Influence of the forming process on springback

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Abstract. The use of advanced high-strength steels (AHSS) is associated with increased springback and represents a great challenge for today's press shops with regard to the dimensional accuracy of cold-formed sheet metal parts. Springback, its appearance and characteristics are mainly dependent on the stress state introduced by the forming process and part geometry before opening the tools. With the aim of determining the influence of the forming process on springback, sheet metal forming simulation is used in this contribution to analyze a hat profile from a high-strength dual-phase steel (DH1000) by three different forming processes: crash forming, bending and drawing. For this purpose, the stresses generated by these processes and resulting springback are examined considering the respective forming history. The results show the strong influence of the material flow controlled by the process and tool geometry on the stress state before springback, which leads to significant differences in the springback of the hat profile among the forming processes: springback increases from crash forming to bending and drawing.

1. Introduction

The appearance and extent of springback are determined by the stress state, stress distribution and magnitude of elastic deformations in the direction of the sheet thickness. In this context, evenly distributed elastic stresses over the sheet thickness causes an uniform contraction or expansion in the respective cross-section upon unloading. In contrast, unloading of unevenly distributed elastic stresses over the sheet thickness leads to unfolding or curvature in the respective cross-section [1]. Compared to low alloyed steels, springback is significantly increased by the use of advanced high strength steels (AHSS) [2]. The reason for this are the mechanical properties such as higher work hardening with correspondingly higher yield stresses and consequently higher elastic strains [3]. The forming process determines the stress states and stress distribution in the part, which is why special attention must be paid to its selection with respect to springback. Frequently used demonstrators, such as u-bend or hat-shaped profiles, are formed by dominant bending stresses due to their geometry. Accordingly, springback dominates due to unevenly distributed stresses across the sheet thickness. In the press shops, hat-shaped profiles are produced by classical forming processes like drawing [4], bending [5] and crash forming [6]. For example, a hat profile produced by drawing shows a significant curvature of the part walls. This is a result of an intensive and alternate bending of the retained material as it is moved over the die radius into the part side wall [6]. In contrast, the intensity of the alternate bending as well as the curvature of the side wall can be reduced without restraining the sheet by a blank holder, as in crash forming [7]. Accordingly, the material flow associated with the process must be of great importance with respect to springback. Hence, the influence of the forming process on springback of a hat profile is determined in this contribution. For this purpose, the material flow is analyzed within the forming history using sheet metal forming simulation for the forming processes drawing, bending and crash forming. Subsequently, the resulting stresses from the different processes are evaluated with regard to springback. Finally, a complex hat profile based on geometrical features of longitudinal members is produced by bending and crash forming to confirm the determined influence of the forming process on springback.

2. Scope of investigations

2.1. Parts and process tools

Figure 1 (a) shows the hat profile "geometry 1" used exclusively for the simulation in AutoForm R8.0, together with its basic dimensions. The embossing of the hat profile represents a connection surface for assembly in a serial part. In figure 1 (b), characteristic features of longitudinal members of a vehicle's body-in-white are combined in "geometry 2": inclinations in the bottom and flange areas as well as steps on the flange due to its structural position or stiffness function. "Geometry 2" is analyzed to ensure the prediction accuracy of the forming simulation with regard to the springback calculation within the respective process.

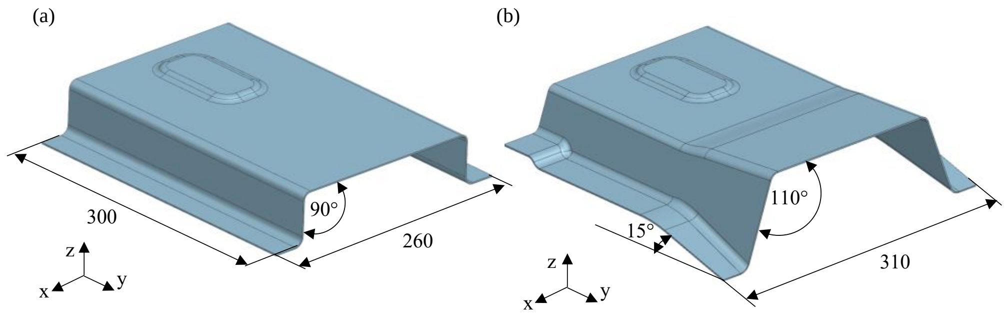

Figure 1. Hat profile "geometry 1" used for investigations in forming simulation (a), hat profile "geometry 2" used for experiments (b).

The forming processes and required tool parts are shown in figure 2. The tool set for crash forming consists of two tool parts, die and punch, between which the blank is crashed. The bending process is characterized by two operating steps, for which a four-piece and three-piece tool is used, as shown in figure 2 (b). In the first forming step, a blank holder forms the bottom of the part and simultaneously retains the sheet for the bending process. Then, the flanges are formed in a similar way to v-bending, for which the side walls initially have an angle greater than 90° to the bottom of the part, resulting in a larger radius between the bottom and the wall. In the second forming step, the walls are formed by bending while the bottom is retained by the blank holder. In the drawing process, the tool consists of four parts as shown in figure 2 (c). In contrast to the two previous processes, the target geometry is located on a stepped punch. For this reason the blank holder always acts on flat surfaces outside the target geometry. In this way, firstly, the intensity of alternate bending during forming the side walls is reduced, and secondly, flat blank holder surfaces also result for geometry 2 even with inclined flange areas. During the process, the sheet is drawn by holding the flange areas. At the same time, a pre-leading blank holder 2 reduces the strong curvature of the sheet in the bottom area of the part and is closed until the remaining drawing depth is formed. For all three processes the blank is located in the respective tools of the forming processes via two pilots.

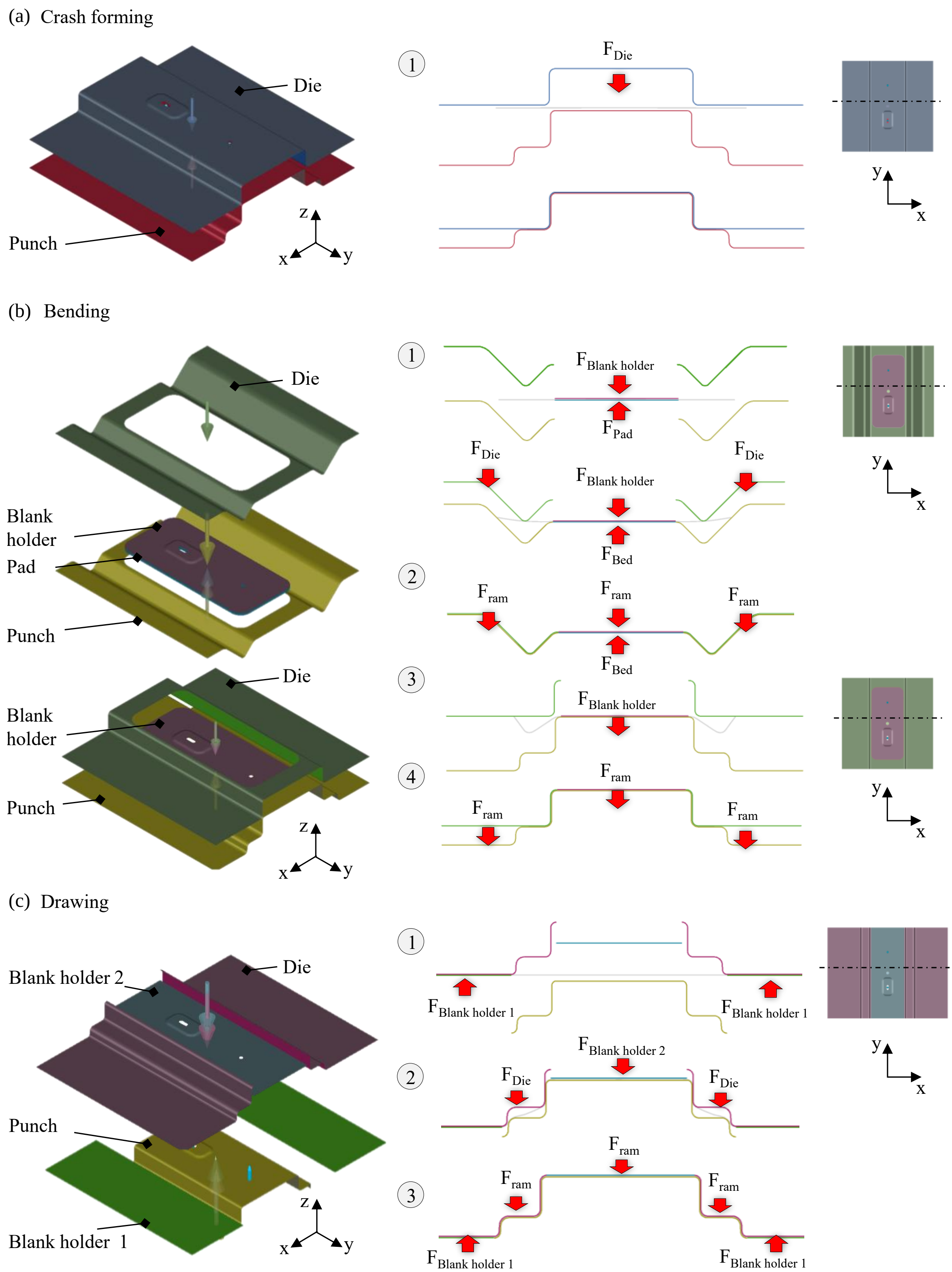

Figure 2. Tool set and process design for crash forming (a), bending (b) and drawing (c).

In comparison to previous studies, design and definition of the forming processes may differ. For this reason, Table 1 summarizes and classifies the investigated forming processes based on their tool set and process feature.

Table 1. Classification of the forming processes for based on the tool set and process features.

Process	Tool set	Process feature
Drawing	Die, Punch, Blank holder(s)	Controlled forming of sheet metal by blank holder(s)
(Wipe) Bending	Die, Punch, Counter punch	Controlled forming of sheet metal along straight axis
Crash forming	Die, Punch	Uncontrolled forming due to missing blank holder; sheet metal is "crashed" between tool parts

2.2. Measurements

In the simulation, springback calculation is conducted by two pilots and additional acting clamps as shown in figure 3 (a). The clamps prevent the part from tilting. In order to exclude any influence of the clamping force on springback, an internally defined force limit of the clamping force is taken into account.

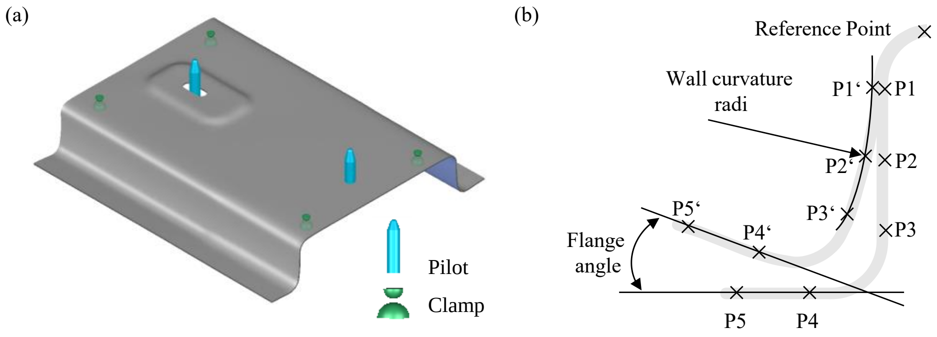

Figure 3. Measurement conditions for springback calculation (a), determination of the angular deviation and wall curvature schematically (b).

In addition, the meshes of the parts before and after springback are exported from the simulation into CAD for the determination of form deviations in a cross-section. To determine the flange angle deviation and curvature of the side wall, five points are set on the reference curve starting from a reference point. These are also transferred to the curve of the deviating component via their distances from the reference point. The points P1-P3 are used to determine the wall curvature. Since this can be different for each component, the points are adjusted for each component in such a way that the closest possible approximation of the curvature can be ensured. Points P4 and P5 as well as P4' and P5' form the lines for determining the angular deviation at the flange.

2.3. Simulation conditions

The material properties of the dual-phase steel used, named CR700Y980T-DH GI50/50-U (trivial name DH1000) according to VDA 239-100, are adjusted as well as supplemented in an existing material map with results from uniaxial tensile and tension-compression tests [8]. The isotropic kinematic hardening is modeled by the AutoForm model, which is based on the approach of Kubli et al [9]. In addition, the corresponding friction model from TriboForm has been imported into AutoForm R8.0, allowing the Coulomb friction coefficient to be calculated as a function of the local contact pressure, relative sliding velocity and strain of the sheet material during the process [10]. In particular, the consideration of isotropic kinematic hardening and the application of the advanced friction modeling by TriboForm have shown a significant enhancement of the springback prediction for a hat profile [11]. Therefore, sufficient accuracy of the simulation can be assumed in this study as well. The validation of the springback prediction is performed with geometry 2. More information about the simulation conditions can be found in Table 2.

Table 2. Simulation setup.

Material	DH1000	Element type	Elastic-plastic shell
Nominal sheet thickness	1.5 mm	Maximal element size	10 mm
Extrapolation hardening curve	Gosh	Refinement level	6
Yield criterion	Barlat	Forming velocity	35 mm/s

3. Results

3.1. Material flow and stress distribution

As already mentioned, the material flow during forming is determined by the tool set and process design. Therefore, the forming processes are compared with respect to the material flow and the currently acting stresses on a cross-section in several time steps. In the stress representation, the stresses in the rolling direction (r-axis) are selected due to their dominance during forming. In Figure 4 (a) it can be seen that the material initially bulges strongly during crash forming due to missing blank holders, which means that more material is stored in the bottom region. In this way, tensile stresses are introduced on the upper side and compressive stresses on the lower side in the bottom region. Subsequently, the excess material in the bottom is partially drawn into the side walls by the die, as shown in figure 4 (b).

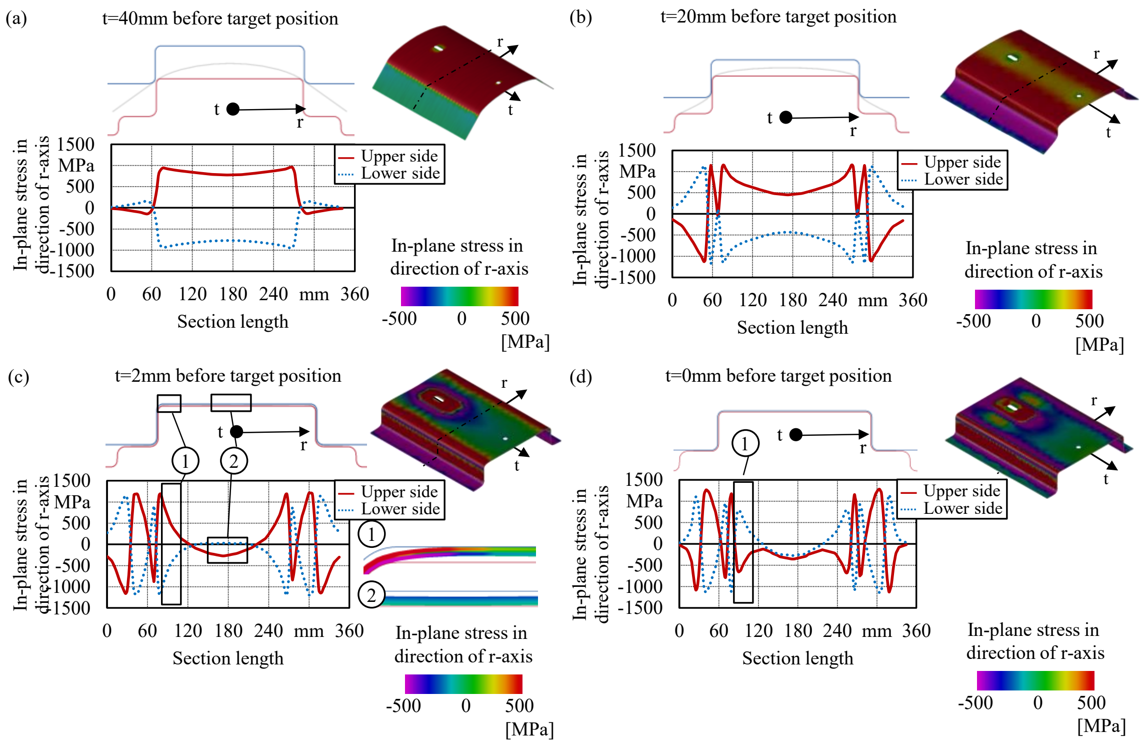

Figure 4. Images of crash forming process and stress state as well as stress curves on upper and lower side of blank for tool positions 40mm (a), 20mm (b), 2mm (c) and 0 mm (d) before target position of process tools.

At the same time, the sheet in the flange areas is moved freely over the radius into the sidewall. In the upper and lower areas of the wall, the sheet is bent alternately. This is illustrated in the stress profile by the alternating stress amplitude in the area of the wall and the radii, which is more pronounced in the further process step, see figure 4 (c). As the process progresses, the excess material in the bottom of the part is displaced towards the radii with the initial contact of the die. As shown in the detailed picture, tensile stresses continue to prevail near the radius on the upper sheet side and compressive stresses on the lower sheet side. At the end of the process, these stresses are reversed. In analogy to alternate bending at the part walls, the side of the sheet stressed by tension is superimposed with compressive stresses and the side previously stressed by compressive stresses with tensile stresses. The stresses after crash forming are concentrated in five areas of the part (high amplitudes in the stress curve), in which inverse stresses are introduced across the sheet thickness by bending and alternate bending.

In the first step of the bending process, the material is retained at the bottom of the hat profile and the embossing is freely formed. The subsequent bending is performed by the contact of the tool radii, which form the radius between the part's flange and wall. Bending stresses appear at the radii as shown in the stress profile in figure 5 (a). The compressive stresses in the center of the part are caused during the forming of the embossment. In the second forming step, the bottom of the part is reshaped by the blank holder and is held in position for the subsequent process. Afterwards the large radii between bottom and wall of the preformed geometry is formed into smaller radii by the bending die, causing the preformed component walls to collapse almost completely in the direction of the punch wall. In the stress profile on figure 5 (b), this becomes apparent through narrower amplitudes in the area of the radii.

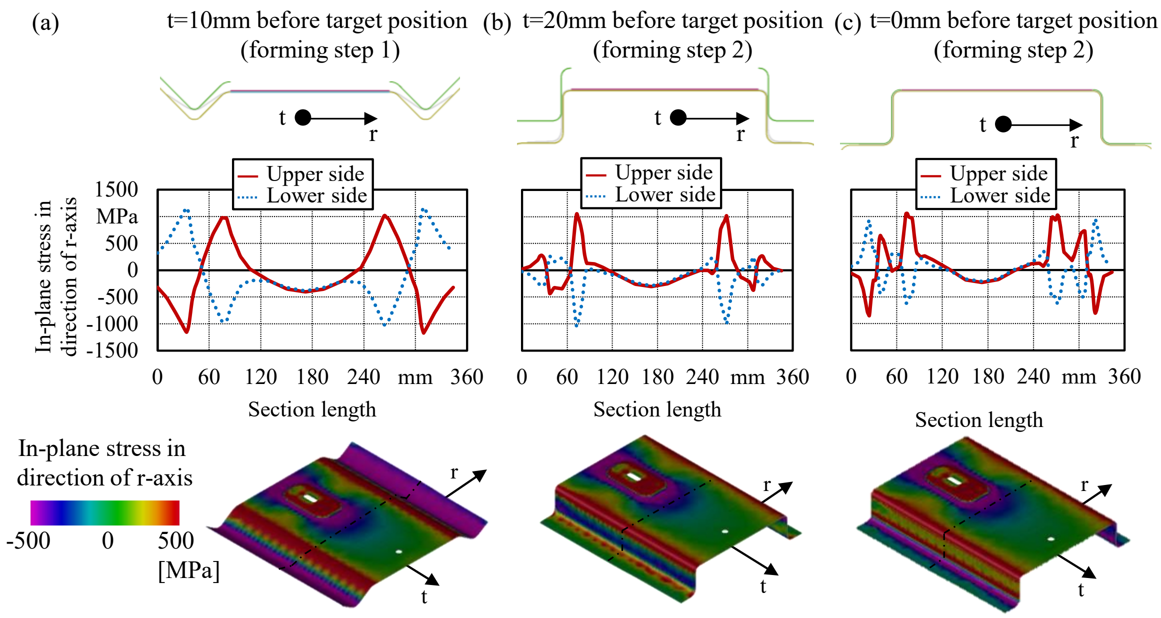

Figure 5. Images of the bending process and stress state as well as stress curves on upper and lower side of blank for tool positions 10mm (a) before target position of process tools in forming step 1, 20mm (b) and 0 mm (c) before target position of process tools in forming step 2.

When the dies are closed completely, the upper radii are completely formed and the flanges and lower component radii are calibrated as well. In this process the stresses are almost unchanged compared to the previous time step, except for the slight stress superposition near the lower radius due to the remaining shaping. After the two-step bending process, the stresses on the component are mainly concentrated in the radii.

The material flow in the drawing process is controlled by the acting blank holders 1 and 2. Firstly, the sheet is drawn over the punch while it is held outside by the blank holder 1. In the meantime, the curvature of the sheet at the bottom of the part is reduced by a pre-leading blank holder 2. Compared to the forming processes above, a subsequent trimming of the oversized blank after drawing is required to represent the target geometry. Due to the stepped punch, the material is alternately bent in the areas of the flange as can be seen in the stress changes in figure 6 (a) and (b). With the superimposed tensile stresses due to the acting blank holder 1, the following stress distribution results when the tools are closed: The bottom area is characterized by tensile stress distributed over the entire sheet thickness. Near the radii, the tensile stresses are increased successively until inverse stresses are formed on the upper and lower side of the sheet due to single or alternate bending.

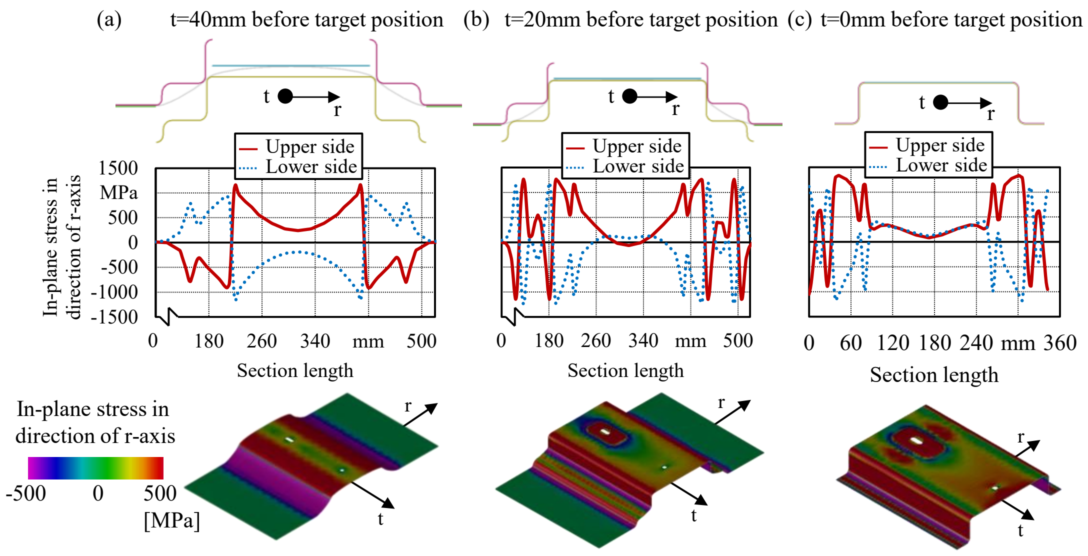

Figure 6. Images of the drawing process and stress state as well as stress curves on upper and lower side of blank for tool positions 40mm (a), 20mm (b), and 0 mm (c) before target position of process tools.

In the following, the forming processes are compared with each other. As already described in the introduction, unevenly distributed stresses over the sheet thickness leads to unfolding or curvature in the unloaded area. Rather, the stress difference in the sheet thickness direction generates a bending moment. Based on this, the bending moments acting on the component before springback are demonstrated in figure 7 (a) on almost one half of the part. In figure 7 (b) their effective direction and position for the different forming processes are listed schematically.

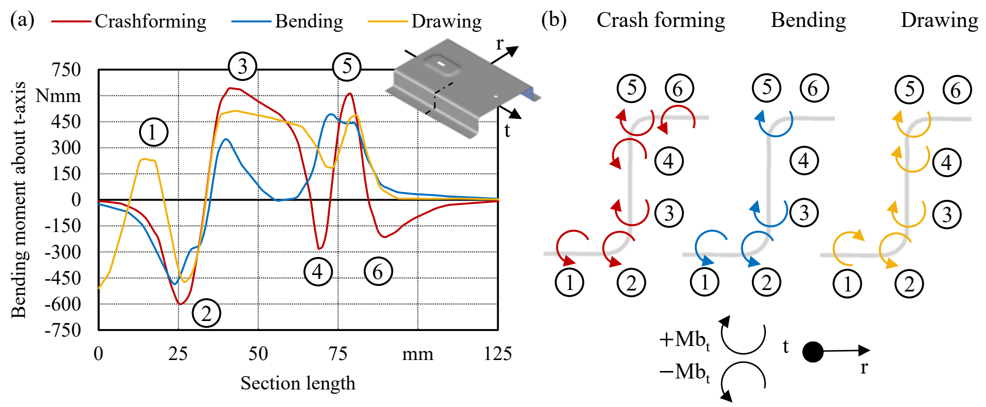

Figure 7. Bending moments along a cross section of the hat profile for the different forming processes (a), Schematic representation of the bending moments, their position and direction of rotation along a cross section before springback for the hat profile produced by crash forming, bending and drawing (b).

The comparison of the bending moments illustrates the differences of the forming processes in the numbered areas. The deviating amplitude of the drawn part in area 1 compared with the other processes can be explained by the alternate bending in the flange due to the stepped punch. Advantages of the stepped punch can be seen in area 3, where the drawn part has an even smaller bending moment than the crash forming as a result of less alternate bending. The hat profile produced by bending shows a significantly reduced bending moment due to the distribution of the bending moments and their unloading among two forming stages. In areas 4 and 6, the hat profile produced by crash forming shows negative bending moments which are generated by alternate bending during the material flow from the bottom area to the wall and by the forming of the excess material in the bottom.

3.2. Evaluation of the springback

In figure 8 (a), the springback of the parts are visualized on a limited cross-section. Starting from the reference, the crash formed hat profile shows the smallest deviations, followed by bent and drawn part. This can also be seen when comparing the flange angles in the bar chart demonstrated in figure 8 (b). In contrast, the curvature of the wall shows a different gradation: while the curvature of the bent part is negligible, the values of the crash formed and drawn hat profile are at the same level. This can be explained by the comparable bending moments in figure 7 (a) (area 3) and their interpretation in the previous chapter.

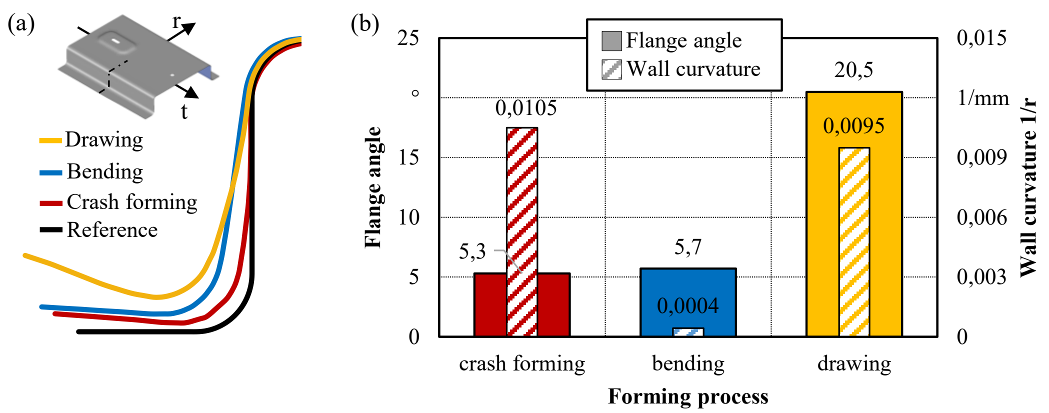

Figure 8. Comparison of the component springback for the different forming processes in a partial cross section (a), quantified angular deviation and wall curvature (b).

Beyond the extent of the bending moments, their position and direction of rotation obviously shows a strong influence on springback, which is why springback is the smallest for the crash formed hat profile. As a result of a hat shaped geometry, there is a greater influence of bending moments on springback of the flanges that are positioned closer to the center of the part. Thus, the negative bending moment of the hat profile in the upper region of the side wall (area 4 in figure 7) of the crash formed part leads to a reduction of the deviations in the wall and at the flange. A further reduction is brought about by the negative bending moment at the bottom near the radii (area 6 in figure 7). The origin of these bending moments is mainly based on the excess material in the bottom of the part, which is created when the blank is curved during eccentric tool contact. Without the excess material, there would be no material flow between the part's bottom and the part walls, which would cause the bending moment to be absent in the upper region of the side wall (area 4). On the other hand, the bending of the material at the part's bottom near the part radii is imposed by the excess material as well as its displacement to the radii. Overall, the hat profile can be graded according to its underlying forming processes with decreasing springback in the sequence drawing, bending and crash forming. Since there are several ways to design a drawing or bending process in particular, it is important to mention that the results discussed in this contribution refer to the described operations.

Based on the previous results from "geometry 1", it can be assumed that the forming processes bending and crash forming are more suitable for producing a hat profile using AHSS. For this reason, springback is only verified for these two forming processes with the help of "geometry 2". In principle, the validation of the springback prediction is legitimate, being a product of the calculated stresses and their distribution within the entire forming process. A comparison between the predicted springback from AutoForm and the optical measurements of the stamped parts by GOM Atos is visualized in figure 9. A sufficient accuracy of the forming simulation can already be determined by the visual comparison of the springback images. Furthermore, Figure 9 confirms the significantly lower springback of the hat profile produced by crash forming than by the bending process.

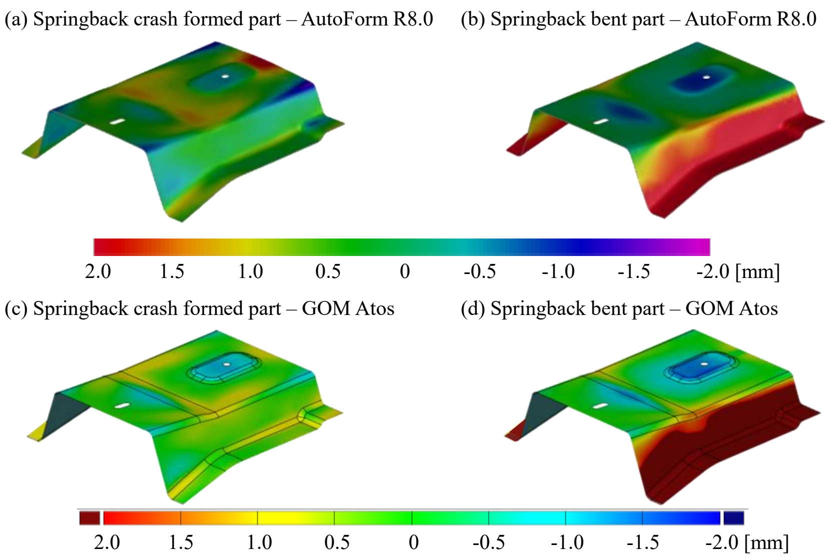

Figure 9. Optical measurement of form deviations GOM Atos for hat profile geometry 2 produced by bending (a) and crash forming (b).

Analogous to the previous investigations, figure 10 shows the bending moments before unloading along the cross section on almost one half of the hat profile. It can be seen a negative bending moment on the bottom of the crash formed part near the radii (area 6), which mainly causes the slight positive deviation near the radii and reduces the total springback.

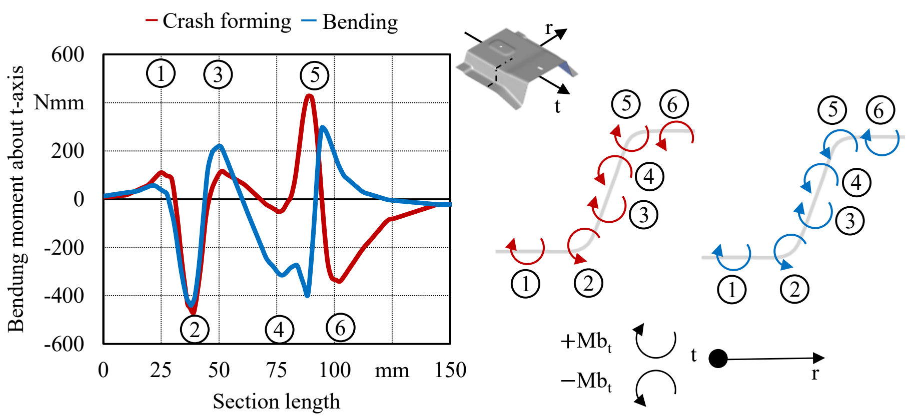

Figure 10. Bending moments before unloading along a cross section of “geometry 2” for the processes bending and crash forming as well as a schematic representation of the bending moments, their position and direction of rotation along a cross section before springback.

4. Summary

Sheet metal forming simulation is used to investigate the influence of the forming process crash forming, bending and drawing on the springback of a hat profile. A decreasing springback from drawing to bending and crash forming is found. The investigations have shown that the distribution and intensity of the bending stresses and subsequently unloaded bending moments are determined by the material flow during forming. Consequently, the material flow influences the springback significantly. In contrast to the springback of the bent part, the resulting springback from drawing and crash forming are controlled by bending stresses which are introduced during alternate bending of the material. Overall, the hat profile can be graded according to its underlying forming processes with decreasing springback in the sequence drawing, bending and crash forming. Since there are several ways to design a drawing or bending process in particular, it is important to mention that the results discussed in this contribution refer to the described operations.

5. References

[1] Ayres A 1984 *Shapeset: A process to reduce sidewall curl springback in high strength rails* Applied Metalworking **3** 127-134
[2] Mori K 2011 *Application of Servo Presses to Sheet Metal Forming* Key Engineering Materials **473** 27-36
[3] Billur E, Altan T 2013 *Three generations of advanced high-strength steels for automotive applications, Part I: The first generation*, STAMPING Journal November/December
[4] Gang L, Zhongqin L, Youxia B 2002 *Improving dimensional accuracy of a u-shaped part through an orthogonal design experiment,* Finite Elements in Analysis and Design **39** 107-118
[5] Komgrit L, Hamasaki H, Yoshida F 2016 *Elimination of springback of high-strength steel sheet by using additional bending with counter punch* Journal of Materials Processing Technology **229** 199-206
[6] Yoshida T, Hashimoto K, Katayama T, Kuriyama Y 2003 *Shape Control Techniques for High Strength Steel in Sheet Metal Forming,* Nippon steel technical report No.88
[7] Yoshida T, Isogai E, Sato K and Hashimoto K 2013 *Springback problems in forming of high-strength steel sheets and countermeasures,* Nippon steel technical report No.103
[8] Durmaz U, Heibel S, Schweiker T, Merklein M 2021 *Assessment of Springback Behaviour of 800-1200 MPa Dual-Phase Steel Grades* Key Engineering Materials **883** 151-158
[9] Kubli W, Krasovskyy A and Sester M 2008 Modeling of reverse loading effects including workhardening stagnation and early re-plastification, *Int J. Mater Form* Suppl **1** 145-148
[10] Sigvant M, Pilthammar J, Hol J, Wiebenga J H, Chezan T, Carler B and van dan Boogaard A H 2018 *Friction in Sheet Metal Forming Simulations: Modelling of New Sheet Metal Coatings and Lubricants, IOP Conf. Series: Materials Science and Engineering* **418**
[11] Durmaz U, Heibel S, Schweiker T, Merklein M, Berahmani S, Hol J and Naegele P 2021 *Enhancement of springback prediction of AHSS parts by advanced friction modelling* IOP Conf. Series: Materials Science and Engineering **1157**