Compensating the springback of ultra-high-strength steel parts by specific stress superposition during sheet metal forming

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Abstract. Ultra-high-strength steel sheets offer considerable advantages in car body construction regarding the permanent requirements for vehicle weight reduction as well as the increase in crashworthiness of sheet metal parts. However, when forming such sheet metal materials, the main problem relates to their distinctive springback behaviour, which occurs after the formed part has been released. This paper shows a methodology for springback compensation based on the superposition of stresses acting in the meridian direction of the formed sheet metal part. These stress superposition effects are induced via the tool radii by alternating blank draw-in during deep drawing. As a result, the workpiece areas contacting the punch radii during the deep drawing process are subjected to repeated bending and unbending. In order to analyse occurring stress superposition effects and their influence on springback appearance, simulation was performed using the FE-code LS-Dyna. Furthermore, an optimal blank draw-in kinematic could be defined using the forming simulation, which significantly reduced springback of a double-curved hat-shaped component made of DP 980 steel sheet after forming. Finally, this numerically determined methodology for springback compensation has been experimentally proved using tool that enables alternating blank draw-in during sheet metal forming.

1. Introduction
The continuing efforts to reduce CO₂ emissions in the automotive industry are leading to higher demands on car body lightweight design. In order to achieve these demands, OEMs have focused on the reduction of car body weight by using lightweight materials as well as sheet metals with smaller thicknesses, leading to the increased use of high and ultra-high-strength steels for manufacturing of structural car body components (UHSS) [1]. The aforementioned car body parts are usually manufactured by deep drawing or draw-bending processes [2]. When the part is removed from the die cavity after such forming operations, a stress relaxation happens to reach a state of balanced stress distribution in the part. As a result of this stress relaxation, the springback or certain deviation between the formed part and the reference geometry occurs. Springback in general appears in several forms: angle change, sidewall curl, radii change and twisting or torsion of cross section along part longitudinal axis [3], [4]. Particularly when forming car body structural components from UHSS in cold stage, an extremely high amount of springback occurs after part release, which is difficult or sometimes impossible to compensate successfully with currently existing methods [5], [6]. Therefore, in order to form such UHSS with a die in a cold stage, it is necessary to define forming processes with new boundary conditions, or even to develop new forming processes while keeping manufacturing costs as
low as possible. Radonjic et. al. showed that springback amount can be significantly reduced when deep drawing sheet metal material DP 980 with alternating blank draw-in [2], [7]. The objective of this manuscript is to thoroughly analyse the dependency between the acting stresses throughout the sheet thickness of the part during deep drawing and the springback occurring after unloading, as well as to subsequently define an optimal blank draw-in kinematic during the forming process which will lead to an even lower amount of springback.

2. Springback simulation when forming a hat channel shaped part geometry

In order to analyse occurring stress distribution during forming of one hat channel shaped part geometry and its influence on springback appearance, simulation was prepared using the software eta/DYNAFORM 5.9 and calculated by using the FE-Code LS-DYNA. The software CATIA V5-6 was used for modelling the tool active surfaces and blank shape, as shown in Figure 1.

![Figure 1. Tool geometry used in simulation (length measurements are in mm)](image)

The modelled tool active surfaces were meshed using shell elements type Belytschko-Tsay (ELFORM 2) and were defined as rigid bodies using the material model *MAT_020 (*MAT_RIGID) in the simulation. The blank was meshed with fully integrated shell elements (ELFORM 16) considering seven integration points throughout the sheet thickness. Employed material model for blank was *MAT_125. This material model combines Yoshida’s non-linear kinematic hardening rule with material model *MAT_37. Material properties for the blank material (DP 980) with the sheet thickness of 0.97 mm were obtained from a uniaxial tensile test (according to DIN EN 6892). Furthermore, tests were carried out to determine strain dependent reduction of apparent Young’s modulus as well as parameter of the Bauschinger effect. Detailed description on material characterisation as well as modelling can be found in [5]. The applied blank holder force in this case was 300 kN.

The main reason for simulative work was to analyse the stress distribution in characteristic part areas during the forming process as well as to determine part shape deflections after the part release. After the simulation was calculated, the results obtained showed that a significant springback amount occurs after part release (Figure 2b). In order to identify potential causes for this enormous springback amount, the stresses generated in the part during forming were analysed in more detail. Thereby, it was found that the significant cause for springback represent the stresses that act over the sheet thickness (stresses acting in meridian direction of the part) at the end of the forming process. Distribution of the 1st-principal stress on the outside and inside of the part cross section at the end of the forming process is shown in Figure 2a. Here, it can be seen that in the radius area between the component flange and the sidewall, compressive stresses act on the outer side and tensile stresses on the inner side of the part. During bending and reverse bending of the workpiece over the die radius, the stresses acting in meridian direction across the sheet thickness are superimposed at the transition point between mentioned radius and part sidewall. Due to that, compressive stresses act from the inner and tensile stresses from the outer side of the part sidewall. The similar stress distribution is noticeable in the upper radius area (radius between the sidewall and part bottom), since this part area is bent in the same direction as the part sidewall due to bending and reverse bending over the die radius. As it can be seen in Figure 2a, a significant stress difference acts between the outer and inner side of the part sidewall and the radius
areas at the end of the forming process. Nevertheless, a noticeable decrease of the stress difference between the outer and inner side was observed towards the middle of the part bottom area. As already mentioned, after the part release, a stress relaxation happens to reach a state of balanced stress distribution in the part. As shown in Figure 2b, the part areas that exhibited a significant stress difference between the outer and inner part sides at the end of the forming process show the highest amount of springback after part release.

![Figure 2](image)

**Figure 2.** (a) Stress distribution on the outside and inside of the part cross section at the end of forming process, (b) part cross-section after springback

3. **Compensation of springback by forming with alternating blank draw-in**

Forming with alternating blank draw-in can be used in manufacturing of hat channel shaped parts with open ends. The main advantage of this forming approach is the significantly reduced amount of springback after release, even when using ultra-high-strength steel sheets for blank material [2], [5]. The uniqueness of this kind of forming process lies in the fact that the blank is first drawn to a defined drawing depth $h_1$ from only one side, while the blank draw-in from the opposite part side is disabled. After achieving the first specified drawing depth (end of step 1), the side of the blank draw-in is changed, as shown in Figure 3. During this kind of forming process, the workpiece areas being in contact with the punch radii are subjected to repeated bending and unbending, whereby it can be assumed that this causes a superposition of stresses acting in meridian direction throughout the sheet thickness [1]. The one-sided blank draw-in needed in this process is enabled by different restraining forces applied by the blank holder on the respective opposite side of the part. Figure 3 shows a concept of forming with two-step alternating blank draw-in.

![Figure 3](image)

**Figure 3.** Concept of forming with two-step alternating blank draw-in [1], [5]
In order to obtain both part flanges having equal size at the end of forming process, the workpiece had to be drawn to a depth of \( h_1 = 23.3 \) mm in the first forming step. Thereby, the blank draw-in was enabled from the right side of the workpiece and prevented on the opposite side. After achieving the mentioned drawing depth, the side of the blank draw-in was changed and the workpiece was formed to a final drawing depth of \( H = 40 \) mm in the second step. A detailed procedure for determining the drawing depths in each forming step when forming with alternating blank draw-in can be found in [5]. Considering the aforementioned values of drawing depth after the first and second forming step, a simulation was performed to analyse the stress distribution in the part after forming and the resulting springback amount after the part release. On the blank side, which was allowed to draw in, a blank holder force of 50 kN only was applied, as this force was sufficient to ensure contact between the workpiece and the entire punch face (punch bottom area) during forming. In order to prevent the blank draw-in from the opposite side, a blank holder force of 200 kN was applied. After the simulation was calculated, the stress distribution (in meridian direction) on the outside and inside of the part formed with two-step alternating blank draw-in as well as part cross-section after springback were evaluated (Figure 4). In this context, Figure 4a depicts the acting stresses after first and Figure 4b after second forming step. As shown in Figure 4b, at the end of the forming process, tensile stresses act on the outer side of the entire left part sidewall and compressive stresses on the inner side. This workpiece area was bent and straightened in the second forming step over die radius on the left side, whereby the stress superposition occurred at the transition between die radius and part sidewall. Furthermore, during forming in this step, reverse bending occurs at the transition between upper part radius on the left side and the bottom area, whereas the stresses initially acting in the left part sidewall are superimposed by stresses with opposite algebraic signs. On the opposite (right) part side, the area that was bent over the punch radius during the first forming step is drawn back into the part sidewall in the second forming step. Thereby, this workpiece area is bent backwards at the transition between upper radius and part sidewall once again. Because of that, compressive stresses act on the outer and tensile stresses on the inner side on the upper half of the part sidewall area at the end of the second forming step (see Figure 4b). However, the lower part of the right sidewall area was not bent back in the second step. Therefore, the stress distribution induced in the first step is effective in this area. Due to such stress distributions in this part sidewall, an s-shaped curl is formed after release, as shown in Figure 4c. Since tensile stresses were effective at the outer side of the entire left part sidewall and compressive stresses on the inner side, an outward oriented curvature appeared in the entire sidewall of the part left side after release.

![Figure 4. Stress distribution after (a) first and (b) second step during forming with alternating blank draw-in, (c) part cross section after springback [5]](image)

Considering the results obtained by the forming strategy disclosing a two-step alternating blank draw-in, further attempt was made with a three-step process to reduce the part shape deviations after load release even more significantly. Thereby, it was assumed that the upper areas of both part sidewalls must be bent and straightened again to the equal extent along the respective punch radius. To achieve this, in the third step the blank must be drawn-in from the opposite side for the half of the blank draw-in realized in the second step [5]. As already shown in Figure 4b, even though the upper half of the right part sidewall was bent and straightened over the punch radius during forming with two-step alternating
blank draw-in, a remarkable s-shaped curl occurred after part release. In order to further reduce these shape deviations of both part sidewall areas, an additional forming stage was included during last 5 mm of the drawing depth, whereby the part sidewall undergo pure plastic stretching. Here, a blank holder force of 300 kN was applied uniformly on both part flanges. In this regard, the blank was drawn-in alternating only up to a drawing depth of 35 mm. Taking into account the known values of initial blank width ($B_0=160$ mm), the blank draw-in to be realised in each step (assuming that $b_3=b_2/2=b_1$) as well as the inclination angle of the part sidewall ($\alpha$), it was possible to determine drawing depth at the end of each forming step. Thereby, the drawing depth up to which the blank must be drawn in from one side in the first step, amounts to $h_1=13.5$ mm. In the second step, the blank needs to be drawn in for the next 14.5 mm of drawing depth from the opposite side ($h_2=h_1+14.5=28$ mm). Afterwards, during the following 7 mm of drawing depth the blank is drawn in from the first side (right hand side in Figure 5) once again ($h_3=h_2+7=35$ mm). Figure 5 shows part cross section after each change of the blank draw-in side during forming with three step alternating blank draw-in and subsequent stretching of the part sidewalls [5].

![Figure 5](attachment:figure5.png)

**Figure 5.** Part cross-sections after each change of the blank draw-in side ($b_1$, $b_2$, $b_3$, $b_4$ - blank edge draw-in for the given forming step) [5]

The simulation results regarding the stress distribution on the outside and inside of the part cross-section reveal that at the end of the forming process an almost balanced stress distribution occurs in the right and left part sidewall. In the upper area of both part sidewalls tensile stresses act on the inner and compressive stresses on the outer side. As shown in Figure 6, in the lower areas of both part sidewalls, tensile stresses act in the outer volume layer and compressive stresses in the inner volume layer.

![Figure 6](attachment:figure6.png)

**Figure 6.** (a) Stress distribution on the outside and inside of the part section after the forming process with three-step alternating blank draw-in and subsequent stretching of both part sidewalls, (b) part cross section after springback [5]
After release of the part formed using the method described above, significantly smaller cross-section deviations occur compared to forming with two-step alternating blank draw-in (Figure 6b). Thereby, slight inwardly oriented curls in upper and also slight outwardly oriented curls in the lower areas of both part sidewalls can be observed.

4. Transfer of the forming process with alternating blank draw-in on a double curved hat channel shaped part geometry

In order to approve the applicability of the newly developed forming approach disclosing the three-step alternating blank draw-in for processing of more complex part geometries, the same blank draw-in kinematic was applied by forming of a double curved hat channel shaped part geometry (see Figure 7a). This was conducted experimentally using the deep drawing tool shown in Figure 7b. As shown in Figure 7b, the tool is equipped with four hydraulic cylinders (two hydraulic cylinders from each side of the punch) which were driven with a hydraulic aggregate during the forming process. These hydraulic cylinders were mounted on the blank holder support plate from the upper side. During the forming operation, they act against the tool upper plate, which is connected to a die. By applying the appropriate pressure in each hydraulic cylinder, it was possible to influence contact surface pressure between workpiece flange and each side of the blank holder and thus to control blank draw-in during forming in single stroke. Thereby, a higher pressure was provided in the corresponding two hydraulic cylinders on the side of the part where the blank had to be drawn in during forming. Experiments were conducted with a single action servo driven press having a 1500 kN die cushion. The die cushion was used to provide the total blank holder force. Here, a blank holder force of 1000 kN was applied during forming of the part geometry shown in Figure 7a. In order to enable blank draw-in from only one side of the part during the specified drawing depth, a pressure that ensures acting force of 200 kN needed to be generated for each of the two hydraulic cylinders on the respective side. In each of the two hydraulic cylinders on the opposite side, a pressure ensuring a force of 0,5 kN was generated.

![Figure 7. (a) Part geometry, (b) tool used in experiment](image)

After forming, the obtained parts were digitized by using the optical measurement system GOM ATOS 5M. Figure 8a shows shape deviation for a whole part geometry obtained by forming with alternating blank draw-in. Despite the high strength of the blank material used, relatively small part shape deviations occurred after the part release. In order to demonstrate the advantages of this new deep drawing strategy regarding to springback amount, several parts were conventionally deep drawn with the same tool. During conventional deep drawing, a blank holder force of 1000 kN was homogeneously applied onto both part flanges. Hydraulic cylinders mentioned earlier were out of operation in this case. Figure 8b shows occurred part shape deviations after conventional deep drawing. To ensure
comparability of the results obtained, springback amount after part release was evaluated in three characteristic cross-sections by comparing the part shape deflections with the reference geometry of the part. Two cross-sections were defined near the part’s end, 220 mm away from the middle of the part. Third cross-section was defined in the middle of the part and is oriented perpendicular onto the tangent of the part longitudinal curvature. When comparing the results shown in Figure 8, it can be stated that after forming with alternating blank draw-in a significantly smaller springback amount occurs compared to conventional deep drawing.

Figure 8. Measured part shape deviations; (a) after forming with three-step alternating blank draw-in and subsequent stretching of part sidewalls, (b) after conventional deep drawing

5. Conclusion

In this paper, a new process design for springback compensation based on the superposition of stresses acting in the meridian direction of the formed part was presented. Following conclusions could be drawn:

- Alternating blank draw-in during forming of sheet metal part causes repeated bending and unbending (reverse bending) of the part sidewall and bottom area over the punch radii.
- Simulation results showed that such repeated bending and reverse bending of workpiece during forming causes a superposition of acting stresses throughout the sheet thickness in meridian direction of the component.
- Furthermore, it was shown that it is possible to define an optimal blank draw-in kinematics during forming for each considered blank edge side, which leads to a relatively low springback after release of the part.
- This kind of forming process was successfully transferred to an example of a double curved hat channel shaped part geometry. For this purpose, a tool was equipped with additional hydraulic cylinders in order to be able to control the blank draw-in during forming in one single stroke.

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