Improved bendability characterization of UHSS sheets

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Abstract. Bendability characterization of UHSS sheets is often limited by punch-sheet-liftoff during standardized bending tests. This phenomenon is characterized by a smaller radius on the bent sheet than the desired tool radius and might lead to a misinterpretation of the admissible bending radii from such tests. An alternative bending setup is proposed suppressing punch-sheet-liftoff. The proposed setup aims at imitating bending in multistage stamping processes and to some extent also roll forming. The target bending radius to sheet thickness ratios of the investigated UHSS sheets were chosen to be 2.0. Alternative tool geometries are investigated as well. Short segments of an Euler spiral between the tool parts exhibiting the target curvature and the linear neighbor regions are used to avoid triggering strain localizations at these curvature discontinuities, further decreasing the admissible bending ratios. Finite element simulations of the proposed bending test were conducted in order to identify the optimal tool shape. All results were compared to corresponding results from standardized bending tests of the respective UHSS sheets. The proposed setup succeeded in suppressing punch-sheet-liftoff for the desired bending ratios and was able to provide smaller bending ratios for the investigated UHSS sheets as compared to the ratios from standardized bending tests.

1. Introduction
The characterization of bendability is one of the key mechanical tests during the formability assessment of sheet metal. Different standardized tests have been established, mainly proposing bending into a V-shaped die or free 3-point bending on supports [1-3]. While these bending operations might be considered relevant for pressbrake bending into V-shaped dies, the validity of such tests for other industrial bending operations such as roll forming, brake bending, folding or hemming might be questioned. These operations exhibit an asymmetric deformation process in contrast to the typically symmetric standardized bending tests.

While performing standardized bending tests of ultra-high strength steel (UHSS) sheets with a low work hardening capacity, frequently so-called punch-sheet-liftoff can be observed (Figure 1). The radius on the inner side of the sheet after the test is lower than the desired tool radius [4]. This phenomenon can be seen in industrial bending processes as well. It is caused by severe strain localization during bending and has been shown to depend on the work hardening rate of the respective material [4-5]. The high bending strains caused by the locally high curvature may then lead to surface cracks and subsequently to fracture during bending. Even if the material is able to sustain these high strains, geometry deviations might still be a problem, e.g. an improper initial unfolded length for a closed profile. Punch-sheet-liftoff has also adverse implications during standardized bendability characterization. Typically the tool radius to sheet thickness ratio, \( r_{TOOL}/t \)
is reported as measure for bendability. Obviously the occurrence of punch-sheet-liftoff leads to $r_{\text{TOOL}}/t$ being larger than the actual $r_{\text{IN}}/t$ with $r_{\text{IN}}$ as the true inner sheet radius, which might be a better indicator for the actual bendability (Figure 1).

![Figure 1: Punch-sheet-liftoff during standardized bending tests and industrial press brake bending of UHSS sheets: $r_{\text{IN}} < r_{\text{TOOL}}$.](image)

However, the determination of $r_{\text{IN}}$ is elaborate and adds an undesired additional process step to material characterization e.g. during quality control. Thus a bending test directly depicting $r_{\text{TOOL}}$ on the inner contour of the sheet is desired. The idea is to force the UHSS sheets into a series of minor strain localizations instead of a single severe strain localization during bending. This can be achieved for pressbrake bending into a V-shaped die by several ways, including e.g. bending and subsequent coining into a die with the desired outer radius (with the disadvantage of a thickness dependent outer radius), or bending into an elastic polymer substrate (possibly not withstanding the forces during punch-sheet-liftoff of UHSS sheets) [6].

Herein an alternative bending setup is presented. The features of the proposed setup are discussed in detail. The results of this bending process are compared to corresponding standardized bending into a V-shaped die with respect to the inner radius as well as the bending strains on the outer fiber. The device is tested for an UHSS grade exhibiting $R_m \geq 1180\text{MPa}$, where typically problems with punch-sheet-liftoff and all of its implications are observed.

## 2. Materials and Methods

### 2.1. Materials tested

The investigated material was an UHSS grade for cold forming with an ultimate tensile strength $R_m \geq 1180\text{MPa}$, namely CR900Y1180T-CP in uncoated condition according to VDA 239-100 [7] in 1.49mm sheet thickness. The characterization of the anisotropic elasto-plastic material behavior was conducted according to Hackl and Till [8] using uniaxial tensile tests in rolling, transverse and diagonal direction as well as hydraulic bulge tests.

### 2.2. Bendability characterization

A standardized bendability characterization, i.e. bending into a 90° die of 50mm width according to ASTM E290 [2], shows 4.0mm as the feasible $r_{\text{TOOL}}$ for CR900Y1180T-CP 1.49mm, i.e. without cracks or surface wrinkling. This leads to $r_{\text{TOOL}}/t$ of 2.68. Measuring the true inner radius using a radius gauge reveals $r_{\text{IN}} < 3.0\text{mm}$, i.e. $r_{\text{IN}}/t < 2.01$, serving as an excellent example of the shortcomings of the standardized V-bending setups during bendability assessment. Thus a bending radius of 3.0mm was chosen for the first investigations using the proposed bending device.
2.3. Proposed Testing device

The proposed bending test device was planned to imitate bending or flanging operations performed in multi stage stamping lines, i.e. clamping of one half of the specimen and bending the sheet using a vertical tool movement. Thus the bending deformation pattern differs from the symmetric setups in the bendability characterization tests as it is now an asymmetric bending deformation. In order to reduce the effect of friction, the descending part of the tool was chosen to be a roll which was left free to rotate (Figure 2). Despite the fact that no die angle is prescribed in the standards for bendability characterization [1-3], many actual V-bending setups exhibit a 90° die opening angle. However, in 3-point bending setups, typically no specific final bending angle is targeted [1-3] and the specimens are often bent to 180° afterwards. Thus a 90° bending angle was not seen as a requirement and subsequently the bending angle of a first setup was chosen to be 135°, while a 90° option is planned in the future. In order to facilitate different bending radii, exchangeable bits of different tool radii were manufactured.

The whole setup was designed to fit into a standard 2- or 4-column die set to be mounted into an industrial forming press or to be operated by a hydraulic cylinder on a test bed. FEM simulations of the setup were conducted using the linear elastic solver provided by the used CAD system (Autodesk Inventor). These simulations revealed that the expected elastic deformations in lateral direction for a force level occurring during testing a 100mm wide sheet of $R_{P0.2}\geq1000\text{MPa} \& t=1.8\text{mm}$ (upper limit of the targeted steel grade/thickness combination) were <0.1mm which was deemed to be acceptably small. It can be further reduced by using narrower samples down to a minimum of 8 times sheet thickness, the minimum width recommended for an undisturbed plane strain bending region in the sample center [9].

Figure 2: Proposed bending test device - sample sheet in blue, exchangeable radius bit in red (left) and mounting situation in a 2-column die set (right).

Inspecting the curvature progression of a typical bending tool reveals that the contour alternates between a curvature of 0 for the straight tool parts and more or less sharp transition to a constant curvature of $1/\text{R_{TOOL}}$. This sharp transition has been observed as fracture initiation region during first bending tests trials using this setup. However, such transitions are usually burnished during the finishing of industrial stamping tools prior to their application. In order to “burnish” the curvature transition of the tools used herein in a controlled manner so called Euler spiral sections were adopted. These are capable of providing continuous curvature transitions. Herein so called normalized Euler spirals are used. The spiral sections are to replace the first 22.5° of the 135° bend from both sides ($\beta$ in Figure 3; for a mathematical derivation of the normalized Euler spiral see Appendix). The short Euler
spiral sections were discretized via 50 line segments and the exchangeable radius bits were manufactured by EDM wire cutting from a block of hardened tool steel.

![Graph](image-url) Figure 3: Comparison of bending tool geometries: sharp curvature transition tool (dashed green) of R3 and Euler spiral segment tool (red, dashed black: Euler spiral segments with $\beta=22.5^\circ/\alpha=2.0$) for R3E - contour of the tools (left) and curvatures along unwound length (right).

The desired radius for the investigated UHSS grade was 3.0mm, yielding a bending ratio of 2.0 for the target thickness of 1.5mm. This radius was investigated with (R3E) and without Euler spiral segment (R3).

2.4. FEM Simulation

To assess the bending strains as well as differences of the strain distributions of the standardized ASTM E290 V-bending test as compared to the proposed bending device, 2D models of the bending processes have been simulated using ABAQUS 6.14-4, utilizing the plane strain condition in the sample center. The material behavior was simulated using anisotropic Hill48 plasticity and isotropic hardening. Both the bending process and the corresponding unloading were simulated. The bending strain distribution as well as the local curvature along the inner and outer contour of the sheet are determined after unloading. Next to the simulations of the proposed bending device the ASTM E290 V-bending tests were simulated as well for $r_{TOOL}$ of 3.0mm.

3. Results and Discussion

3.1. FEM Simulation

The simulation results show that the proposed bending device succeeded in transforming the single strain localization in standardized V-bending into a series of strain localizations (Figure 4). The number of localizations depends on the bending ratio and the bending angle. The local strain maxima seen in the proposed setup using tools without transition, i.e. R3, had been reduced by 26.2%, respectively (Figure 5, left). The R3E setup delivers a strain reduction of 48.9% as compared to the respective standardized V-bending setups. It can be seen that R3E does not show any local strain maxima any more (Figure 5, left). The bending zone of R3E appears to show a constant bending strain along the inner and outer fiber. The bending strain on the outer contour is in good agreement with a theoretically estimated $\Delta(r_{TOOL}/t)$, based on the Bernoulli-hypothesis for slender beams, for this bending ratio.
Figure 4: Bending strain distribution of the standardized V-bending (left), proposed bending device (middle) and proposed bending device using an Euler spiral segment (right) of $r_{\text{TOOL}} = 3.0\text{mm}$.

The curvature progression along the inner sheet contour confirms that the standardized V-bending setup R3v shows punch-sheet-liftoff, i.e. the maximum curvature is larger than $1/r_{\text{TOOL}}$ (Figure 5, right). The proposed testing device should be capable of completely suppressing punch-sheet-liftoff for the R3E tool, and almost eliminated for R3 tool.

![Figure 5: Calculated strain distribution along the outer fiber of the bent sheets (left) and calculated inner curvature progression (right) of the proposed as well as standardized bending setups for $r_{\text{TOOL}}$ of 3mm; strains compared to $\epsilon(r_{\text{TOOL}}/t)$; curvature compared to desired curvature of $\kappa_{\text{IN}} = 1/r_{\text{TOOL}}$.](image)

### 3.2. Bending tests using the proposed device

Bending tests were performed using the two different tool radius bits available for the proposed bending device. After the tests, images from the bent edges as well from as micrographs prepared from the bending zones were taken. The images from the microsections were processed using image processing software (HALCON HDevelop 18.11) to extract the inner curvatures of the bent samples.

The images of the bent sample edges and their corresponding micrographs reveal that the proposed bending test device is actually able to almost completely suppress punch-sheet-liftoff using the R3 tool as compared to R3v (Figure 6, left). However, surface wrinkles and a slight flattening can still be observed for R3. A further improvement of the contour can be seen on the bent samples using the R3E tool, although surface wrinkling could still be observed to some extent (Figure 6, left). The curvature progression along the inner sheet side (Figure 6, right) shows reasonable agreement with the corresponding simulation results for the proposed test setup using both the R3 and the R3E tool (see Figure 5, right).

The investigation will be expanded to a broader variety of UHSS grades and also tested for different tool radii.
Figure 6: Edges of the bent samples (left, top row) and corresponding profiles extracted from microsections (left, bottom row) as well as calculated inner curvature progression of the bent sheets and extracted from the microsections (right) compared to the desired curvature of $\kappa_{IN}=1/r_{TOOL}$.

4. Conclusions

The proposed bending test device is able to depict the tool radii on the inner side of the bent sheets suppressing punch-sheet-liftoff. As a consequence more realistic bending ratios for UHSS could be reached as compared to those from standardized bending tests. By mimicking the burnishing process of industrial bending tools using a defined transition between straight tool parts and the targeted curvature, the depicted inner radius on the sheets was even in better agreement with the tool radius.

References

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Appendix – Mathematical description of the Euler spiral segments

θ…local slope of the Euler spiral  k…local curvature  s…arc length variable
L…total arc length  R…final radius  β…final slope of Euler spiral

The curvature $k$ is defined as:

$$k = \frac{d\theta}{ds} = \frac{\frac{d^2y}{dx^2}}{(1+\left(\frac{dy}{dx}\right)^2)^{3/2}}$$  \hspace{1cm} (A1)

with

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \ dx$$  \hspace{1cm} (A2)

A general Euler spiral is defined by:

$$\theta = \frac{c}{a+1} s^{a+1}$$  \hspace{1cm} (A3)

with $a$ as curvature transition parameter. If $a = 1$ the general Euler spiral becomes a Klothoide. The arc length variable $ds$ can be split into its Cartesian components $dx$ and $dy$:

$$\begin{pmatrix} dx \\ dy \end{pmatrix} = \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix} ds$$  \hspace{1cm} (A4)

Integration between 0 and $L$ with $l \in [0, L]$ reads as:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \int_0^l \begin{pmatrix} \cos \left( \frac{c}{a+1} s^{a+1} \right) \\ \sin \left( \frac{c}{a+1} s^{a+1} \right) \end{pmatrix} ds$$  \hspace{1cm} (A5)

Substituting $s$ and $ds$ for $s'$ and $ds'$ by:

$$s' = \frac{a+1}{c} \sqrt{c+1} s$$  \hspace{1cm} (A6)

$$ds' = \frac{a+1}{c} \sqrt{c+1} ds$$  \hspace{1cm} (A7)

yields:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \int_0^{\frac{a+1}{c} \sqrt{c+1}} \begin{pmatrix} \cos \left( s'^{a+1} \right) \\ \sin \left( s'^{a+1} \right) \end{pmatrix} \sqrt{\frac{a+1}{c}} ds'$$  \hspace{1cm} (A8)

The boundary conditions of the Euler spiral read as:

$$\frac{1}{R} = k = \frac{d\theta}{ds} \bigg|_L = cs^a \bigg|_L = cl^a$$  \hspace{1cm} (A9)

$$\beta = \theta \bigg|_L = \frac{c}{a+1} s^{a+1} \bigg|_L = \frac{c}{a+1} l^{a+1}$$  \hspace{1cm} (A10)

inserting (A9) into (A10) and eliminating $c$ yields:

$$\beta R = \frac{1}{a+1} l$$  \hspace{1cm} (A11)
or:
\[ L = (a + 1)\beta R \]
Inserting (A12) into (A9) yields:
\[ c = \frac{1}{(a+1)^2} \frac{1}{\beta^2} \frac{1}{R^{a+1}} \]  
(A13)

(A8) can now be written as:
\[ \left( \begin{array}{c} \dot{x} \\ \dot{y} \end{array} \right) = \frac{a+1}{[(a + 1)R]^{a+1} \beta^2} \int_0^t \left( \begin{array}{c} \cos(s'^{a+1}) \\ \sin(s'^{a+1}) \end{array} \right) ds' \]  
(A14)

For a general position of the Euler spiral the start coordinates \( x_0 \) and \( y_0 \) as well as the starting angle \( \theta_0 \) have to be considered in the following way:
\[ \left( \begin{array}{c} \dot{x} \\ \dot{y} \end{array} \right) = \left( \begin{array}{c} x_0 \\ y_0 \end{array} \right) + \frac{a+1}{[(a + 1)R]^{a+1} \beta^2} \int_0^t \left( \begin{array}{c} \cos(s'^{a+1}) \\ \sin(s'^{a+1}) \end{array} \right) ds' \]  
(A16)

If only the end coordinates \( x_L \) and \( y_L \) are known, \( x_0 \) and \( y_0 \) can be obtained by:
\[ \left( \begin{array}{c} x_L \\ y_L \end{array} \right) = \left( \begin{array}{c} x_0 \\ y_0 \end{array} \right) - \frac{a+1}{[(a + 1)R]^{a+1} \beta^2} \int_0^t \left( \begin{array}{c} \cos(s'^{a+1}) \\ \sin(s'^{a+1}) \end{array} \right) ds' \]  
(A17)

Solving this integral will be done by substituting \( \sin \) and \( \cos \) by their respective series forms:
\[ \cos s = \sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n)!} s^{2n} \]  
(A18)
\[ \sin s = \sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n+1)!} s^{2n+1} \]  
(A19)

The integration terms then read as:
\[ \cos s'^{a+1} = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!} s'^{(a+1)2n} \]  
(A20)
\[ \sin s'^{a+1} = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!} s'^{(a+1)(2n+1)} \]  
(A21)

and the respective integrals result to:
\[ \int_0^t \cos s'^{a+1} ds' = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)![(a+1)2n+1]} t^{(a+1)2n+1} \]  
(A22)
\[ \int_0^t \sin s'^{a+1} ds' = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)![(a+1)(2n+1)+1]} t^{(a+1)(2n+1)+1} \]  
(A23)

with
\[ t' = \frac{a+1}{[(a + 1)R]^{a+1} \beta^2} \]  
(A24)

As the series expressions for \( \sin \) and \( \cos \) are alternating, the error of the series up to \( N \) instead of \( \infty \) w.r.t. \( \sin \) and \( \cos \) is given by:
\[ \left| \int_0^t \cos s'^{a+1} ds' - \sum_{n=0}^{N} \frac{(-1)^n}{(2n)![(a+1)2n+1]} t^{(a+1)2n+1} \right| \leq \frac{(-1)^N}{(2N)![(a+1)2N+1]} t^{(a+1)2N+1} \]  
(A25)
\[ \left| \int_0^t \sin s'^{a+1} ds' - \sum_{n=0}^{N} \frac{(-1)^n}{(2n+1)![(a+1)(2n+1)+1]} t^{(a+1)(2n+1)+1} \right| \leq \frac{(-1)^N}{(2N+1)![(a+1)(2N+1)+1]} t^{(a+1)(2N+1)+1} \]  
(A26)