New Physical Scaling Approach to compensate the part contraction in drawing operations

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Abstract. Further increasing requirements to the quality of car body components represent a huge challenge for the process planner. Springback effects are causing dimensional deviations of the car body components from their respective target geometry. Both elastic membrane and bending stresses result in global and regional distortions and deflections. In addition to these effects in particular the membrane stresses furthermore result in a contraction of the drawshell with the effect that the drawshell is smaller than the tool after drawing. In order to compensate this contraction the drawing tool has to be increased. This process is known as the so-called scaling. An appropriate scaling should result in a contracted part which has the same surface area and unwound lengths as the target geometry. In case of deviations of the unwound lengths unwanted plastic deformations of the part in subsequent operations have to be expected and the part’s assembly dimensions will differ from the target geometry which can cause significant quality issues in the car body. Today the scaling is usually done by increasing the tool with a unique global scaling factor or with different scaling factors for different directions. However, since the contraction varies along the part surface in reality the results are only suboptimal. Here a new scaling approach is being presented which uses the simulation results to scale the tool surfaces locally. By doing so the locally different contractions can be better compensated.

1. Introduction

Springback is the change of geometry which occurs in stamped parts during the opening of the dies; it is caused by the release of elastic energy. On the one hand the elastic springback results in dimensional deviations from the target part caused by bending ups, distortions or something like this. To reduce these kinds of deviations the common approach is to modify the tool geometries in the opposite direction of the dimensional deviations. This proceeding is called springback compensation and therefore a few of methods have been developed [1], [2].

On the other hand the elastic energy which is introduced in the forming part during the drawing operation – as a result of the increase in surface area – causes a contraction of the part during the opening of the tool. To compensate this behaviour the dimensions of the drawing tool have to be increased. This doing is the so-called tool scaling or only scaling.

In case of an inadequate scaling of the drawing tool there are two main problems. First the absolute part dimensions could be out of tolerance, which causes quality problems in the assembly process.
Secondly the part could even be plastically deformed by closing the pad in subsequent operations, because these operations commonly are designed with the lengths of the zero geometry [3].

The common approach to scale the drawing tool is to increase the dimensions of the tool with global factors. By doing so the selection of the global factors are based on a simple material-based approach or by practical experience. The main problem of these procedures is, that the contraction of the drawshell is not constant along its surface and so a global scaling approach only represents an approximation to the given conditions. In this paper a New Physical Scaling Approach is being presented which considers the local different contraction effects by using the results of the forming simulation and so to reduce the problems of the known scaling approaches.

2. Common scaling approaches
In [3] Birkert et al. it is mentioned that for steel materials in practice a scaling factor between 1.0007 to 1.0012 has proved to be useful. With these factors the tools are usually enlarged in all directions. In the simulation software AutoForm Forming R8 an approximate approach to estimate the scaling factor is implemented which is based on Hooke’s law. Therefore the biaxial yield stress and the Young’s modulus of the respective part material is being used as in equation (1).

\[ F_{\text{scale}} = 1 + \frac{\sigma_{\text{biax}}}{E} \] (1)

In Figure 1 the effect of a global scaling approach is shown at an exemplary tool section. In addition to define a scaling factor a scaling centre has to be defined. The scaled geometry is generated by increasing the distance of each point of the zero geometry according to its distance from the scaling centre by the defined factor.

![Figure 1. Effect of global scaling approach.](image)

In addition to the approach with one common scaling factor, also different factors for different directions can be chosen. This is very useful, if the respective part is significantly more stressed in one rather than in the other direction, as hat profiles for instance. For other parts, such as roof panels or hood outer panels, tool makers quite often use their own scaling factors which are based on practical experience.

3. Deficits of today’s scaling approaches
The present studies have been carried out on the example of an aluminium headboard (sheet thickness 2.5 mm). The production process of the headboard has been simulated with the FE-Software Forming R8 from AutoForm. The manufacturing process is shown in Figure 2. It starts with a drawing operation (D20). Then the part is being separated from the addendum by a laser cut (T30). Finally two flange areas are formed in a flanging operation (F40). To evaluate the scaling quality the springback has been calculated after the laser cutting step (T30) in a virtual measurement operation (M35). Scaling quality means the difference between the springback part geometry and the zero geometry referred to the surface area and the unwound lengths.
The deficit of a global scaling approach is that the tool dimensions are increased by a constant percentage in each part area. In contrast to that the part contraction is locally different. To show this part behaviour the strain change by springback of the headboard has been evaluated (Figure 3). In the shown section the outer part areas underlie a negative strain change which represents a contraction, whereas the centre area of the part shows a positive strain change which causes an increasing section length.

Figure 2. Manufacturing process of the headboard.

Figure 3. Strain change during springback along a representative section.

4. New Physical Scaling Approach
The New Physical Scaling Approach differs from the known ones insofar that it does not change the tool dimensions globally over the whole surface but takes into account the locally different surface contraction. The different contraction is caused by the locally varying stresses. To visualize the
workflow of the new approach, the principle part behaviour is shown in a unidimensional stress-strain-diagram (Figure 4). In a first step the blank is being formed with an unscaled drawing tool (0→1). If the subsequent operations are pure cutting operations (without any forming), they should be part of this first step, but without calculating a springback step between the single operations. This is important, because the surface area of the part may be changed if the addendum is separated from the drawshell. From this state the springback can be calculated as usual (1→2) which causes a part contraction, represented by the negative strain $\varepsilon_{SB}$ in the diagram.

According to the new approach the stress state must be adjusted (1→3) before the springback calculation step is done. To explain the following considerations the definitions of the local stresses and the local coordinate systems are done on a finite shell element. The local coordinate system $(x_1, x_2, x_3)$ is aligned in such a way that $x_1$ and $x_2$ lie in the tangential plane of the shell element. Therefore $x_3$ represents the thickness direction of the shell (thickness direction of the sheet). Relating to this coordinate system the stress state can be described by the Cauchy tensor $\sigma = (\sigma_{ij})$; $i, j = 1, 2, 3$.

Because only the components $\sigma_{11}, \sigma_{22}, \sigma_{12}$ and $\sigma_{21}$ have an influence on the elastic surface area change, the other components are set to zero. In order to be able to map the different stresses and strains along the sheet thickness with only one element, shell elements with several integration layers are used in sheet metal forming simulations. The stresses along the sheet thickness can be split into membrane stresses on the one hand and bending stresses on the other hand. For scaling only the membrane stresses are being used. These are being handled by averaging over the shell thickness according to equation (2).

$$\sigma'_{ij} = \frac{1}{t} \int_0^t \sigma_{ij}(x_3) \, dx_3$$

Subsequently the signs of the membrane stress components have to be inverted. Insofar an initially positive membrane stress component (tensile stress) turns into a negative one (compressive stress) and vice versa. With the so modified stress state $\sigma'$ a springback calculation step is being simulated now (3→4). By the release of the elastic energy an increased surface area is the result, which is represented by the positive strain $\varepsilon_{scaling}$. This deformation is now used to scale the tool surface of the drawing tool (4→5). Now the manufacturing process is being simulated with the scaled tool (0→5) and after the
springback calculation step (5→6) the part is expected to have the same surface area and unwound lengths as the zero geometry.

5. Comparison of the results of the new approach with those of an existent approach
In this chapter the results of the simulation setups without scaling, with global scaling and with the New Physical Scaling Approach (NPSA) are compared to each other. For that purpose the surface area and the unwound lengths of the tools and springback geometries are compared with the zero geometry. Furthermore the plastic deformations of the part by closing the pad in the flanging operation have been evaluated.

In the first simulation setup the process has been simulated with an unscaled drawing tool. The second setup was simulated with a globally scaled drawing tool by a scaling factor – calculated by equation (1) – of 1.001919. Finally, in the third simulation setup the NPSA has been used. The simulated springback results (nodal displacements) then have been used to generate springback CAD-geometries and after that the surface area and the unwound lengths of those have been compared to the zero geometry.

5.1. Evaluation of the surface areas
For the comparison of the springback surface areas out of the differently scaled tools the surface patches of the CAD-model have been numbered as shown in Figure 5.

![Figure 5. CAD-model and numbering of the surface patches of the headboard.](image)

The evaluation of the scaling quality of the different scaling approaches with regard to surface area deviations is shown in Figure 6. The connecting lines between the single patch deviations shouldn’t describe a dependency between the single values and are only used for a better visualization. By using the unscaled tool the deviations of the respective springback geometry (SBG-unsca)l amount to roundabout 0.3% in average with a bandwidth of 0.2%. By using the globally constant scaling factor the tool surfaces have been globally increased by 0.38%. The respective springback geometry (SBG-globalsca)l shows more or less the same local contraction effect as the SBG-unsca, but with an offset of 0.38% to the unscaled curve. This means that the deviations after scaling move close to the zero geometry in average but still show the same bandwidth as without scaling. Insofar with this approach only a certain compromise can be achieved, as long as the contraction of the different patches is not constant, which is being expected for the most real parts.

With the NPSA however the tool can be increased locally differently. By doing so the maximum deviation of the SBG could be reduced from 0.17% (SBG-globalsca)l to 0.07% (SBG-physca). In addition to this the bandwidth of the deviations could be reduced from 0.2% to 0.1% which corresponds to an improvement of 50%.

General findings through the evaluation of the measured curves:
1. The physically compensated curve (Tool-physca)l does not represent the exact mirror image of the unscaled springback curve (SBG-unsca). This is also expressed by the fact that the sum curve formed from both (SBG-unsca+Tool-physca)l does not correspond to the zero line.
2. The reason for the deviations is a non-linear reaction of the zero geometry to membrane stresses of equal magnitude and different signs.
3. Due to the fact that this sum curve \((SBG\text{-unscal} + \text{Tool-physscal})\) corresponds almost perfectly with the physically scaled springback geometry \((SBG\text{-physscal})\) shows the scaling measures is well received by the springback geometry \((SBG\text{-physscal})\).
4. Based on this findings it should be possible to adjust the for the physical scaling used stress state locally to bring the sum curve \((SBG\text{-unscal} + \text{Tool-physscal})\) – and thus also the springback geometry \((SBG\text{-physscal})\) – closer to the zero line.

![Figure 6](image-url)  
**Figure 6.** Evaluation of the scaling quality with regard to surface areas when using different scaling approaches.

5.2. Evaluation of the lengths of the patch boundary curves
As in chapter 5.1. the patches itself, here the boundary curves of the patches have been numbered (Figure 7).

![Figure 7](image-url)  
**Figure 7.** CAD-model and numbering of the surface boundary curves of the headboard.

The evaluation of the scaling quality of the different scaling approaches with regard to boundary curve length deviations is shown in **Figure 8**. The results are similar to the findings of the surface area deviations. By using the global scaling approach the deviations of the unscaled setup have only been
shifted. This results in huge residual deviations of the $SBG$-$globalscal$ curve lengths from zero especially in such sections where the contraction is very low (curves 1, 2, 19, 20).

![Graph showing boundary curve number and relative deviation](image)

**Figure 8.** Evaluation of the scaling quality with regard to surface boundary curve lengths when using different scaling approaches

5.3. Evaluation of unwanted plastic deformations after pad closing
As mentioned in the previous chapters before, an inadequate scaling could result in unwanted deformations of the part when closing the pad in subsequent operations. Therefore the plastic deformations after pad closing in $F40$-$Flanging$ have been analysed. To detect any unwanted plastic deformations the AutoForm postvariable $Plastic Strain Rate$ in the last simulation time step of the pad closing process has been used ($Figure 9$). With the unscaled setup there are plastic deformations of respectable size in a lot of part surface areas. By using the global scaling approach the number and the size of areas with plastic deformations could be decreased, in other areas (marked area) however plastic deformations occur where there were none before. The best result is clearly achieved by using the $NPSA$. Here in only two larger areas plastic deformations occur. A couple of smaller plastic deformations occur along some radii. These can easily be eliminated by appropriate radius clearances.

![Images showing plastic deformations](image)

**Figure 9.** Unwanted plastic deformations after pad closing in the flanging operation ($F40$)
6. Conclusion
Only such scaling approaches which enable to increase/decrease the tool surface locally are capable to produce parts with the same surface area and unwound lengths as the zero geometry. If this requirement is not fulfilled, any unwanted plastic deformations in subsequent operations and problems in the assembly process may occur. In contrast to a global scaling the New Physical Scaling Approach does not only provide an approximation to the target surface based on practical experience or average material parameters. The new procedure uses the locally existent membrane stresses which cause the elastic part contraction to scale the drawing tool. By doing so the root cause of the problem itself is directly used to solve the problem. This approach compensates one part of the dimensional deviations caused by the elastic springback. In order to be able to transfer it to other forming processes, the respective stress states and the resulting geometrical deviations would have to be examined more closely.

The evaluation of the surface deviation after drawing shows that with the NPSA the maximum deviations could be reduced from 0.17% (achieved by a global scaling) to only 0.07%. Furthermore the bandwidth of the deviations along the different surface patches could be reduced from 0.2% to 0.1% which corresponds to an improvement of 50%! With regard to the boundary curve lengths the maximum deviation could be reduced from 0.19% to 0.07%. Both evaluations show, that with a global scaling only a more or less good compromise can be achieved, especially if the contraction dimensions are not homogeneous along the whole part.

In addition to the geometrical deviations the part also with regard to any unwanted plastic deformations in the flanging operation has been analysed. By using a global scaling the areas with unwanted plastic deformations could be reduced modestly whereas plastic deformations occurred in other areas where none were before. With the NPSA such areas have been reduced drastically.

In order to compensate the remaining dimensional deviations in a multistage manufacturing process the NPSA can be included in a geometrical springback compensation method. Thereby it has to be observed that the compensation method doesn’t have a negative impact on the surface area and the unwound lengths because this would also result in a bad dimensional quality. The Physical Compensation Method [4] fulfils these requirements of equal-in-surface compensated tool geometries with high accuracy.

Current and future research work is still being done to further improve the New Physical Scaling Approach. Based on the findings that the local tool dimensions should be modified exactly by the amount of surface change during springback in the opposite direction, the simulated membrane stresses can be selectively modified to reach this requirement. Therefore the surface area of each element should be geometrically compared to the target geometry after springback in order to create an adjustment factor for the stresses.

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