An incremental analysis of a deep drawing steel’s material behaviour undergoing the predeformation using drawbeads

H Schmid¹, S Suttner¹ and M Merklein¹

¹ Institute of Manufacturing Technology LFT, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstr. 13, 91058 Erlangen, Germany

Email: harald.schmid@fau.de

Abstract. Nowadays lightweight design in metal forming processes leads to complex deep drawing geometries, which can cause multiple damages. Therefore, drawbeads are one way to regulate and control material flow during the forming process. Not only in research, but also in industrial practice, it could be determined that material is work hardened passing drawbead geometries. It particularly means when material is pre-deformed with tensile and alternating bending loads. This incident also gives the opportunity to utilize it in a reasonable way if examined properly. To investigate these findings, a process oriented and comprehensive analysis of the material behaviour during these forming operations is needed.

In this paper, sheet metal strips are linearly drawn through a drawbead and stopped after passing the drawbead. Within this forming operation, the material undergoes non-linear straining before reaching the in-plane position again. Here, the process will be stopped to investigate a permanent strengthening local along the sheet thickness. Therefore, microhardness measurements are realized before and after passing the drawbead. Because of its common use and its wide known material data, a deep drawing steel DC will be used for these studies. Additionally, the strategy is applied to advanced high strength steel.

1. Introduction

For deep drawing parts, which are nowadays more complex in geometry and material, some techniques can be used to control material flow. Next to changes in the lubrication system, surface properties or the blank holder force, the use of drawbeads is widely common in deep drawing processes. Drawbeads impede material flow of the sheet metal, but also change mechanical properties. This gives the necessity to examine material behaviour after passing a drawbead.

Courvoisier et al. [1] show that material is pre-strained by a load reversal when passing a drawbead. This load reversal leads to different strain routes on the inner, outer and middle area of the sheet. In [1], the authors describe the differences between an analytical model and a FE simulation. For mapping the material behaviour under load reversal, different hardening models like kinematic and isotropic were proposed. Larson suggested [2] a mixed isotropic-kinematic model to implement the hardening process for a mild steel in his numerical studies. Samuel [3] built up a numerical drawbead model to calculate different values like pull or shearing forces as well as bending moments. These simulations are in good agreement with his experiments. Especially for using high strength steels like HCT780X (also known as DP800), Li et al. [4] describe that hardening rates are higher than for other steels.
Halkaci et al. [5] found out, that aluminium AA5574-O improves its drawing ratio about 10% by adding a drawbead into the system. This indicates that pre-straining through a drawbead could also be used to optimize deep drawing processes to reach higher drawing depths. Currently, the change of material behaviour during passing a drawbead is merely insufficient investigated. Therefore, a need of analysing the material during and after passing a drawbead is significant to understand the mechanisms that lead to the improvement of drawability. Hence, Groche and Christiany [6] analyse the potential of different tool materials for advanced high strength steels in a drawing process with a drawbead.

Within this contribution, a strip drawing test is modified to observe the material behaviour of a mild steel and a dual phase steel during passing a drawbead. Moreover, the strains on the upper and lower side of the specimen are detected by an optical strain measurement system to determine the amount of pre-strain and to investigate the strain evolution. Finally, the accumulated strain level is correlated with microhardness measurements to analyse the hardening behaviour.

2. Materials

Because of the wide use in deep drawing processes, the mild steel DC04 is analysed within this research work. Moreover, advanced high strength steel HCT780X (DP800) is observed to transfer the experimental methodology from conventional materials to modern materials. DC04 offers high formability for many forming applications. Here, the mild steel is used in a sheet thickness of 1.0 mm. Tensile tests with DC04 resulted in a tensile strength TS of 314.4 MPa and a uniform elongation UE of 25.9%. As an instance for modern advanced high strength steels, which are frequently used in technical processes like car body construction, HCT780X (DP800) is tested with a sheet thickness of 1.0 mm. It shows a significant higher tensile strength TS of 817.9 MPa what justifies the overall higher hardness level in comparison. Although TS is relatively high, a smaller uniform elongation UE of only 12.9% was determined compared to the mentioned deep drawing steel.

3. Experimental setup

For experimental observations of the influence of drawbead, a strip drawing machine is modified to realize drawing through a drawbead. In this observation, the drawbead has a radius of 6.5 mm according to the Numisheet benchmark 2008, as seen in Figure 1 a. The sheet metal strip is inserted in the machine and the tool is closed with a blank holder force, which can be calculated and adjusted to a reasonable blank holder pressure. For this examination a pressure of 5 MPa was used. Afterwards the strip is pulled through the drawbead with a velocity of 10 mm/s while the normal force is controlled. The specimens consist of a sheet metal strip with a length of 700 mm and a width of 50 mm as seen in Figure 1 b and are cut out via laser cutting.

![Figure 1. a) Strip drawing test machine with drawbead geometry and b) scheme of test setup and pulled strip with etched drawbead geometry](image)
To detect the local strains on the upper and lower side of the specimen, the sheet metal strips are etched with a dot pattern composed of a dot diameter of 1 mm and a relative distance of 2 mm. After drawing, the deformed drawbead part are cut out and measured unloaded by the optical measurement system ARGUS (GOM GmbH), which calculates displacements and therefore local elongations. For that, images from various positions are recorded to receive a digital three-dimensional model of the detected surface with local strains. Within the experimental strategy, each configuration is tested with three trials (N = 3) and averaged.

Additionally, Vickers micro hardness tests with HV 0.02 in a Fischerscope HM2000 (Helmut Fischer GmbH) are carried out to correlate the results of local strains with the hardness values. Inner and outer layers are tested in three rows with at least three points per row for every area. For better understanding, the drawbead areas can be divided into five sections as shown in Figure 2.

![Figure 2. Defined forming areas in drawbead geometry and result of optical strain measurement](image)

The five areas are located at around 5 mm, 7.5 mm, 15 mm, 25 mm and bigger than 30 mm. The first section reflects the initial condition of the material, while section two introduces a compressive load in the upper layer and a tensile load in the lower layer. With ongoing drawing, a load reversal from area two to area three occurs, which leads to a tensile load in the upper layer and a compressive load in the lower layer (section three). After section three, a second load reversal appears which introduces compression in the upper layer and tension in the lower layer. Afterwards, further straining under tension is established in the upper and lower layer in section five.

4. Results

The introduction of load reversal leads to different straining levels in the upper and lower layer of the specimen, which are investigated via optical strain measurement. Therefore, five line cuts along the drawing direction x are inserted in the digitalised three-dimensional strain model and averaged to one line cut. Additionally, the averaged line cuts of three specimens are averaged as well. The development of the elongation along the drawing direction x for the upper and lower layer is pictured for DC04 in Figure 3 a) and DP800 in Figure 3 b). For a better vividness, the areas of the drawbead are shown with different colours.
Figure 3. Total strain in x direction over drawbead for a) DC04 and b) DP800

DC04 obviously is able to reach higher long-term tension rates when looking at the rates in the run out in section five. Upper and lower areas are not subject to any elongation in the beginning. When running in section two, the upper side experiences pressure while the lower side is confronted with tension. The tensile strain seems to be about two times higher than the compressive strain, what could be related to the geometry of the drawbead.

When the material is passing section three, the top of the drawbead, a load reversal takes place, what can also be seen in the elongation development. The upper and lower side both possess about 5 % of tension or compression after hitting the turning point. When the material is flowing into the fourth section, another load reversal occurs. This leads to tension in the lower side and compression in the upper side at around 25 mm in x direction. The lower side especially shows a higher tension in the last area what most probably is the consequence of a superposition with a pull out force. The lower side has 10 % of elongation after the drawbead passage for DC04, while the upper side handles only 4 %.

DP800 in Figure 3 b) has smaller elongations in general. While the basic development of tension is nearly the same, it seem to have bigger changes from compression to tension and backwards. Load reversals have a bigger effect on the gradient of the elongation. In the last area, upper and lower side both are located around 4 % long-term elongation.

This noticeable difference could be explained with the higher tensile strength TS of the advanced high strength steel and thereby with the higher amount of springback. This fact most likely illustrates the higher gradients in tension, when load reversal occurs. While DC04 has lower amounts of elastic tension, DP800 with its high tensile strength returns a lot more of elastic tension what leads to the present sequence.

Moreover, the strain history is detected during passing a drawbead, which can be sum up to an accumulated strain. For the observation of the hardness development, the microhardness measurement according to Vickers is referenced to the accumulated strain in Figure 4. Continuative, the hardness evolution is determined for the mild steel DC04 as well as for the dual phase steel DP800. To analyse the material behaviour for the upper and lower side of the blank, the hardness vs. accumulated strain curves are pictured for the lower and the upper side of the sheet metal.
In Figure 4 it can be seen, that hardness increases with higher accumulated tension from the initial condition to the second section. But only for DC04 a further increase exists from section two to three. For DC04 in Figure 4 a) microhardness values develop from about 110 HV up to 180 HV. While the upper side accumulates about 22 % of tension, the lower side sums up about 35 % elongation. This difference most likely evolves from the final elongation in area five for the lower side. The upper side hereby is coming from a compressive load, what does not sum up in the same amount. It can also be analysed that the upper side of DC04 decreases from the third to the fourth area in hardness. Since the material experiences a load reversal, this can be a consequence of the Bauschinger effect. The differences in the reached elongation levels of each section can be explained by the geometrical influences of the drawbead and thereby with overlying influence of cyclic bending load.

DP800 increases from 300 HV up to 390 HV, when passing the drawbead passage. So, the advanced high strength steel has a higher hardness level and coming with it also a higher strength level. DP800 sums up its tension for the upper side until 33 % and the lower side until 26 % what indicates the opposite compared to DC04. It can also be clearly analysed, that hardness decreases for the upper and lower side from the second area (see also Figure 2), which represents the first bending when material is running to the top of the drawbead. When reaching the top level of the drawbead (third area in Figure 2), hardness values are lower on both sides of DP800 compared to the level before.

Differences in hardness development for the advanced high strength steel can arise from the Bauschinger effect, which reduces the hardness after load reversal. Additionally, an overlying effect of springback can lead to a reduction of the introduced hardness, which is higher for DP800 due to the higher level of stress what can be seen in the different tensile strength TS. The strain measurements are conducted offline after springback occurs. To analyse the material behaviour during passing the drawbead online, the detection of local strains during the test can lead to further information. Suttner and Merklein [7] described, that a DP600 steel develops a gentle elastic-plastic transition zone for load reversals from tension to compression. This zone is not observed for a mild steel DC06, what indicates that hardness decrease for DP800 can also arise from the smooth transition from elastic to plastic area. Here, additional scientific investigations need to be performed to find out the strain behaviour online during passing a drawbead. However, it can be noted, that an influence of drawbead occurs, which leads to a load reversal as detected by the offline strain measurement method in this research work. In addition, the strain history leads to an increase of the hardness, which is influenced by the Bauschinger effect and the elastic-plastic material behaviour that affects the amount of springback.
5. Summary
First of all, a test device was modified using a conventional strip drawing test setup and a drawbead geometry to introduce a drawbead passage in a sheet metal strip according to a real forming operation with drawbead. It could be shown that DC04 and DP800 presented the assumed strain development depending on the drawbead geometry and bending direction. Higher elastic springback ratios could explain the sharper changes in strain gradients for DP800 in comparison to the deep drawing steel DC04. The strain course of upper and lower side for both steel types also indicates a change in material properties over the sheet thickness. Therefore, microhardness measurements were carried out on the upper and lower layer of the sheet. The results are visualized versus the accumulated strain for both investigated steels and the upper and lower layer. Here, an overall increase of hardness and accumulated strain during the drawbead passage can be pointed out. Also, a significant decrease in hardness between the second and fourth area for DP800 is observed. Most likely this occurrence evolves from a higher elastic springback effect and the Bauschinger effect due to cyclic loading during drawing. The Bauschinger effect means a decrease in flow stress after load reversal, which leads to a reduction of hardness as determined for DP800. Moreover, dual phase steel consists of a smooth transition from elastic to plastic material behaviour after load reversal, which can also explain the decrease in hardness with load change during passing the drawbead. In the end, hardness increases due to the overlying tensile load and it can be seen, that passing a drawbead leads to an increase of hardness and accumulated strain for both investigated materials. Moreover, the influence of this strain and stress history on formability should be investigated in future. Additionally, this effect should also be observed for further materials.

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References
[1] Courvoisier L, Martiny M and Ferron G 2003 Analytical modelling of drawbeads in sheet metal forming 133 359–370 DOI: 10.1016/S0924-0136(02)01124-X
[2] Larsson M 2009 Computational characterization of drawbeads Journal of Materials Processing Technology 209 376–386 DOI: 10.1016/j.jmatprotec.2008.02.009
[3] Samuel M 2002 Influence of drawbead geometry on sheet metal forming Journal of Materials Processing Technology 122 94–103 DOI: 10.1016/S0924-0136(01)01233-X
[4] Li H, Sun G, Li G, Gong Z, Liu D and Li Q 2011 On twist springback in advanced high-strength steels Materials & Design 32 3272–3279 DOI: 10.1016/j.matdes.2011.02.035
[5] Halkaci H Selcuk, Turkoz M and Dilmec M 2014 Enhancing formability in hydromechanical deep drawing process adding a shallow drawbead to the blank holder Journal of Materials Processing Technology 214 1638–1646 DOI: 10.1016/j.jmatprotec.2014.03.008
[6] Groche P and Christiany M 2013 Evaluation of the potential of tool materials for the cold forming of advanced high strength steels Wear 302 1279–1285 DOI: 10.1016/j.wear.2013.01.001
[7] Suttner S and Merklein M 2014 Characterization of the Bauschinger effect and identification of the kinematic Chaboche Model by tension-compression tests and cyclic shear tests IDDRG 2014 125–130