed.

Figure 6. Springback variation in stochastic forming simulation and series measurements: area 1

Figure 7 shows springback variation results on the outer surface of the sidewall panels for every measuring point along area 2. As already observed in area 1, the springback variation characteristic from the simulation shows strong correspondence to the series measurements. A decrease in the variation is observed near measuring points 2, 8, 14 and 20, which again are located near to the clamping supports. The difference in total amount of springback variation between simulation and measurement appears much higher for area 2 than for area 1. Higher differences in springback variation in-between series measurements can also be observed at the measuring points 11, 12 and 13.

Figure 7. Springback variation in stochastic forming simulation and series measurements: area 2
Figure 8 shows the results of springback variation for the flange of the sidewall panel. As already seen in Figures 2 and 3, springback variation characteristic from simulation fits quite well to the series measurements. A decrease in springback variation can be seen in simulation and measurements near measuring points 9, 10 and 19 which are also close to the clamping supports. As already observed in Figure 6 for area 1, the total amount of springback variation from simulation in area 3 is found slightly below the series measurement.

![Stochastic simulation vs Measurements](image)

**Figure 8.** Springback variation in stochastic forming simulation and series measurements: area 3

4.2. Discussion

In general, the results of the stochastic sheet metal forming simulation show strong fit with the series measurements regarding the characteristic of springback variation along the outer car-body panel. Therefore, springback sensitive areas were correctly calculated by performed stochastic simulation.

From the results it can be observed that springback variation is varying along the part. This indicates that for the same part contour different tolerances can be achieved, depending on the clamping support system. Near to the clamping supports springback variation decreases and therefore tighter tolerances can be realized. Thus, an improved clamping support system contributes to achieve tight tolerances. As a result, the simulation method could be used to develop optimal clamping support systems in terms of springback variation and achievable tolerance limits. This will be more sufficient than changes in tool geometry or forming method. Here, of course assembly has to be considered.

Despite the fact that the characteristic of springback variation is predicted in good agreement with the series measurements there are discrepancies in the total amount of the springback variation. The derivation of process-reliable tolerance limits from the results of the stochastic sheet metal forming simulation therefore is restricted. When regarding areas 1 and 3, simulation prediction is slightly below the measured springback variation. It should be noted in this respect, that even series measurement results from left and right sidewall panel show differences. The differences between the simulation and the measurement as well as in-between the series measurements could result from statistical errors in the determination of the standard deviation. The error bars are not displayed in the result plots for reasons of oversight but can be anticipated from Figure 2.

Moreover, a reliable springback measurement of large outer car-body panels with high accuracy remains quite challenging. Errors in the measurement can therefore not be excluded. Shipping and handling of the compliant outer car-body panels might also influence the real measurement results but this is not considered by the simulation. The bigger differences in the total amount of springback variation in area 2 could result from intense tool rework in tryout decreasing the robustness of the tool. As the simulation was performed with uncompensated die surfaces it is also possible that springback compensation has influence on the total amount of springback variation leading to bigger differences. In this regard, further research is required for evaluating the effect of springback compensation of large outer car-body panels on the total amount of resulting springback variation.

Regarding the stochastic simulation method, it can be assumed that the spread of inputs will define the spread of output. Better fit in total amount of springback variation therefore might be achieved, when real scatter in input parameters will be measured and used for stochastic simulation.
5. Conclusion and outlook

In this paper, on the example of a sidewall panel, it is shown that stochastic sheet metal forming simulation can be used to predict the springback variation for large outer car-body panels. The stochastic simulation was performed with variations of the material parameters yield strength, tensile strength, anisotropy and blank thickness and the process-related parameters lubrication, blank holder force and x-y-plane positioning of the blank.

The characteristic of springback variation along the analyzed sidewall panel was predicted in strong accordance with series measurements. Extending deterministic multi-stage springback simulation in the virtual design stage to stochastic multi-stage springback simulation therefore demonstrates the real structural springback variation behavior of an outer car-body panel during production.

Moreover, results show that near to the clamping supports springback variation decreases, indicating a strong effect of the clamping support on springback variation. An improved clamping support system therefore contributes to achieve tight tolerances for outer car-body panels. In general, it is important in this respect to take into account the assembly process when considering clamping support systems and tolerances of sheet metal parts. Therefore, stochastic sheet metal forming simulation in combination with body-in-white assembly simulation could be used to develop optimal clamping support systems.

In total amount of springback variation, differences between simulation and series measurements were observed. This leads to limited expressiveness with regard to the determination of process-reliable tolerance limits by stochastic sheet metal forming simulation. Further research is needed to evaluate the differences in the total amount of springback variation.

Overall, feeding back the digital manufacturing results of a stochastic sheet metal forming springback simulation into component engineering will save time and costs in the die manufacturing process. The springback sensitive areas will be predicted correctly and as a consequence the part tolerances or the clamping support system can be accordingly adjusted.

References

[1] Birkert A, Haage S and Straub M 2013 Umformtechnische Herstellung komplexer Karosserieteile (Berlin, Heidelberg: Springer Berlin Heidelberg)
[2] Klinger J F and Bohn M 2013 Procedia CIRP 7 353–358
[3] Bohn M 1998 Toleranzmanagement im Entwicklungsprozess: Reduzierung der Auswirkungen von Toleranzen auf Zusammenbauten der Automobil-Karosserien Dissertation Universität Karlsruhe
[4] Klinger J F and Bohn M 2012 International Conference on Accuracy in Forming Technology, ICAF
[5] Stockinger A and Meerkamm H 2009 International Conference on engineering design, ICED
[6] Lindau B, Andersson A, Lindkvist L and Söderberg R 2012 Using Forming Simulation Results In Virtual Assembly Analysis ASME International Mechanical Engineering Congress and Exposition 31–8
[7] Brüggemann H and Bremer P 2020 Grundlagen Qualitätsmanagement: Von den Werkzeugen über Methoden zum TQM (Wiesbaden: Springer Fachmedien Wiesbaden)
[8] Beckmann A, Bohn M and Gust P 2015 Procedia CIRP 27 35–40
[9] Emrich A 2013 Systematik zur Robustheitsanalyse von Umformprozessen für Karosseriekomponenten aus Blech Dissertation Universität Stuttgart