Approaches for springback reduction when forming ultra high-strength sheet metals

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Abstract. Nowadays, the automotive industry is challenged constantly by increasing environmental regulations and the continuous enhancement of standards with regard to passenger’s safety (NCAP, Part 1). In order to fulfil the aforementioned requirements, the use of ultra high-strength steels in research and industrial applications is of high interest. When forming such materials, the main problem results from the large amount of springback which occurs after the release of the part. This paper shows the applicability of several approaches for the reduction of springback amount by forming of one hat channel shaped component. A novel approach for springback reduction which is based on forming with an alternating blank draw-in is presented as well. In this investigation an ultra high-strength steel of the grade DP 980 was used. The part’s measurements were taken at significant cross-sections in order to provide a qualitative comparison between the reference geometry and the part’s released shape. The obtained results were analysed and used in order to quantify the success of particular approaches for springback reduction. When taking a curved hat channel shaped component as an example, the results achieved in the investigations showed that it is possible to reduce part shape deviations significantly when using DP 980 as workpiece material.

1. Introduction
One of the most important tendencies in nowadays automotive industry is the development of lightweight car body structures due to increasing demands regarding fuel consumption and carbon dioxide emissions. Car body parts manufactured from ultra high-strength steels (UHSS) have an increased crash performance and are contributing to the improvement of the passenger’s safety accompanied by noticeably reduction of vehicle weight [1]. It is necessary to emphasize that the steels mentioned before do have very high levels of tensile strength at relatively low values of elongation at fracture as well as relatively low anisotropy values. These mechanical properties mean that UHSS usually do have bad formability, a strong tendency towards wrinkling, and a tremendous elastic recovery or springback after forming. While such new steel alloys are becoming increasingly stronger, they simultaneously are more difficult to form into automotive parts. Larger amounts of springback are affected by many parameters such as sheet metal thickness, blank shape, level of ultimate tensile strength, hardening rate, Young’s modulus, method plan, tool radii, tool clearance, and forming conditions as well. Springback in general can appear in several forms: angle change, sidewall curl, radii change, and twisting or torsion [2,7] (Figure 1). Angular change is the angle created between reference geometry and after forming obtained part sidewall shape. Sidewall curl is the curvature created in the sidewall of the part and usually occurs as a result of bending and unbending when a
blank is deep drawn over die radius or through draw beads. Twist or torsion is caused by torsion moments in the longitudinal cross-sections of the part and it is more pronounced if the cross-section changes along the parts longitudinal direction. Besides these parameters inhomogeneous strain distribution along the formed part together with the elastic-plastic behavior of the workpiece material affects springback occurrence too. Due to that, the use of UHSS is actually increasing existing problems in manufacturing processes regarding quality control requirements and process robustness. In order to form these materials with a die, it is necessary to define the forming process with new boundary conditions, but keep the manufacturing costs as low as possible.

![Figure 1. Different kinds of springback](image)

There are different strategies which may contribute to reduce the springback amount after forming. Some of them are taking into account the application of geometrical methods such as the implementation of stiffening features into the part shape as well as addendum and binder surface modifications [3,6]. The other possibility which may contribute to achieve the final goal in terms of dimensional accuracy considers a range of methods based on modifying the stress-strain conditions in the part by appropriate arrangements such as additional restraining forces or even adjustable and controllable blank holding forces which are time dependent to punch stroke travel [2,4].

In this work, several, already known strategies for the reduction of springback were tested by forming one curved hat channel shaped component. First, the possibility to reduce springback was simulated using an additional operation (restrike) in the forming process. For this purpose, the vertical stiffening beads were embossed into the part sidewalls after the deep drawing process using appropriate tool shapes in one additional forming step.

The possibility to reduce the springback amount was investigated experimentally by applying different blank holder forces. The required experimental try-outs for this purpose were provided at the servo driven press AIDA.

At the end of this work, a new approach for springback reduction when forming ultra high-strength steel sheets is presented. The new approach implies the forming with the alternating blank draw-in. After such a forming process, the part geometry has an almost negligible deviation after the release with regard to the required part shape geometry. Forming with the alternating blank draw-in was tested experimentally as well.

2. Sheet material properties

HCT 980 X steel sheet (regarding to DIN EN 10338 standard) is selected as blank material for this investigation. The material mentioned belongs to a group of high strength dual phase steel grades. This material consists of a ferritic matrix including a hard martensitic second phase in the form of islands which generally cause relatively high strength level. Due to that, material HCT 980 X has very high values of ultimate tensile strength and yield strength, while the value for elongation is very small. HCT 980 X material has anisotropy parameters smaller than 1. Material properties for steel grade HCT 980 X are shown in Table 1.
### Table 1. Material properties for steel grade HCT 980 X

| Material type | HCT 980 X |
|---------------|-----------|
| Thickness [mm] | 1.15      |
| Poisson’s ratio | 0.28     |
| Young’s modulus [GPa] | 210     |
| Anisotropy parameters considering to rolling direction | |
| $r_0$ | 0.735 |
| $r_{45}$ | 0.989 |
| $r_{90}$ | 0.64 |
| Yield strength [MPa] | 745 |
| Ultimate tensile strength [MPa] | 1070 |

### 3. Simulation of springback

Springback results from elastic recovery of the part and can be defined as a shape dimensional change which occurs during unloading when tools are removed in the forming process. In order to analyse springback behaviour of UHSS, various simulations for one curved hat channel shaped part geometry were provided (Figure 2a). The analysed part can be divided into two straight areas having a length of 125 mm and two curved areas with the radius of 325 mm. The drawing depth of the part amounts to 40 mm. The deep drawing process and springback were simulated using the FE-Code LS-Dyna. The modelling of the tool and the preparation of active tool surfaces (Figure 2b) for the simulation was performed using the software CATIA V5. The tool active surfaces were meshed with the shell elements type Belytschko-Tsay Shell (ELFORM 2). The blank was meshed with the fully integrated shell elements (ELFORM 16) taking into account nine integration points through the sheet thickness. During meshing it was paid attention to the existence of approximately one node per 5° of turn angle at the tool radius [5]. In the simulation, the material model *MAT_125 was used. The applied blank holder force was 1500 kN, while the friction coefficient was determined experimentally and amounts to 0.07.

| Forming conditions |
|-------------------|
| Blank holder force [kN] | 1500  |
| Friction coefficient | 0.07  |
| Die radius [mm] | 6    |
| Punch radius [mm] | 7    |

Figure 3 shows the calculated stress distribution for different integration points after the forming process. High tensile stresses dominate within integration point 1 (outer part fibre) in the part sidewall. Solely at the transition between punch radius and sidewall in convex part area compressive stresses are arising. Due to the superposition of bending stresses and the shifting of neutral fibre, integration point 5 in the part sidewall shows tensile stresses. In integration point 9 (inner layer) compressive stresses generally arise. Tensile stress was observed at the transition between punch radius and sidewall in the convex part area.

![Diagram of springback simulation](image-url)
After the part removal from the die cavity this kind of stress is released. The fibres which showed tensile stresses tended to be shorter, while fibres with the compressive stresses were elongated after the release. This will lead to the arising of the part sidewall curl in outer direction. The mentioned change of the part shape appears especially in the straight and concave part areas.

The calculated springback amount is shown in Figure 4a. It can be noticed that the very high part shape deviation in the lower sidewall area occurred (6 mm). This deviation represents the cumulation of the sidewall curl and angle change. Sidewall curl might be understood as the result of the bending stresses which occur due to bending and unbending at the die radius as well as additional tensile stresses in the part sidewall which result from stretching during deep drawing. Figure 4b shows the stress distribution in z direction for one selected finite element at the part sidewall during deep drawing. It can be seen that after the deep drawing process, a large difference in stress amount between outer (IP1) and inner part fibre (IP9) occurs (more than 2000 MPa). Due to this stress difference a large curl of the sidewall has occurred.

3.1. Reduction of springback through a restrike operation

As aforementioned, the sidewall curl, indeed, has a tremendous influence on the total amount of springback. With the aim to reduce the occurred sidewall curl, a measure was simulated which implies an increase of the part stiffness through additional embossing of the corresponding features into the sidewall shape. The method plan used to achieve the complete part shape in simulation is defined as follows: deep drawing, restrike and springback (release of the part). Regarding to the defined method plan, the simulation of deep drawing was created (considering the forming conditions given in Figure 2) and calculated first. After the deep drawing simulation was finished, the released part was used as a
workpiece for a second defined forming step – the restrike operation. As can be seen in Figure 5, the tool design for the restrike operation was based on a crash forming concept (without blank holder). Punch and die were modelled with the appropriate vertical stiffening features placed in the part sidewall. The width of the stiffening features amounts to 10 mm and the depth was modelled with 1 mm (Figure 5). The distance between particular stiffening beads is 40 mm. In the second forming step (restrike), first the part was positioned appropriately onto the punch bottom surface. Afterwards the die was moved down until the defined clearance with the punch was reached (sheet thickness + 10%). During this forming step, the corresponding stiffening beads or features were formed at the part shape. Resulting from this, the acting stresses in the part were changed. When comparing to the results presented in Figure 4a, this measure has contributed to springback reduction.

Figure 5. Simulation of restrike operation – method plan

Figure 6b shows the stress distribution during the restrike operation for the finite element which was defined at the same place as in the deep drawing operation. It is apparent that the large stress difference that occurred after the deep drawing between outer and inner part fibre will be reduced significantly during the restrike operation. This reduction of the stress difference has resulted in a smaller amount of springback (Figure 6a). The highest measured shape deviation in the lower part sidewall area now only amounts to 2 mm.

Figure 6. (a) Springback amount after restrike operation, (b) stress distribution in the part sidewall for selected finite element (IP1- outer part fibre, IP5- middle part fibre and IP9-inner part fibre)

4. Influence of blank holder force on springback
To investigate the influence of the blank holder force on the springback amount, numerous experimental tests were performed. For that purpose, three values of the blank holder force were analysed (300 kN, 900 kN and 1500 kN). For each applied blank holder force, five parts were formed at the press. Experiments have been performed at the servo driven press AIDA with a nominal force of 6300 kN and blank holder force of 1500 kN. The specimens were lubricated with 1.5 g/m² of the oil M100 produced by the company Georg Oest Mineralölwerk GmbH & Co. KG. After forming, part shape deflections were measured using the optical measurement system (GOM ATOS), and the results were compared with the reference geometry (CAD of the part). In order to compare the obtained results in an adequate manner, the part shape deviations were evaluated in three characteristic sections. Two cross sections (section 1 and 3) were defined near to the part end, 220 mm away from the middle of the part. Section 2 is located in the middle of the part and is oriented perpendicular onto the tangent
of the part curvature. In these defined cross sections, angle change from both sides (left and right side) was evaluated. Figure 7a shows the deep drawing tool assembled to the servo press as well as the parts which were deep drawn in the experiment (Figure 7b). The defined measurement concept is shown in Figure 7c.

**Figure 7.** Experimental setup; (a) tool for deep drawing, (b) one of the parts formed in experiment, (c) measurement concept

Figure 8 shows measured angle change of the parts regarding different, applied blank holder forces. The highest angle change for a blank holder force of 300 kN is located at section 1 from the right side and reaches values bigger than 15°. By applying higher blank holder forces, the angle change can be reduced. The highest value of angle change for a blank holder force of 1500 kN is measured in the same section as described before and amounts to approximately 13.7°. When comparing obtained results being gained by different blank holder forces (300 kN and 1500 kN), it can be detected that in case of higher applied blank holder forces the angle change will be reduced by approximately 2°.

**Figure 8.** Influence of the blank holder force on springback

5. **Pendular drawing - a novel approach for springback reduction**

Forming with an alternating blank draw-in or pendular drawing shows a great potential for the successful reduction of springback. The uniqueness of this process lies in the fact that during forming the blank is drawn up to a specific drawing depth from only one side, which means that blank draw-in is only allowed from one side. After achieving the defined drawing depth (e.g for two-step forming, half of the total drawing depth), the blank will be drawn from the opposite side of the part. The workpiece area that is formed over the punch radius in the first step is located at the part bottom will be drawn back into the part sidewall in a second step. Resulting from that it comes to a repeated “bending and unbending” over the punch radius during this forming process. Forming with the alternating blank draw-in is shown schematically in Figure 9 (with two steps in Figure 9a and with three steps in Figure 9b).
5.1. Analysis of the forming with the alternating blank draw-in

As mentioned in chapter 3, the bending stresses are one of the main reasons for the occurring of the sidewall curl as well as other kinds of springback. During conventional deep drawing, the corresponding workpiece area will be bent over the punch and the die radius only once. Bending over the die radius will result in a significant difference of stress amount between inner and outer side of the part wall. When forming with the alternating blank draw-in (pendular drawing) considering the phenomenon of the repeated bending and unbending over the punch radius, the difference in stress amount from inner and outer side of the part will be reduced. In order to better understand this phenomenon, forming with the alternating blank draw-in of the part shape geometry described before was simulated. For the first 20 mm of the drawing depth the blank is drawn-in just from the right side, and for the remaining 20 mm of the drawing depth the blank is drawn-in from the opposite (left) side. The alternation of the blank draw-in was influenced by applying the different friction conditions from the left and right side of the part taking into account the defined drawing depth and appropriate blank side. In the simulation, the friction coefficient between tool surfaces and blank for the blank side with the allowable draw-in, was defined with the value of 0.07. For the opposite blank side (not movable), the value of the friction coefficient was 0.17 and the applied blank holder force was 1500 kN. After the simulation was finished, the stress distribution (z-stress) was evaluated through the sheet thickness for one selected finite element placed in the middle of the part sidewall after first and after second forming step (Figure 10).

![Figure 9. Forming with the two step (a) and three step (b) alternating blank draw-in](image)

![Figure 10. Stress distribution (z-stress) through the sheet thickness after first and second step in case of forming with the alternating draw-in](image)
It can be seen that a significant difference in stress amount from the inner and outer part side for the chosen element occurs after the first forming step (from the inner part side the value of stress in z direction amounts to -1255.3 MPa while from the outer part side its value is 1357.9 MPa). This tendency of stress distribution in the part sidewall is comparable with the stress distribution, which normally occurs in conventional deep drawing. After second forming step, this difference in the middle of the part sidewall was reduced significantly (633.4 MPa from the inner part side and 588 MPa from the outer part side), see Figure 10.

It is necessary to say that the part sidewall undergoes a combined bending and drawing process during the classical deep drawing. After the classical drawing, tensile stresses at the outer part fibre and compressive stresses at the inner part fibre can occur, depending on the size of the die radius. During the release of the part, the point of time when the part is taken out of the die cavity, stress relaxation happens. Through the sheet thickness, the asymmetrical stress distribution generates one bending moment, which generally results in the curved part sidewall. During this action, the part fibres with the acting compressive stresses tend to elongate, while the part fibres with caused tensile stresses tend to be shorter.

It was mentioned that forming with an alternating blank draw-in results in a repeated bending and unbending of the workpiece over the punch radius. Due to this phenomenon, a stress superposition happens in the area, which is placed in the part sidewall at the end of forming process. The acting stresses from the outer and inner part fibre will have approximately the same value (Figure 10). Due to a significantly reduced difference in stress amount from the inner and outer part fibre, a smaller amount of springback can be expected.

5.2. Experimental try-out of forming with alternating blank draw-in

In order to verify the opportunities that were noticed in simulations, this kind of forming process was tested experimentally by using the tool shown in Figure 7a, and springback results were compared with the results obtained by conventional deep drawing. The mentioned tool was designed for conventional deep drawing performed on a single action press with a cushion. Because of that one of the possibilities to influence the blank draw-in was alternating lubrication of the appropriate blank side. This means that in case of two-step forming with alternating blank draw-in, just one side of the blank was lubricated (with 1.5 g/m² of the oil M100) while the second side was dry. The applied blank holder force for each step of this forming process was 1500 kN. For the first step, the forming depth on the press was defined to be 20 mm and due to differences in friction values only one side of the blank (the lubricated one) was drawn-in during the press stroke. After forming with the first defined depth, the part was prepared for the second step. Then, the second or opposite side of the blank was lubricated and the remaining oil from the first side was removed. In the second forming step, the opposite side of the blank (left in this case) was drawn-in. The obtained part shapes after the forming process were digitized using the optical measurement system GOM ATOS. An evaluation of the angle change at the cross sections that were defined earlier and part shape deviations in general was performed using the software GOM Inspect (Figure 7c).

Figure 11 shows the measured angle changes for the part which was formed using conventional deep drawing (applied blank holder force was 1500 kN) and for two parts which were formed using the two-step and three-step alternating blank draw-in. It becomes apparent that the part formed by conventional deep drawing has very high part shape deviations. The highest angle change was measured at the cross section 1 from the right side and amounts to 13.7°. Taking into account all angle changes at the defined cross sections for the formed part by conventional deep drawing, the average angle change is higher than 10°. The part formed using the two-step alternating blank draw-in shows significant smaller angle change for the observed cross sections. The highest measured angle change is located at the third cross section from the right side and amounts to 6.3°. It must be mentioned that the angle changes in every other cross sections are smaller than 4°. Furthermore, at the first cross section, the part sidewall from the right side has been deformed in opposite direction. Due to that, the angle change of -1.98° occurred.
Figure 11. Influence of the blank draw-in on the angle change for applied blank holder force of 1500 kN (experimentally obtained results)

Figure 12 shows the deviation between the obtained part shapes according to the forming processes and reference geometries that were defined earlier (corresponds with the results shown in Figure 11). It is noticeable that the parts formed with the two-step alternating blank draw-in have obtained the curl in opposite direction (inwardly) at the part wall which is located from the side which was drawn-in first, (Figure 12b). This phenomenon can be explained due to fact that the part area which was bent over the punch radius in the first step was drawn in the second step back and is located approx. in the middle of the part sidewall. In this case, the stresses caused in the first forming step were superimposed in the second step. In order to minimize these failures, a forming strategy with three step alternating blank draw-in was tested. For this purpose, in the first 10 mm of the forming depth, the blank was drawn from the right side. During the next 20 mm of the press stroke, the blank was drawn from the opposite (left) side. And at the end, for the last 10 mm, the blank was drawn from the right side again. This measure has contributed to reducing of visible bulge or curl in the part bottom area (Figure 12c). When comparing the results obtained with the conventional deep drawing, it can be noticed that the angle change in all considered cross sections was reduced to approximately 3°. But for most of the observed cross sections, the obtained angle change is bigger than in case of forming with the two-step alternating blank draw-in.

Figure 12. Part shape deviations measured by the optical measurement system GOM ATOS
(a) after conventional deep drawing, (b) after two step forming, (c) after three step forming
6. Discussion

The results of this investigation present the applicability of different approaches for springback reduction. The simulation results for one curved hat channel shaped component showed a tremendous amount of springback, when using HCT 980 X as workpiece material. The significant difference in stress amount from inner and outer side of the part sidewall was identified as one reason for the mentioned amount of springback.

In order to reduce the stress difference and the springback amount, the tool geometry with numerous stiffening beads in the part sidewall was defined first (shown in Figure 5). This tool geometry was used to restrike the part shape that was obtained after the deep drawing process. After the restrike operation, the simulation results showed that the difference in stress amount from inner and outer part side in the observed area was reduced significantly. This appearance led to a reduced size of the sidewall curl and to a reduced total springback amount in general. In order to experimentally validate this kind of approach for springback reduction, the corresponding tool parts will be manufactured in this project.

Furthermore, numerous experiments were carried out with the available tool in order to investigate the influence of the blank holder force on the occurrence of springback. The obtained results showed that the level of applied blank holder force has a low influence on the occurrence of springback. In case of higher applied blank holder forces the springback amount will be slightly reduced. In order to reduce the angle change by 2° for the used part geometry it is necessary to increase the blank holder force by more than 1000 kN.

In this investigation, the forming with alternating blank draw-in (pendular drawing) was analysed as well. The simulation results showed that the difference in stress amount from inner and outer part side will be lower in case of forming with the alternating blank draw-in in comparison to conventional deep drawing, which means that this kind of forming process causes a superposition of the acting stresses in the part sidewall. This phenomenon led to a significant reduction of springback when forming steel grade HCT 980 X.

7. Conclusion

In this paper, the success as well as the applicability of several approaches to reduce springback when forming curved hat channel shaped components was analysed. Meanwhile, a new approach to reduce springback when forming curved hat channel shaped components was proposed. Forming with an alternating blank draw-in has shown a promising technique for springback reduction in forming of one hat channel shaped component out of steel grade HCT 980 X. The experimental results showed that after forming with the two-step alternating blank draw-in, the part shape deviations were reduced significantly (more than 50 %) in comparison to the obtained shape deviations that occurred after the conventional deep drawing.

The additional conclusions which can be drawn from this investigation are:

- Using an additional restrike operation during the forming process can be a helpful technique for springback reduction. Simulation results showed that embossing the part sidewall with the appropriate beads in the restrike operation minimizes the stress difference between inner and outer part side and leads to a reduced amount of springback.
- The blank holder force had a slight or almost negligible influence on springback occurrence when forming the hat channel shaped component. Experimental results showed that a higher blank holder force leads to a smaller amount of springback. The parts formed with a blank holder force of 1500 kN have shown an approximately 2° reduced angle change in comparison to the results obtained by forming with a blank holder force of 300 kN.
- When comparing all approaches analysed in this work, it was possible to achieve the most precise part shape geometry, which had the smallest amount of springback, by forming with the alternating blank draw-in.
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