Dimensionally accurate parts made of high-strength steels - compressive stress superposition instead of tool compensation

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Abstract. As a result of the increasing use of high-strength and ultra-high-strength steels as part of the automobile lightweight construction strategies, the issue of dimensional accuracy of component structures is increasingly becoming the focus of toolmakers, pressed part suppliers and automobile manufacturers. In particular, the modern dual-phase steels with strengths of over 800 MPa possess – depending on the respective component geometry and the forming process employed – a pronounced springback behaviour. The compensation measures commonly used so far are more and more reaching their limits, which in turn impairs the process ability of these grades in the cold forming process. The smartform® process developed by thyssenkrupp Steel Europe AG allows the cold forming of high-strength steels with high repeatable accuracy, which significantly expands their areas of application. In this process, the tensile stresses from the forming operation causing the springback of the part are eliminated by compressive stress superposition, which leads to high dimensional stability. There is almost no need to adapt the tool surfaces to achieve a dimensionally accurate part. How close the formed component comes to the dimensional tolerances specified by the end user is usually determined within the framework of numerical method development. In this context, the result of a springback simulation depends on various parameters. The description of the material behaviour is of major importance. Moreover, the use of extended material models can have an influence on the predictive accuracy and reduce the deviations between simulation and real material behaviour. It remains to be identified to what extent the increase in accuracy is proportional to the modelling effort.

1. Introduction

Due to the growing number of model variants and drive types, the OEMs find themselves in a challenging situation with regard to the development times of new vehicle models. It is precisely the change from the combustion engine to alternative drive concepts that makes rapid body/platform development indispensable. The tryout period of the prototype and series tools for the production of the body components must also be taken into account. Besides the geometry- and process-related variables like failure and wrinkling, special attention must be paid to the dimensional accuracy of the parts to be processed, in particular when high-strength and ultra-high-strength materials are used. In the case of parts that are produced in the conventional deep-drawing process, the drawing tool is usually compensated based on the results of the springback simulation. The tryout or the start of series production reveal how close the prediction of the simulation is to the real result. The occurrence of any significant deviations usually entails extensive reworking of the tools and, as a result, project delays and in some cases enormous costs to achieve the specified dimensions of the part [1]. At the same time, the
result of batch variations and the variable rebound behavior is that such compensated tool surfaces only lead to dimensionally accurate parts to a limited extent. In order to save time and costs and to use high-strength steel grades also for complex part geometries, an innovative forming process has considerable advantages over the conventional process.

The smartform® process developed by thyssenkrupp Steel Europe AG eliminates the need for compensation measures for a large field of different part geometries. A forming process without active material flow control with subsequent compressive stress superposition in the sheet plane enables to minimize the deviations from the shaping tool surfaces irrespective of the sheet metal batch. The only necessary optimization measure is to adapt the starting blank. This reduces the time and cost expenditure in the tryout of new forming tools significantly and enables parts production independent of batch fluctuations.

2. Modern dual-phase steels
Cold-rolled dual-phase steels are perfectly suited to meet the requirements of modern automobile production in terms of weight optimization and safety. They are especially well suited for cold forming processes involving a high amount of stretch forming to produce complex crash-relevant structural and car body parts. Thanks to their good dynamic behavior, dual-phase steels are also ideal for crash-relevant components such as longitudinal members or for components subjected to cyclical stresses. The thyssenkrupp Steel Europe AG offers a wide range of DP grades in order provide the right material for the various fields of application in automotive construction [2].

The smartform® process is not material-specific, but it is suitable for all typical steel materials within a broad range of sheet thicknesses. However, high-strength dual-phase steels are ideally suited for the smartform® process, as they offer a great potential in terms of minimizing springback behavior.

3. smartform®
Generally, the formability decreases as the material strength increases. Dual phase steels possess an exceptionally good forming potential despite their high strength. The lightweight construction potential of high-strength and ultra-high-strength grades can be fully exploited by reducing the amount of material used, i.e. by reducing the thickness. However, as the strength increases in combination with small sheet thicknesses, there is also a tendency for increased springback. As a function of the complexity of a component structure, solutions are therefore required that extend the limits of formability while reducing the risk of uncontrolled springback.
The smartform® process offers the possibility of significantly improving the formability of high-strength and ultra-high-strength steel materials. By using an innovative preforming process with a downstream calibration stage, it is possible to eliminate the tensile stresses resulting from the forming process and, as a result, to minimize the springback. Besides the increase in dimensional accuracy, the reduced amount of material used is another advantage. In the smartform® process, an optimally shaped blank is used. This means that a near-net-shape blank is directly used in the forming process, which means that almost no edge trimming of the finished formed part is necessary. Compared to the conventional deep-drawing process, this results in an average material saving of 15 % per component. Moreover, this involves savings in toolmaking and try-out, since compensation measures do not have to be taken into account in the part development process and the loops of tool reworking are largely eliminated. In most cases, only a few loops are required to optimize the final blank contour.

3.1. Process

The patented forming process smartform® is based on a compressive stress superposition across the entire part cross section. This stress state in the part is achieved through a defined material addition during the preforming. When the calibration tool is closed, adjustable cams prevent the supplied material from leaking sideways out of the tool. The sheet is compressed in the plane which leads to an increase of the sheet thickness. Figure 2 illustrates the process and the stress conditions prevailing during the process by means of a hat profile.

In position 1 of the preforming operation, an additional amount of material has already been fed into the bottom of the component. Punch and die thus have an additional curvature in the bottom area. The profile with included material can be seen in the lower dead center of the preforming. When the tools are opened, the component springs back significantly due to the internal stresses. The extent of springback is of rather secondary importance for the following calibration stage of the smartform® process. First and foremost it is important that the springback preform can be put into the calibration tool without clamping. So, above all, it must be ensured that there is no excessive rotation or a so-called curl-in.

In the calibration stage, the preform subjected to residual stresses is placed into the calibration tool. In position 2, i. e. when the tool is closed, the high tensile stresses on the outer wall can still be clearly seen. As the tool continues to close, the material excess applies pressure to the entire cross section of the part. The tensile stresses causing the springback are thus eliminated during the calibration process. Figure 3 shows the elastic, inhomogeneous residual stress state after the springback of the preform (left), fully plastic compressive stress superposition during calibration (in the middle) and resulting, not yet relieved residual stress state (right). The result is a dimensionally accurate component within the specified tolerances with minimized springback [3].
Figure 3: Schematic representation of the stress curves in the sheet metal cross-section during the calibration process (plastic zones are shown in grey) [3]

Figure 4 shows the sequence of a typical series process. During the engineering process, the blank shape is designed in such a way that the blank edge corresponds to the later part edge as much as possible. The forming operations are carried out either without classical blank holders in the crash forming process or with an external blank holder spaced over the thickness of the sheet. In order to achieve a repeatable length of the local developed lengths, no active material flow control during the forming of the preform geometry must take place. This, in turn, has the advantage that the influence of batch variations is minimized. In the preforming stage OP20, there is geometrical flexibility in the design of the tool surface, as the final component contour is not set until the calibration stage OP30. This means that radii can be enlarged and wall angles can be varied in the preform so as to prevent wrinkling and cracks. Where complex geometries are involved, the preforming process can alternatively also be a two-stage process. This results in an optimized forming behavior, which favors the use of high-strength and ultra-high-strength materials. In the calibration process, adjustable cams are used which prevent that the formed material is pressed out of the tool. The side cams are only used for positioning purposes and do not exert any active pressure during the calibration. Finally, the piercing and flanging operations are carried out, as in the conventional drawing process [3].

Figure 4: Flow chart of the smartform® process

3.2. Fields of application
The smartform® process is ideally suited for structural components in automobile engineering (Figure 5), but also for industrial applications, e. g. in machine and plant construction or household...
appliances. The present prerequisite for the smartform® process is a profile structure with open ends and, depending on the wall height and the material strength, a minimum sheet thickness of at least 0.80 mm. Part flanges are not absolutely necessary for the smartform® process, since in principle only the outer edge of the part has to be supported during calibration. A large number of the structural parts installed in the vehicle can be produced with the smartform® process.

![Figure 5](image5.png)

**Figure 5:** Range of suitable smartform® parts

3.3. **Cost-efficient lightweight construction**

So far, the high strength of modern lightweight steels has been a limiting factor in cold forming when designing complex part geometries for car body structures. Owing to the chosen approach of superimposing compressive stress, it is now basically possible to achieve higher strengths with a given geometry. It has been proven within the framework of component-specific development projects that it is possible to achieve at least one higher strength class, e.g. from DP-K® 440Y780T to DP-K® 590Y980T, without any substantial geometric adjustments. This possibility offers enormous potential for cost-efficient lightweight construction. This means that the use of higher strength materials with reduced wall thickness can be considered at an early stage when redesigning a vehicle structure. In pressing tests carried out on real components, tensile strengths ranging from 590 MPa to 1,180 MPa could be processed in the same tool without any changes being necessary. Dimensional accuracy was almost achieved.

![Figure 6](image6.png)

**Figure 6:** Technology Demonstrator smartform® made by thyssenkrupp Steel Europe

![Figure 7](image7.png)

**Figure 7:** Parts made of different strength classes in one forming tool
The batch independence of the smartform\textsuperscript{®} process is also evident in the specially designed Technology Demonstrator geometry (Figure 6). Beginning from the tryout with a MHZ340 up to a DP-K\textsuperscript{®} 850Y1180T with a sheet thickness of 1.50 mm, different strength classes could be pressed with only one tool. Only the blank contour had to be slightly adjusted as a function of the strength. Figure 7 shows the parts after the calibration process for the strengths 800, 1,000 and 1,200 MPa.

4. Simulative prediction of springback
When designing components and processes, the focus is not only on the material behavior in terms of failure and wrinkling, but the springback behavior of the materials is assessed in a much targeted way. A targeted prediction of the springback properties is very important for the general design of forming processes. There are different simulation programs and procedures available to depict the stress conditions and the dimensional accuracy resulting therefrom.

4.1. Engineering process
Thyssenkrupp Steel Europe provides its customers assistance with the methodical development of smartform\textsuperscript{®}-compliant parts in order to enable the OEMs and the suppliers to embark on the smartform\textsuperscript{®} production. This assistance is deliberately divided into two different phases. In the first development phase, the basic forming method is designed by means of incremental-iterative solvers, using shell elements. Here the general feasibility of the part and the method development of the preforming process is in focus. To get the required information’s about the stress situation regarding the springback behavior of the investigated part geometry in interaction with the used material grade, a higher type of modelling is necessary. Therefore the second development phase based on volume elements with three layers over the sheet thickness. Comparisons with the Technology Demonstrator and customer components show a sufficiently good match between simulation and practice.

4.2. Comparison of predicted springback effects
The result of forming or springback simulations depends generally on several factors. Besides the material description, the representation of tribological properties or the consideration of dynamic effects, there are several parameters in the FEM codes which may change the prediction. The following results have been determined with PamStamp using the standard parameters, in order not to influence the comparison of the smartform\textsuperscript{®} calibration simulation by choosing specific parameters.

![Figure 8: Prediction of dimensional deviations – comparison between experiment and simulation](image-url)

Experiments with a DP-K\textsuperscript{®} 440Y780T in 1.50 mm have been conducted for the comparison. The experimental parts were then measured with a Zeiss 3D scanner and compared with PamStamp volume simulations via best fit algorithm. The results in Figure 8 show that a sufficient match between practice and real material behavior can be achieved, even when using standard parameters and the selected model set-up. Especially the position of the walls was correctly predicted by the volume simulation. Slightly
greater deviations occurred in the preforming operation in the area of the B-pillar bottom. These differences may well be reduced by optimizing the material description, for instance.

4.3. Influence of the material modelling on the springback

The flow properties of steel materials can be influenced in the FEM in various ways. The choice of a suitable yield locus influences the forming result just as much as the extrapolation of the flow curve. Based on comparisons from the product development process at thyssenkrupp Steel Europe, a DP-K® 440Y780T is generally described via a bulge extrapolation and the yield locus according to Hill90. As the material description for volume elements in PamStamp, the material for the springback simulation was described via Hill48. When observing the stress states in the component radii, which are mainly responsible for the springback, a superposition of compressive and tensile stresses shows (Figure 9). Several publications have already shown that the use of a hardening description according to Yoshida can bring advantages with respect to the description of this stress state over the sheet thickness. [5][6].

Figure 9: Material description and stress conditions in the radius range

Figure 10 shows the comparison between simulation and practice in case of isotropic and kinematic (Yoshida) hardening for DP-K® 440Y780T in 1.5 mm. While the deviations at the B-pillar bottom are striking in the isotropic description, a marked improvement can be observed when using the Yoshida card, taking the kinematic hardening into account.

Figure 10: Use of a Yoshida card for the springback simulation
In general, when considering the maximum and mean deviations, an improvement in the prediction accuracy is observed. Whether this tendency is also confirmed with other component geometries or with the use of increasing material strengths is the subject of current investigations. A general use of complex material descriptions for the smartform® simulation cannot be recommended at present. However, the result shows that the accuracy of springback simulations can be increased by adapting the modelling.

5. Summary
The smartform® process developed by thyssenkrupp Steel Europe can significantly expand the field of application of high-strength and ultra-strength steels. By superimposing compressive stresses, the tensile stresses responsible for springback can be eliminated. This results in highly dimensionally accurate parts without the requirement of any further compensation measures, while minimizing material usage and edge trimming.

Using the example of the Technology Demonstrator, it was possible to show that even complex part geometries can be processed with different material strengths from 500 to 1200 MPa. All grades were pressed in the same toolset, even with a sufficient dimensional accuracy for a DP-K® 780Y1180T. The batch independency and the reduced amount of material for the initial blank as well as the shorter tryout time are the main advantages of the innovative patented smartform® process.

For the development of the preforming and calibration process a high quality of FEM based prediction is important. Comparison between simulation and practical result shows a good match in most areas of the Technology Demonstrator. In particular the walls, which are important for the statements about the springback behavior, the differences between simulation and experiment tend towards zero. Larger deviations only occur in torsion-prone areas in the head and the bottom of the part. The investigations regarding the influence of different material models have shown that the use of kinematic hardening can have a positive effect on dimensional accuracy. In the areas with torsional stress in particular, it was possible to reduce the maximum deviation without negatively affecting the areas with low deviations.

Current customer projects from prototyping to series application show excellent properties of the smartform process on real part structures.

6. References
[1] Roll K, Lenke T and Wiegand K 2004 Simulationsgestützte Kompensation der Rückfederung (Bamberg: Daimler Chrysler AG, LS-Dyna Forum)
[2] thyssenkrupp Steel Europe AG 2017 Produktinformation Dualphasen-Stähle (Duisburg)
[3] Nierhoff D 2017 Beschnittreduziertes kalibrierendes Tiefziehen von Stahlblechen zu hochmaßhaltigen Schalenteilen (Freiberg)
[4] thyssenkrupp Steel Europe AG 2020 https://www.thyssenkrupp-steel.com/de/branchen/automobiltrucks/smartform/ (Duisburg)
[5] Yoshida F and Uemori T 2003 A model of large-strain cyclic plasticity and its application to springback simulation International Journal of Mechanical Sience, 45(10), 1687-1702
[6] Grubenmann M Et al. 2018 Analysis of yield locus description on springback behaviour of CR780Y980T-DP steel IDDRG 37th Annual Conference, Material Science and Engineering 418(2018)012108