Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 1582–1587

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Investigations on Springback in High Manganese TWIP-Steels using U-Profile Draw Bending

Angela Quadfasel[a]*, Johannes Lohmar[a], Gerhard Hirt[a]

[a]Institute of Metal Forming (IBF), RWTH Aachen University, Intzestr. 10, 52072 Aachen, Germany

Abstract

High manganese (HMn) steels as part of the second generation of high strength steels are characterized by an excellent combination of mechanical properties, such as a high yield strength and ultimate tensile strength combined with a high ductility. These outstanding properties are a suitable basis for their application in light weight automotive body parts and especially for passenger safety components. However, concerning the sheet metal forming of high manganese steels a large amount of springback after forming due to elastic recovery is a common problem. The high yield strength of high manganese steels in combination with a low elastic modulus introduces high reversible elastic strains during cold forming that will partially recover after forming. Beside the mechanical properties of the material also process parameters e.g. blank holder force in U-profile draw bending have an influence on springback. Therefore, a thorough understanding of the factors influencing springback behavior after forming operations is crucial to establish high manganese steels for industrial sheet metal forming processes. As a first step this paper investigates springback of three different high manganese TWIP steels after U-profile draw bending in comparison to a conventional dual phase steel DP800. Draw bending is an economical characterization method for assessment of springback, because the collective load is comparable to simple deep drawing operations and only a fair amount of experimental effort is needed. The comparison of bending angles of U-profiles after springback of the different steel grades shows a significant higher springback than expected for the HMn steel grade without aluminum, which can't be explained by specific strength, Young's modulus and sheet thickness. Springback is also influenced by microstructure in high manganese steels visible in the comparison of the grades X60MnAl23-1 and X60Mn22 because latter shows more twinning in tensile testing. Additionally it is shown, that the variation of the blank holder force can be used to reduce springback in an HMn steel effectively without damage of the sheet.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: springback; high manganese steel; compensation; U-draw bending

1. Introduction and State of the Art

Advanced high strength steels (AHSS) are promising materials for safety components in automotive lightweight designs. Especially some second generation AHSS with high manganese (HMn) amounts and high hardening rates, due to twinning induced plasticity (TWIP), combine a high formability with a high strength resulting in a high energy absorption ability during deformation before failure. For an industrial use of these materials, the common drawback shared with all ultra-high strength materials, namely the high amount of springback has to be controlled. Springback is the shape change of a part after the release of the forming tools e.g. after deep drawing. Especially in bent areas of a metal sheet the release of the elastic strain induced during forming causes large deviations from the desired part geometry. Springback is conventionally investigated after pure bending or after draw bending.

* Corresponding author. Tel.: +49 241 80 95948; fax: +49 241 80 92234.
E-mail address: quadfasel@ibf.rwth-aachen.de

1877-7058
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.1052

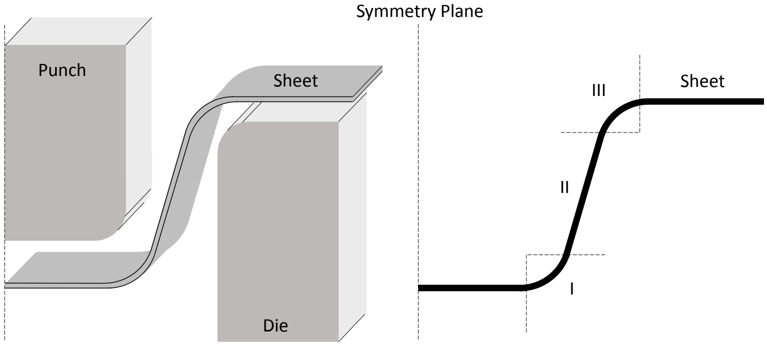


Fig. 1. Schematic view of a U-profile after springback.

Test methods including draw bending have the advantage, that the forming state is closer to industrial deep drawing operations. A common method to investigate springback of a material after draw bending is the U-profile bending [1, 2]. In U-profile bending the shape deviation is influenced by two major factors: First springback in the punch and die shoulder, where stretch bending occurs (region I and III in Fig. 1) and second side wall curvature in the area first stretch bent by the die shoulder and then unbent again (region II). For all regions springback is caused by a bending moment due to an uneven stress field in thickness direction [3, 4]. The amount of elastic strain introduced during bending increases with increasing initial yield stress σ_y and decreasing Young´s Modulus E. Based on the beam bending theory it is thus common to use the ratio σ_Y/E as a first estimate for the amount of springback [5]. Lee et al. extended this simple assumption to $\sigma_Y/(E * d)$ to account different sheet thicknesses d. They successfully compared springback after cylindrical bending of different materials with sheet thicknesses from 1.5 mm to 1.2 mm. As springback is also sensitive to the ratio between bending radius R and sheet thickness R/d, springback increases when the sheet thickness decreases [6]. Furthermore Zhang et al. [4] postulated that the amount of springback is reciprocally proportional to d^3 based on an analytical model for springback after U-profile draw bending. In conclusion currently no consistent strategy to account for the influence of the sheet thickness is found in literature.

Preceding investigations on springback after three point bending of different high manganese steels in comparison to a DC04 [7] showed, that high manganese steels have a high amount of springback due to the high yield strength and low Young's Modulus compared to the 210 GPa typically observed for steels. Furthermore the ratio of $\sigma_y/(E*d)$ was successfully used to estimate springback although these steels show complex forming mechanisms with twinning acting in addition to dislocation glide during bending. Busch et al. [8] compared the springback of a TWIP/TRIP material to a DP800 and a DP1000 and observed a higher amount of springback for the TWIP/TRIP material in comparison to a DP800 with similar yield strength.

In order to manufacture sheet metal products with narrow tolerances in geometry, there are two common ways to overcome deviations caused by springback. First, minimizing springback by increasing sheet tension and second compensating for springback via over bending or tool design. While the first approach uses the blank holder force (BHF) to increase sheet tension as is common practice for deep drawing operations, the second approach requires precise material models for tool layout by simulation [9]. Applying a stretching force via a blank holder reduces the bending moment which is necessary for plastic bending and therefore reduces the elastic strain introduced during bending [3, 4].

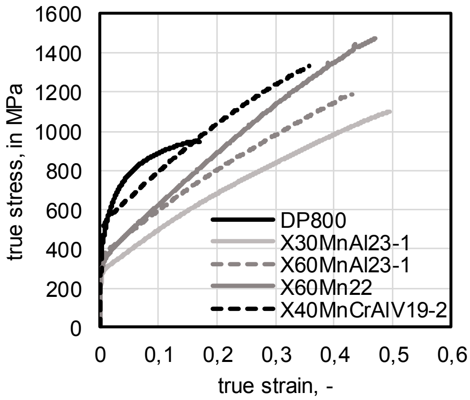


Fig. 2. True stress- true strain curves from tensile tests for the investigated materials

Table 1. Process parameters and mechanical properties of an industrial (ind.) DP800, as well as three laboratory (lab.) HMn steels and an industrial HMn steel X40MnCrAlV19-2.

Material	Sheet Thickness (d) [mm]	Yield Strength $R_{p0.2}$ [MPa]	True Tensile Stress for a True Strain of 0.1 $\sigma_{0.1}$ [MPa]	Young's Modulus (E) [GPa]
DP800 (ind.)	1.14	379	888	211
X30MnAl23-1 (lab.)	1.19	272	498	165
X60MnAl23-1 (lab.)	1.09	344	598	176
X60Mn22 (lab.)	1.10	308	624	173
X40MnCrAlV19-2 (ind.+lab.)	0.94	520	795	185

The reduction of springback by BHF was experimentally observed by Lajarin et al. for high strength steels [10], and analytically predicted by Zhang et al. [4] for aluminum and by Ahn et al. [2] for TWIP steels.

In the present study the springback of three HMn steel grades produced on laboratory scale was investigated after U-profile draw bending and compared to the springback of an industrial HMn steel grade and an industrial DP800 steel. The first aim was to investigate whether the dependency of the amount of springback on mechanical properties known from conventional steel grades does also hold for the HMnS steels despite their more complex microstructure. The second aim was to validate that the conventional concept to reduce springback by applying a stretch force (i.e. increase the BHF) can be successfully transferred to HMn steels. This investigation was carried out using the industrial HMn steel X40MnCrAlV19-2.

2. Materials and Methods

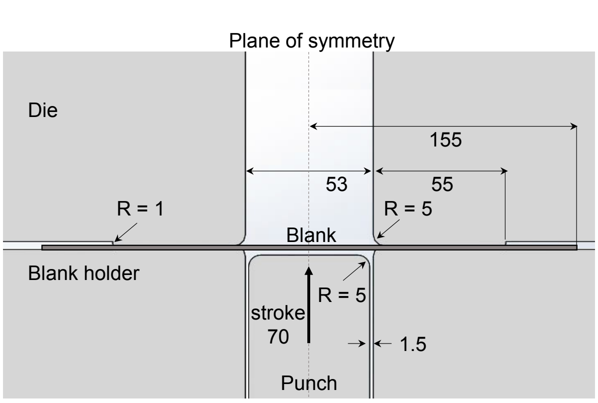
2.1. Material processing and characterization

The three HMn steel grades X30MnAl23-1, X60MnAl23-1 and X60Mn22 were produced by the Collaborative Research Center SFB 761. The steel grades with an carbon content of 0.6 wt.% were strip cast at the Institute of Metal Forming (IBF), homogenized and afterwards cold rolled to final sheet thickness according to Tab. 1. The X30MnAl23-1 was ingot cast at the Department of Ferrous Metallurgy (IEHK) and then forged, homogenized and hot as well as cold rolled at the IBF. All three steel grades were cold rolled from 2 mm to their final sheet thicknesses near 1.1 mm in several passes and annealed under argon atmosphere at 900 °C for 20 to 30 min to achieve a fully recrystallized microstructure. After quenching in water the sheets had to be levelled. The X40MnCrAlV19-2 was provided as hot-rolled material in 2 mm by thyssenkrupp Hohenlimburg GmbH. The hot-rolled steel sheets were then processed to cold-rolled material in the same manner as the previous mentioned SFB steel grades and afterwards levelled for 2%. It is known from literature [1], that springback is sensitive to the mechanical properties especially the yield strength and the Young's modulus. Hence, the plastic behavior was investigated by quasistatic tensile tests (see Fig. 2) while the Young's modulus of the materials was measured by ultrasonic tests at the IEHK (see Tab. 1).

2.2. U-profile draw bending

Springback was investigated after draw bending of U-profiles with a tool geometry according to the benchmark test setup presented at NUMISHEET'93 conference by Markinouchi. The tool geometry was designed according to [11]. In Fig. 3a the schematic view of the used test set up is shown. Sheets of 310 mm x 35 mm were cut with length direction parallel to the rolling direction and cutting edges were deburred. For the investigation of springback in the different grades, tests were repeated twice, while the springback compensation trials with X40MnCrAlV19-2 were based on four specimen for each BHF. The samples were lubricated with teflon foil and deep drawing oil between sample and foil as well as between foil and tool to reduce the influence of friction during the draw bending process. During forming, the blank was clamped by the blank holder using the three different blank holder forces 40 kN, 100 kN and 200 kN, that were kept constant over the whole drawing process. The area of clamping didn't change during processing because the sheet was longer than the end of the clamping zone visible in Fig. 3a. Hence, the stress introduced by the blank holder was constant, too.

(a)



(b)

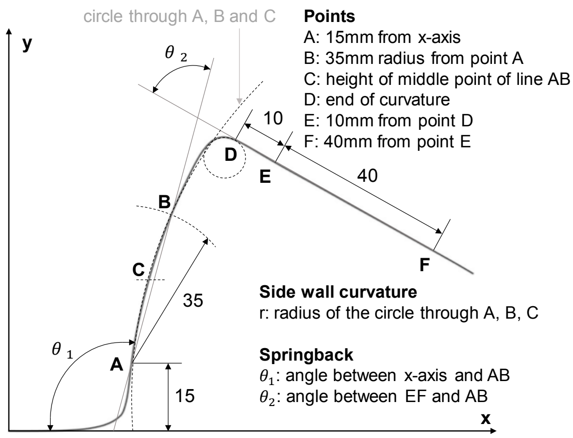


Fig. 3. (a) Schematic view of 2D draw bending test with dimensions according to [11]; (b) Parameters for springback and side wall curl evaluation according to [4]. All dimensions in mm.

The experiments were conducted on a hydraulic press with a punch stroke of 70 mm and a punch velocity of 5 mm/s. After forming, the outer surface of the U-profiles were digitalized with EinScan PRO 3D-Scanner and a longitudinal section was taken out of the middle of the sample. According to the benchmark of NUMISHEET'93 the following points visible in Fig. 3b were determined on the U-profile to obtain the springback angles θ_1 and θ_2 and the radius of the side wall curvature r. Point A is 15 mm from the x-axis, while B is 35 mm from A and C in the middle of A and B. Point D is located at the end of the die shoulder and E and F are located 10 and 40 mm from D. The bending angle θ_1 is located at the punch shoulder of the U-profile between a line through AB and the x-axis and θ_2 at the die shoulder between the lines of AB and EF. Both angles should ideally have 90° but springback causes a deviation which results in θ_1>90° and θ_2<90°. This deviation is calculated by $\Delta\theta_1=\theta_1$-90° and $\Delta\theta_2$=90°-θ_2. The springback of the side wall is measured by means of the radius r of side wall curvature, which should be ideally indefinitely large. For reasons of clarity in the following the curvature of side wall will be prescribed as κ=1/r. In this way all three parameters $\Delta\theta_1$, $\Delta\theta_2$ and κ should be small for low amounts of springback. During the analyzing procedure the profile was divided into a left and a right part. Parameters were calculated for both sides and averaged. This was necessary because for higher BHF the process becomes sensitive to small process parameter fluctuations that lead to small deviations between both sides of the profile.

3. Results and Discussion

3.1. Springback in high manganese steels

As already stated it is well known that springback is sensitive to the mechanical properties and therefore an indirect influence of alloy design on springback can be assumed. From the stress-strain curves of the material shown in Fig. 2 it is visible that an increasing carbon content increases the yield strength of X60MnAl23-1 and X60Mn22 in comparison to X30MnAl23-1 by interstitial hardening [12]. The addition of aluminum leads to a decrease of the hardening rate, which becomes visible in the comparison of X60MnAl23-1 and X60Mn22. Aluminum reduces the tendency to deform via twinning [13].

Figure 4a shows the amount of springback obtained in the U-profile bending experiments with 40 kN BHF in terms of $\Delta\theta_1$, $\Delta\theta_2$ and side wall curvature κ for the HMn steels in comparison to an industrial DP800. The sheet thickness of the different materials does vary in these experiments and is given in Fig. 4a as it does also influence springback. For all investigated materials the amount of springback in the punch and die shoulder and the amount of side wall curvature are correlated. X40MnCrAlV19-2 is the material with the largest $\Delta\theta_1$, $\Delta\theta_2$ and κ values and thus the highest amount of springback. This high amount of springback is not surprising as the X40MnCrAlV-2 is 0.2mm thinner in thickness and the yield stress is much higher compared to the other HMn steels. Other investigated HMn grades exhibit an amount of springback that is comparable to DP800. For X30MnAl23-1 however $\Delta\theta_1$ and $\Delta\theta_2$ and κ values are lower than for a DP800.

A good first estimate of the amount of springback is commonly obtained via the ratio of mechanical properties σ_y/E. Hence, this ratio is used as an indicator to compare the springback behavior of all the different grades investigated in this paper. The bending theory used by Lee et al. [1] to derive this ratio assumes ideal plastic material i.e. the yield strength is constant during the process. When using this ratio to estimate springback in real bending processes it might be necessary to replace the yield strength by a strain dependent stress value.

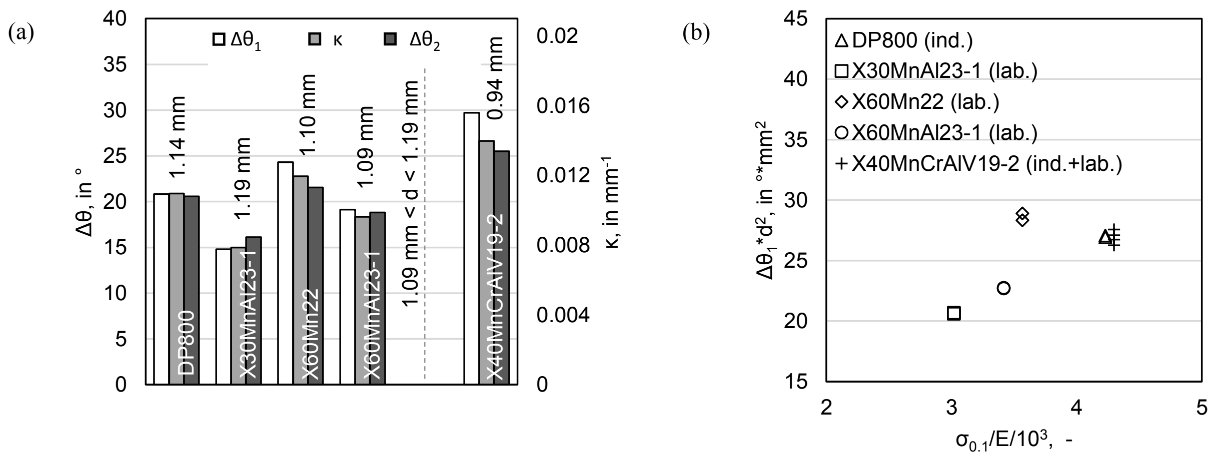


Fig. 4. (a) Experimental values of springback Δθ and side wall curvature κ after deep drawing with BHF of 40 kN for DP800 and laboratory HMn steels with comparable sheet thickness and the 0.2 mm thinner X40MnCrAlV19-2; (b) Prediction of springback with sheet thickness compensation based on the mechanical properties in relation to experimental values for $\Delta\theta_1$.

For this investigation the stress values corresponding to a true strain of 0.1 was chosen, because FEM simulations showed a maximum strain of 0.1 at the outer fiber of the bent areas close to punch and die. Accordingly the ratio of mechanical properties will be calculated via $\sigma_{0.1}/E$ here. Because the slight differences in sheet thickness of the investigated materials already have a large effect on the amount of springback the influence of the sheet thickness should be compensated in the analysis. As no consistent strategy was found in literature a compensation factor was derived based on beam bending theory from the maximum stress on the

$$\sigma_{max} = \frac{M}{I} * \frac{d}{2} = \frac{12M}{d^3} * \frac{d}{2} = \frac{6M}{d^2}, \quad (1)$$

outer fiber with a distance of $d/2$ from the middle fiber of a bended beam as:
where M is the bending moment and I ($I=d^3/12$) is the inertia moment of the cross section per unit width. The resulting factor d^2 is derived from simple mechanics and the influence of sheet thickness on M still has to be investigated in more detail. However when applying this compensation factor to the experimental results shown in Fig. 4a the expected strong correlation between mechanical properties and resulting amount of springback is achieved. Therefore Fig. 4b shows the ratio of mechanical properties for the different steel grades in relation to the compensated values of $\Delta\theta_1$ with d^2. It is visible that X30MnAl23-1, X60MnAl23-1, DP800 and X40MnCrAlV19-2 lie on a straight line, thus proving that $\sigma_{0.1}/E$ is a useful criterion for HMn steels to compare the amount of springback as it is for conventional steels. When compensating for the sheet thickness the X40MnCrAlV19-2 exhibit an amount of springback on the same level as the DP800 in accordance with a similar ratio of $\sigma_{0.1}/E$. For X60Mn22 the ratio of σ_{01}/E is similar to that of X60MnAl23-1 but the experimental value of $\Delta\theta_1$ is higher. This is surprising as a similar amount of springback is to be expected from the similar sheet thickness and mechanical properties at a strain of 0.1 of X60Mn22 and X60MnAl23-1 (cf. Tab. 1). Therefore the higher amount of springback of the X60Mn22 might be caused by differences in microstructure. Especially the higher hardening rate visible in the stress-strain curve shown in Fig. 2 suggests that X60Mn22 exhibits a higher amount of twinning than X60MnAl23-1. Hong et al. [13] reported that the addition of aluminum in HMn TWIP steels restrains the formation of deformation twins and therefore decreases residual stresses, which contribute to the effect of springback. Those residual stresses might influence the plastic behavior of the material under reverse loading. Additionally Lee et al. [1] and also Ahn et al. [2] showed that early yielding during reverse loading observed in AHSS and also for TWIP steels, called Bauschinger effect, has an influence on the springback and side wall curvature.

3.2. Springback compensation via blank holder force

The previous results show that HMn steels exhibit springback on the same level as an industrial DP800 AHSS after draw bending. To qualify HMn steels for industrial applications it is furthermore important to quantify the ability to compensate a part of the springback by increasing the BHF. For this test the industrial X40MnCrAlV19-2 was chosen due to its strength in the relevant strain area of 0.1 in close proximity to the conventional DP800. Figures 5a and 5b shows the springback and side wall curvature of X40MnCrAlV19-2 with increasing BHF. The springback at the punch shoulder of the U-profile shows the greatest effect of an increasing BHF visible in the reduction of $\Delta\theta_1$ in Fig. 5a. In contrast the decline of κ is lower, while the lowest effect of BHF on springback is visible in $\Delta\theta_2$ located at the die shoulder of the profile. A greater effect of the blank holder force on the reduction of θ_1 and κ than on θ_2 can also be observed in results of Woellner et al. [14], who investigated the effect of different force amplitudes on springback of AHSS. However the BHF seems to be as effective to reduce springback in deep drawn parts made of HMn steels as it is for other AHSS.

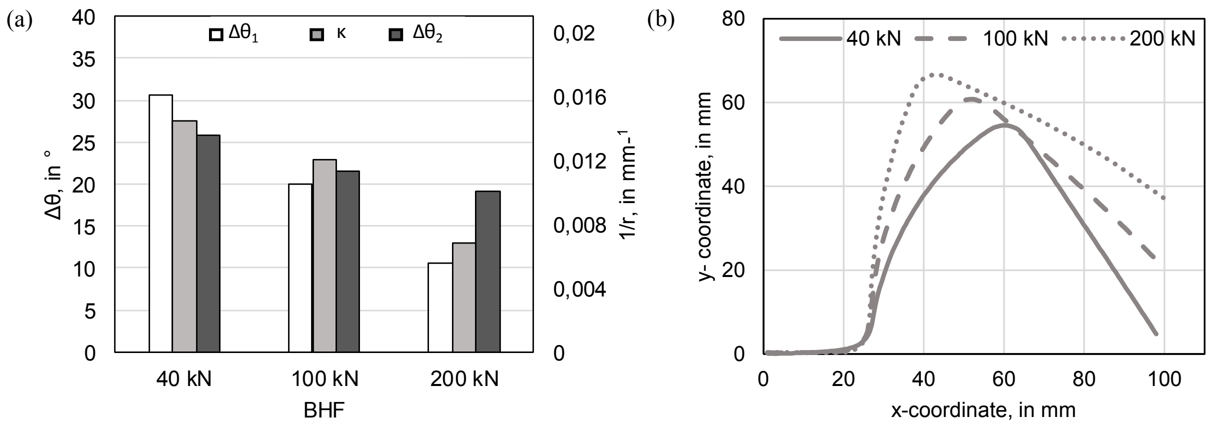


Fig. 5. (a) Mean values of springback Δθ and side wall curvature κ after deep drawing of X40MnCrAlV19-2 with different BHF; (b) Contours of U-profiles after draw bending with different BHF.

Because increasing the BHF of the draw bending process can lead to sheet thinning and in extreme cases to failure of the material the sheet thicknesses of the investigated material is determined. The sheet thinning after draw bending with different BHF is presented in Tab. 2. The thinning was measured at three points of the sidewall Δd_1 1 cm from θ_1, Δd_2 in the middle of the sidewall and Δd_3 1 cm from θ_2. Sheet thinning increases along the side wall from θ_1 to θ_2. Still the maximum sheet thinning Δd_3 is only 8% of the initial sheet thickness for the highest BHF. Therefore high BHF can be used to reduce the springback after U-profile draw bending in HMn steels without severe sheet thinning or even damage.

Table 2. Sheet thinning in side wall after draw bending with varying BHF.

BHF [kN]	Sheet thinning of sidewall after deep drawing (Δd_i) [mm]		
	Δd_1 near θ_1	Δd_2 middle of side wall	Δd_3 near θ_2
40	0.009 ± 0.007	0.018 ± 0.007	0.022 ± 0.009
100	0.013 ± 0.008	0.034 ± 0.007	0.047 ± 0.010
200	0.027 ± 0.014	0.057 ± 0.010	0.076 ± 0.010

4. Conclusions

Springback of four HMn steel grades was investigated after deep drawing of U-profiles and compared to a commercial DP800 steel. The following conclusions can be drawn from the experimental results:

- For all steel grades the amount of springback in the bent shoulders and the side wall are correlated. Steel grades with a high springback in θ_1 and θ_2 also have a high curvature of side wall.
- For DP800 and HMn steel grades, that do not show a high amount of twinning, the common relation of the mechanical properties $\sigma_{0.1}/E$ can be used as a first estimate for the severity of springback if sheet thickness effects can be ruled out. Hence, for HMn steels not undergoing twinning the conventional prediction methods do hold.
- A higher twinning fraction might cause the higher amount of springback observed in X60Mn22 in comparison to X60MnAl23-1 despite of similar mechanical properties and sheet thickness. This is still to be verified by microstructural analysis planned in the near future.
- As for conventional AHSS springback after U-profile draw bending can be effectively reduced by increasing the BHF without fracture or significant sheet thinning for X40MnCrAlV19-2.

Acknowledgements

The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center (SFB) 761 “Steel –ab initio”. They also thank thyssenkrupp Hohenlimburg GmbH for providing the X40MnCrAlV19-2 steel grade and the Department of Ferrous Metallurgy (IEHK), RWTH Aachen University for providing tensile test data for X40MnCrAlV19-2 and an ultra-sonic elasticity test devices.

References

[1] M. G- Lee et al.; Spring-back evaluation of automotive sheets based on isotropic-kinematic hardening laws and non-quadratic anisotropic yield functions, part III: applications, Int. J. of Plas. 21 (2005) 915-953.

[2] K. Ahn et al.; Springback prediction of TWIP automotive sheets, met. Mater. Int 15 (2009) 637-647.

[3] T. Yoshida et al.; Shape control techniques for high strength steels in sheet metal forming, Nippon steel technical report no. 88 (2003) 27-32.

[4] D. Zhang et al.; An analytical model for predicting springback and side wall curl of sheet after U-bending, Comp. Mat. Sci. 38 (2007)707-715.

[5] K. Mori et al.; Springback behavior in bending of ultra-high-strength steel sheets using CNC servo press, Int. J Mach Tool & Manu 47 (2007) 321-325

[6] Z. Tekiner; An experimental study on the examination of springback of sheet metals with several thicknesses and properties in bending dies, Journal of Material Processing Technology 145 (2004) 109-117

[7] A. Quadfasel et al.; Investigation of springback of high manganese TWIP-steels using three-point-bending, 3rd international conference on high manganese steels, Chengdu (2016)

[8] C. Busch et al.; Properties and application of high-manganese TWIP-steels in sheet metal forming, Procedia Engineering 81 (2014) 939-944.

[9] R. H. Wagoner; Sheet springback, in D. Raabe et al. (Eds), Continuum scale simulation of engineering Materials, Wiley-VHV, Weinheim, 2004, pp 777-794.

[10] S. F. Lajarin et al.; Influence of process and tool parameters on springback of high-strength steels, J Engineering Manufacture 229 (2015) 295-305

[11] F. Pourboghrat, E. Chu; Prediction of spring-back and side-wall curl in 2-D draw bending, J. of Mat. Proc. Tech., 50 (1195) 361-374

[12] W. Song, T. B. W. Ingendahl; Control of Strain Hardening Behavior in High-Mn Austenitic Steels, Acta. Metall. Sin. 27 (2014) 546-556.

[13] S. Hong et al.; Residual stress analysis in deep drawn twinning induced plasticity (TWIP) steels using diffraction method, Metall. Mater. Trans. 45A (2014) 1953-1961

[14] N. Woellner et al.; Blank holder force influence on the springback of advanced high strength steels, COBEM 2013,Ribeirao Preto, Brazil