New sheet metal forming process for springback reduction by continuous stress superposition

D Briesenick¹, M Liewald¹ and K R Riedmüller¹

¹ Institute for Metal Forming Technology, University of Stuttgart, Germany

E-mail: david.briesenick@ifu.uni-stuttgart.de

Abstract. The use of ultra-high-strength steels (UHSS) enables a lightweight and resistant design of sheet metal parts in modern car body structures. In terms of manufacturing such dedicated materials, intense springback phenomena reduce the process stability and dimensional quality. In this context, new developments in springback compensation show promising results when superimposing stresses. Therefore, this paper deals with a new approach, which modifies conventional deep drawing of open profiles by substituting the blankholder by L-shaped sliders. This allows an additional application of horizontally acting forces along the edge of the flange and leads to advantageous free buckling and rolling of the material onto lateral punch surfaces. A numerical feasibility study of this new forming method was performed in this work, showing that compressive stresses and alternate bending through buckling in fact does reduce the amount of springback remarkably compared to conventional deep drawing.

1. Introduction

Today’s social demand for sustainable, intelligent and future-oriented mobility as well as for passenger safety at the same time leads to continuous development of lightweight construction solutions in automotive industry. A promising way to produces lightweight, economical and resistant car body structures consists in the use of sheet metal parts made of ultra-high-strength steels (UHSS) [1]. Such dedicated multi-phase steels show beneficial high tensile strengths, but also accompanied by drawbacks for conventional deep-drawing processes such as low formability, high process loads and tremendous springback phenomena [2]. Latter occurs when releasing the sheet metal components from the tool after the forming process and is mainly influenced by material characteristics such as Young’s modulus and hardening rate, tool geometry, forming method and strain distribution [3].

In order to extend manufacturing limits when forming ultra-high-strength steels (UHSS) and to increase dimensional quality and process robustness, various springback compensation methods have been developed during the last decades. Forming manganese-boron steels at elevated temperatures, for example, results in high dimensional quality, lower forming forces as well as global or local enhanced part strengths due to quench hardening in cooled tools [4]. In terms of required cycle time, lubrication effort and piece cost, however, press hardening technology still shows some deficits. For this reason, new approaches based on cold forming technologies have recently been developed in order to exploit the high economic efficiency of these processes while maintaining high component quality. Here, a commonly used method for springback compensation consists in the controlled overforming of the sheet metal part [5]. However, this procedure requires exact prediction of springback phenomena and often results in cost-intensive iterations on tool base with extended tryout time. A further approach consists
in the geometrical modification of invisible structural parts by embossing sidewalls or radii during restrike operations [6], [7]. In general, successful springback compensation is based on the controlling of strain distribution during forming, which is frequently achieved by using variable blankholder forces or drawbeads [8]. However, processing UHSS often meets its limits due to insufficient available press and cushion forces. In this respect, modifications of conventional forming operations such as the trim-free deep drawing (smartform) demonstrate successful and practicable compensation strategies. In this process, the component is formed within two subsequent stages, i.e. a preform operation and a subsequent sizing stage. Thereby, inhomogeneous stress states are superimposed by compressive stresses and springback effects occur mainly in plane. As a result, dimensional quality is only slightly affected [9]. Radonjic et al. [10] presented a decreasing springback behavior when forming with alternating draw-in of the blank. Based on an exemplary S-Rail geometry it could be shown both experimentally and numerically that almost complete compensation can be achieved due to alternating bending of the material over the tool radii.

A look at the state of the art emphasis the need for a cold forming technology, which reduces springback, press loads and an economical realization via simple, single-stage tool concepts. Against this background, this paper presents a new cold forming process called Transversal Compression Drawing (TCD), which combines two springback compensation strategies, compressive stress superposition and alternating bending.

2. Process modelling and simulation

The numerical feasibility study of the new TCD process presented in the following was carried out on commercial FE-code LS-DYNA. Figure 1 shows the implemented modifications of a conventional tool set for deep drawing of hat-shaped channels having a drawing depth of 40 mm. The substitution of a typical blankholder with L-shaped sliders allows an application of transversal forces on the blank edge and the ability of knuckling and roll bending in forming direction towards non-supported areas. An additionally implemented counter pad prevents a lift up of material and may form features in the bottom area of more complex parts in future. In simulation, tool surfaces were assumed to be rigid shell elements and blank was modelled by volume elements with a square base area of 1 mm². Five volume elements were used for modelling the blank thickness of 2 mm (see Figure 1). In this case, the reason for using volume elements is the limitation of default shell elements with regard to the consideration of transversal contacts and three dimensional stress states. However, as simulation with flat hexagonal volume elements may cause locking phenomena for bending dominated problems of thin walled structures, an efficient and accurate fully integrated S/R (selective reduced) solid formulation for elements with poor aspect ratio was used for LS-DYNA (ELFORM = -1) [11]. The forming processes were simulated by using explicit integration method, whereas springback calculations were performed by implicit integration routine. Thereby, bottom area is clamped at three points to restrain global part displacements.

![Figure 1. Schematic representation of the process related tool modifications for a) Transversal Compression Drawing TCD compared to b) conventional deep drawing and c) investigated blank size.](image-url)
The high-strength dual-phase steel DP 980 was selected as blank material to be investigated. Owing to the alternating loads occurring during the TCD process, the material model according to Yoshida et al. [12] was chosen for describing material behavior. This material model particularly considers material characteristics which directly influence springback phenomena, thus leading to an increased accuracy and quality of springback calculation when forming high-strength steel sheets. These characteristics are the strain dependent Young’s modulus, transient softening, kinematic hardening and the Bauschinger effect [13], [14]. In previous work of authors, a method for parameter identification of the Yoshida-Uemori model (YU-model) was developed, based on cyclic shear tests and extended by a calibration on formed and unloaded parts [15]. For the simulation of Transversal Compression Drawing (TCD) and a reference deep drawing process, model parameters were obtained according to this method. The flow curve was extrapolated by the approach of Swift and Hockett-Sherby based on uniaxial tension and bulge tests [15]. Finally, the Y-U model was additionally combined with anisotropic elastic-plastic material behavior by using LS-DYNA material subroutine *MAT_125.

To identify sensitivity of transversal force $F_Y$ and cushion force $F_Z$, a numerical study was implemented in LS-OPT to carry out sensitivities on springback and process limitations. Nominal process setup for Transversal Compression Drawing (TCD) amounted $F_Z = 90$ kN and $F_Y = 35$ kN per slider and presented together with investigated parameter space in Table 1. As reference and for classification of new forming method, deep drawing process with a pad ($F_{Pad} = 100$ kN) and a conventional blankholder exerting a total force of 200 kN was simulated.

Table 1. Investigated parameter space for transversal $F_Y$ and vertical force $F_Z$ and pad force $F_{Pad}$.

| Parameter | Nominal | Max | Min |
|-----------|---------|-----|-----|
| $F_Z$ [kN] | 90      | 100 | 1   |
| $F_Y$ [kN] | 35      | 50  | 1   |
| $F_{Pad}$ [kN] | 100 | -   | -   |

3. Results and discussion

At the beginning, results and discussion focuses on force-controlled version of Transversal Compression Drawing (TCD) on hat-shaped channels with constant transversal and vertical applied forces on sliders. After a detailed examination of numerical results for the nominal process setup and a discussion of springback compensation effect in section 3.1, correlation between transversal forces, springback and buckling behavior was investigated (section 3.2). Based on these findings, a stroke controlled tool concept was developed and simulated for more complex part geometry and examined in terms of springback compensation and energy consumption (section 3.3).

3.1. Analysis of nominal force controlled Transversal Compression Drawing

In order to identify main influencing parameters and general effects of the TCD process on springback compensation, an in-depth analysis of the material movement during the forming process and of the stress distribution after the entire process was performed. In this respect, Figure 2 a) shows different forming stages of the TCD process of hat-shaped channel part and under corresponding nominal process forces (Table 1). Due to constant transversal force applied, the blank tends to buckle towards non-supported areas on the opposite side of the moving die at the beginning of the process. At drawing depths between 5 mm and 25 mm, almost linear movement of force controlled slider can be observed in YZ-direction, leading to a constant buckling and rolling of the material towards the lateral punch surfaces. Radius of punch is completely formed after a certain forming stroke and the pad successfully prevents sheet metal material from lifting off the punch face. When reaching a drawing depth of 28 mm, buckling and rolling of the material can no longer be sustained by the selected transversal force $F_Y$ and the formed kink is drawn out within the following 5 mm of die movement. Once the required force exceeds the provided transversal force, remaining forming stroke proceeds comparable to conventional deep drawing.
Figure 2. Forming process for Transversal Compression Drawing with a) buckling and rolling phases for $F_Y = 35$ kN and b) comparison of stress gradient over thickness $\Delta \sigma$ and springback amount.

The stress gradient along thickness direction was determined by the difference of first principal stresses at the inner and outer element, representing blank surface. Analysis of stress gradients of the final formed hat-shaped channel part along sheet thickness direction reveals a possible reason for improved springback compensation of the new forming method compared to conventional deep drawing (see Figure 2 b)). Here, solid lines illustrate stress differences $\Delta \sigma$ between outer and inner part side before springback, which significantly influence resulting shape deviations of the unloaded part. The flange and die radius areas (A - C) show minor differences between the TCD and the conventional deep drawing simulations. However, in the sidewall (C - D) and punch radius (D - E) areas, stress gradient $\Delta \sigma$ of TCD oscillates around zero while showing relatively high positive values for conventional deep drawing. These positive values imply to some extent high tensile stresses on the outer part side, which in turn are mainly responsible for typical springback phenomena such as sidewall curl and flange displacements. The dimensional deviations caused by these springback phenomena are visualized by dotted lines in Figure 2 b). It can be observed that the small stress gradients of TCD lead to reduced flange displacements of more than 60 %. As a consequence of these results, a sensitivity analysis was carried out with regard to the correlations between transversal forces in TCD and springback compensation, which is described in the following section.

3.2. Sensitivity of transversal forces on forming process and springback of component

The sensitivity analysis presented here includes parameter sampling of vertical cushion force $F_Z$ and of transversal forces $F_Y$ by using the Monte Carlo method. The range of parameters examined is presented in Table 1. Evaluation of gained results considers largest flange displacement after springback simulation and maximum of buckling during forming, measured as distance between largest formed kink and horizontal contact area of slider and blank.

Figure 3 reveals a strong correlation between the transversal force $F_Y$ and flange displacement, whereby an increased force decreases springback. Compared to conventional deep drawing ($F_Y = 0$ kN), flange displacement as a function of transversal force decreases in an exponential manner up to a certain process limit ($F_{Y,\text{max}} = 43$ kN). Further increased forces lead to strong non-linear buckling of blank resulting in a folded sidewall geometry and process instabilities at the beginning of forming process. The described non-linear behavior can be observed from the maximum buckling values plotted in Figure 3. Here, maximum buckling height slightly increases up to a transversal force of approximately 35 kN, afterwards buckling intensifies. On contrary, vertical cushion force revealed no significant impact on springback or buckling behavior and can be minimized ($F_{Z,\text{min}} = 10$ kN) in order to reduce process loads and friction forces.
Figure 3. a) Influence and b) limitation of transversal force $F_Y$ on buckling behaviour and correlation on springback represented by c) maximal flange displacement.

In summary, the results presented indicate a reasonable correlation between springback compensation and buckling behavior during TCD, but also show process instabilities at the beginning of the forming process when high constant transversal force is applied. Therefore, it can be assumed that even better springback results can be achieved by means of a variable adjustment of transversal force along the drawing depth or a stroke-controlled tool concept with cams may overcome such related drawbacks. Latter mentioned approach is accompanied with further advantages for TCD like the reduction of tool complexity with cams instead of additional drives for transversal forces and an application on presses without cushion systems. Such a stroke-controlled buckling behavior is investigated on a more complex part geometry (NUMISHEET’96 S-Rail) in the following section.

3.3. Stroke controlled forming process for more complex part geometry

Figure 4 shows the transfer of the force controlled TCD process of the hat-channel to a stroke controlled tool setup for a multiple curved profile geometry (S-Rail). Here, blank thickness is reduced from 2 mm to 1 mm, but material remains DP 980. As a reference, conventional deep drawing simulation performed with identical numerical settings, a blankholder force of 500 kN and pad force of 100 kN was run. Herein, maximum draw-in of blank for deep drawing amounted 35 mm and was set as a comparative quantity between both forming methods. Therefore, total displacement for the sliders amounted also 35 mm with constant linear movement towards punch in Y-direction during forming stroke in Z-direction of 40 mm. This results into buckling effects of blank within and along the non-supported area between sliders and punch prior forming of the respective radii (see Figure 4 c)), stage 1). As die movement progresses, material is constantly buckled and roll bended towards the lateral punch surfaces (stage 2). Between stage 3 and the final shape, formed kink is drawn out and die radius is formed into the part at the very end of the forming process.
Figure 4. Transfer from a) force controlled to b) stroke controlled TCD and c) forming simulation of S-Rail geometry by kinematic coupled sliders on cams.

In Figure 5, the simulation results calculated for conventional deep drawing and for TCD of an S-Rail component are compared. Previous described effects of reduced stress gradients in part sidewall areas contribute to an efficient springback compensation for TCD compared to deep drawn sheet metal part as shown in Figure 5 a) and b). It is noticeable that the part formed with the new forming method shows significantly smaller shape deviations in relation to the conventionally deep drawn part and thus reduced springback. More precisely, maximum displacement of flange could be reduced by almost 50 % and moved from convex to concave area of the part boundary. Furthermore, the bottom area of the TCD formed part geometry remains completely flat, whereas conventional deep drawing results in an asymmetric twist between clamped areas. In Figure 5 c), the dimensional accuracy of the component cross-sections produced by the two different forming methods is evaluated by comparing the deviated shapes to the nominal CAD-geometry. For TCD, left-hand component area remains almost in CAD-shape, while springback on the opposite side is reduced by half compared to conventional deep drawing. In particular, typical sidewall curls are nearly eliminated by TCD and flange displacements are remarkably reduced by using the new forming method. Besides an improvement regarding springback related shape deviations, less contact zones with relative motion between blank and tool require less process loads and energy consumption due to a reduced impact of friction. When considering the calculated external work per stroke, a first numerical estimation provides an efficiency improvement around 40 % from 8.3 kJ (deep drawing) to 4.9 kJ (TCD).

Figure 5. Comparison of springback results for a) Transversal Compression Drawing and b) conventional deep drawing, c) cross-section analysis referred to CAD-geometry.
4. Conclusions and outlook

The feasibility study presented in this paper investigated a new forming process for springback reduction when forming structural parts made of UHSS, called Transversal Compression Drawing (TCD). Here, additional transversal forces are applied to the blank edge during the forming process by substituting the blankholder with sliders. These transversal forces do cause an alternating effect of bending and compressive stresses on the sheet metal material, leading to a beneficial stress superimposition at sidewall and punch radii areas.

First numerical studies, which investigated the forming of hat-shaped channels using force controlled TCD, revealed a strong correlation between transversal forces, buckling and springback behavior of formed component. In deep drawing, applying additional blankholder forces is a traditional way to reduce springback due to increased plasticization of part sidewall [3]. On contrary, those vertical applied forces appeared to be insignificant on springback result when new forming method is applied and can be minimized to prevent an opening of sliders and reduce friction related forces. However, if a certain force limit is exceeded, exerting constant transversal forces causes process instabilities and constraints of springback compensation. Here, a promising solution is the implementation of a stroke controlled transversal force application by a kinematic coupling of sliders on cams in order to regulate buckling by constant transversal displacement over the drawing depth. Additionally conducted numerical study on more complex part geometry (S-Rail) introduced an efficient compensation of shape deviations compared to the deep drawn reference part. Furthermore, presented tool concept with transversal displacement by cams offers the possibility to form structural parts on presses without cushion systems, while process loads and energy consumption may decrease.

Based on these findings, future investigations will address a sensitivity analysis of process and material parameters like sheet thickness or material strength. Also an optimization of process settings like displacement curve of sliders, blank geometry, crowning of transversal contact areas or punch surfaces will be elaborated. Further, a combination between TCD and overforming [5] may provide an opportunity to overcome current limitations of forming undercuts. Basic experimental tests on the combination of buckling and roll bending within a forming tool for profile parts with different thicknesses will proof the concept and simulation results. As a conclusion, presented new forming method can extend current state of the art for springback compensation methods and may improve forming of structural parts made of UHSS.

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