Experimental issues in the instrumented 3 point bending VDA238-100 test

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Abstract. The instrumented 3-point bending test according to VDA238-100 test standard is increasingly used within the steel and automotive industry. Originally developed for aluminum hemming characterization, this bending test has been shown to be also relevant for local formability and crash foldability assessment originally of press-hardened steel grades and more recently for newly developed advanced and ultra high strength AHSS/UHSS steels grades. This instrumented bending test delivers bending load vs. bending angle curves. It is commonly assumed that material failure shortly happens beyond maximum load after a 30N load drop. The bending angle at maximum force \( \alpha_{F_{\text{max}}} \) characterizes then the bendability of the investigated material. The assumption maximum force = bending crack initiation, while being true for press-hardened grades, is in too many case not valid for steel grades with tensile strength \( \leq 1200\text{MPa} \) and cannot be universally trusted. An alternative approach is presented using passive acoustic emission sensors placed in the vicinity of the bending punch. The interpretation of such acoustic data is however quite subjective and still in trial status. Redundant crack detection systems based on load, acoustic as well as optical measurements may have to be considered together for increasing crack detection reliability within the VDA238-100 bending test specification.

1. Introduction
The instrumented 3 point bending test according to VDA238-100 has established itself in the last decade as a reference standard test for automotive sheet steel bendability characterization [1]. One major motivation is the correlation between bending angle at maximum load commonly assumed to describe crack initiation with axial & side impact crash ability for automotive PHS press-hardened steels ([2]-[4]) as well as for AHSS/UHSS advanced/ultra high strength steels ([2],[5]). Some correlation of bending angle at crack initiation (but not necessarily with bending angle at maximum load) has been found with material fracture toughness in [6]. The correlation with local formability from (notched) tensile test thickness fracture is however not that obvious [7]. There are some ongoing investigations for increasing VDA238 testing accuracy with regard to bending angle formula [8], test set up stiffness characterization and optimization [9]-[11], thickness dependency of bending angle at maximum load [12] or punch-sheet-liftoff and its prevention [8],[13]. The validity of maximum bending load as universal material bending failure criteria is questioned in [5],[6],[14]. Recently interest shifts therefore towards digital image analysis DIC assisted VDA238 bending test both for optical accurate crack detection as well as plane strain fracture strain determination for damage model calibration [14]-[19].

Some investigations deal with alternative acoustic measurement for damage evolution assessment during bending test [20]-[22]. The present investigation gives a critical assessment of the reliability of the bending angle at maximum load with regard to physical crack initiation detection in VDA238
bending test. The results shown in this contribution originate from R&D activities covering the last decade and are neither representative of the current material development and specification status nor of the actual test setup development stage.

2. Experimental procedure

Figure 1 shows the bending test setup and test parameters. In the following investigation and figures, VDA238-100 standard bending test conditions as defined in Figure 1 apply if not specifically mentioned differently. Sample failure is supposed to occur in the maximum load range. After reaching the maximum load, the test is however not interrupted but is performed up to a bending angle around 160°, which is dependent on the sheet thickness. The recorded bending load/displacement curve is used to calculate the bending load/bending angle curve. Longitudinal/transverse designation refer to a bending punch tool line 0°/90° to rolling direction RD according to VDA238 specification.

![Bending test setup and test parameters](image)

- punch diameter: 0.8mm; roll diameter: 30mm
- roll distance = 2xthickness+0.5mm; punch testing speed: 20mm/min
- free rotating rolls, as delivered condition, no lubricant, no Teflon film
- sample size: 60x60mm (alternatively 30x60mm).

Figure 1: VDA238-100 instrumented three-point bending and acoustic test set-up.

Figure 2a illustrates the load based bending properties. Additionally to the VDA238 bending angle at maximum load (\(\alpha_{F_{\text{max}}}\)), the average (absolute) postuniform slope between maximum force and inflection point \(\left|\text{PUBS-F}\right|\) has proved useful within own previous PHS material investigations [3]-[4]. Figure 2b delivers an insight on acoustic emission based properties. A passive piezoelectric acoustic sensor (Vallen ASCO P-AE type) is located in the vicinity of the bending punch (Figure 1). It delivers via peak holder some Acoustic Emission event amplitudes \(\text{AE}(i)\) which are then integrated (summed up) over time as a Cumulated Acoustic Emission signal (CAE, equation 1) and synchronized at 50Hz versus punch displacement and load. The cumulated acoustic emission CAE can be divided into a continuous friction-related and a crack-related acoustic event contribution (Figure 2b).

![Bending curves with (a): Load based postuniform bending slope PUBS-F; (b): Cumulated Acoustic Emission CAE based postuniform bending slope PUBS-CAE.](image)
The baseline friction contribution can be fitted as a 2nd order polynomial vs. bending angle (equation 2). A clear upper deviation of this baseline is observed for the CAE signal at onset of material failure. The crack-related CAE* contribution can then be derived by subtracting the CAE friction fit contribution from the total recorded CAE signal (equation 3). The postuniform bending slope is derived based on CAE signal between crack initiation and bending test end at 160° with or without the friction contribution (PUBS-CAE: equation 4, PUBS-CAE*: equation 5). The analogy based on bending force vs. bending angle would be the postuniform bending slope |PUBS-F| between maximum force and inflection point as defined in equation 6 and Figure 2a.

\[
CAE(i) = \sum_{i=1}^{n} AE(i) \tag{1}
\]

\[
CAE_{\text{Crack free Friction Fit}} = -0.029555.\alpha^2 + 13.669319.\alpha \tag{2}
\]

\[
CAE^*_{\text{friction free}} = CAE_{\text{Recorded}} - CAE_{\text{Crack free Friction Fit}} \tag{3}
\]

\[
PUBS-CAE = (CAE_{160\degree} - CAE_{\text{Crack initiation AE}}) / (160\degree - \alpha_{\text{Crack initiation AE}}) \tag{4}
\]

\[
PUBS-CAE^*_{\text{friction free}} = CAE^*_{160\degree} / (160\degree - \alpha_{\text{Crack initiation AE}}) \tag{5}
\]

\[
|PUBS-F| = (F_{\text{max}} - F_{\text{inflection point}}) / (\alpha_{\text{inflection point}} - \alpha_{F_{\text{max}}}) \tag{6}
\]

The CAE signal is much smoother to analyze and can be considered as an integral acoustic energy of all acoustic events ever recorded (sample-punch first contact and friction, sample-rolls friction, roll bearing intrinsic friction). Tribological, hydraulic test setup as well as surrounding laboratory environment noise sources are therefore superposed on the actual material failure crack-related acoustic events of interest. The acoustic burst events range for the actual test set-up between 5 and ≈75dB depending on thickness and material strength and are often clearly audible for the operator (Figure 3).

Some samples break in a massive way (Figure 3a,b), other stepwise with individual acoustic peaks (Figure 3c), other sample only show some regular accumulated support roll friction noise and test artefacts which are not clearly linked to sample failure (Figure 3d). Isolated peaks before maximum force (Figure 3b-d) may be due to surrounding machine testing environment or maybe inner cracks on the compression side which do not affect the bending load curve. Slip-stick of bending rolls may (rarely) be an issue as well as possible lateral sample sliding under the punch (Figure 3d).

Due to the relative subjectivity of acoustic emission interpretation in the applied test setup, an automatic reliable test stop cannot be achieved. However it enables useful post-mortem analysis in order to check roughly within ±5° the bending crack initiation angle with regard to F_{\text{max}} location. If large discrepancies are detected between \alpha_{F_{\text{max}}} and \alpha_{\text{acoustic material failure}} then this should be reported in the test result protocol. Run out bending tests without material failure at all can be rather easily identified as friction driven without significant crack-related acoustic burst events accumulation.

It is also recommended to let the test run until maximum achievable displacement (≈14mm) and bending angle (≈160°), in this way the postuniform bending crack behaviour can be also assessed, since fracture mechanic and local ductility as well as crash behaviour (crashindex) do not solely depend on \alpha_{F_{\text{max}}} level but also on how fast cracks propagate under bending loading [3]-[6].

A pre-load is advantageous to avoid initial impact vibration noise at punch-sample contact. The acoustic sensor should be ideally placed on an immobile tool to avoid dynamic inertial effects as well as hydraulic cylinder noise. It should be fixed somewhere on a flat surface on the punch grip as mostly found in the literature ([20]-[22]). The configuration immobile punch with moving rolls may be more suitable than moving punch and fixed rolls with regard to parasitic vibration noise. The less connecting parts and distance between AE sensor and the sample, the better for the signal quality.
A frequency range for the AE sensor (100kHz-400kHz) is suitable for metals. An application of the AE sensor directly on the sample (Figure 1) however does not bring significant advantages (as also seen in [20],[21]), moreover it could lead to damage of the sensor and is not practicable for mass scale testing. A mechanical damping of the testing frame should not to be necessary in usual laboratory conditions.

Figure 3: Typical bending curves with AE instrumentation (a): Massive AE-signal with sudden break; (b): Double dip AE-signal 75dB; (c): AE-Signal with single peaks; (d): AE-signal artefacts.

3. Experimental results of crack-free bending curves
Over the past years many examples have been collected with obviously no cracks at all observed on 160° fully bent samples, which actually compromises the whole VDA238 bending test significance. Exemplary bending curves with no visual sample failure are given for mild and high strength low alloy HSLA samples (Figure 4a) as well as for AHSS up to 1000MPa tensile strength (Figure 4b). Misleading $\alpha_{\text{Fmax}}$ VDA238 values between 100° and 140° can still be determined. Bending samples may not fail at all while a pronounced bending angle at maximum force $\alpha_{\text{Fmax}}$ is delivered as test result (Figure 5).

A mild steel in the as delivered and 15% uniaxial pre-strained condition showed obviously no cracks up to 160° (Figure 5a). $\alpha_{\text{Fmax}}$ even increases with increasing pre-straining level, which contradicts the assumption that pre-straining should decrease $\alpha_{\text{Fmax}}$. This is rather linked to support roll transverse stiffness vs. sample thinning after pre-straining. Figure 5b shows bending curves with 20 replicates (crack-free at 160°) for HSLA grade HX340LAD, which unusually match together with atypical low scattering in $\alpha_{\text{Fmax}}$. Figure 5c shows HX500LAD bending samples with crack-free metallographic sections neither at maximum force nor after 160° bending. The usual anisotropy between longitudinal and transverse direction for $\alpha_{\text{Fmax}}$ also unexpectedly disappear. Figure 5d shows a DP600 steel grade with varying thickness with no cracks up to 160° (only friction contribution below 5dB in AE-signal). A decrease of $\alpha_{\text{Fmax}}$ with increasing thickness is even suggested, which rather is a consequence of increasing lateral bending force triggering the maximum force sooner. Figure 5e,f show similarly results
for DP800 and CP800 steel grade with $\alpha_{F_{\text{max}}}$ between 100° and 160° without any cracks and low 5dB AE-signal. Thinner material often show a strictly monotonic increasing bending curve ($\alpha_{F_{\text{max}}}=160°$).

Figure 4: Bending curves with $\alpha_{F_{\text{max}}}$ without failure (a): Mild/HSLA steels; (b): AHSS steels.

Figure 5: Bending curves with maximum force without failure (a): DC04; (b): HX340LAD; (c): HX500LAD; (d): DP600; (e): DP800; (f): CP800.
Some attention should be paid in minimizing the outward elastic lateral displacement of support rolls under loading conditions. There is some evidence that such a transverse stiffness issue do trigger maximum force arbitrarily depending on test setup design [9]-[11]. The maximum force if not due to material failure is rather a result of work hardening, strength, thickness, overall bending angle level and bending roll distance (2xthickness+0.5mm) interacting with lateral support roll stiffness.

As shown in Figure 6a with an older test setup [9], a 0.2mm support rolls elastic deformation triggers a maximum bending load regardless of the material investigated (no cracks at 160°). FE simulations (Abaqus explicit, CPE8R plane strain 2D shell elements, Hill48, no damage, no friction) show a high sensitivity of \( F_{\text{max}} \) location to bending roll transverse stiffness (fixing the rolls on a horizontal linear spring with stiffness \( K \), Figure 6b). The horizontal compliance of the rolls produces a force maximum due to the altered geometric conditions during the bending test without any material failure occurrence.

The horizontal force acting on bending rolls assuming rigid tools in FEM Simulations reads [9]:

\[
F_{\text{Rollx, Rigid}} = 0.5 * F_{\text{Stamp, Rigid}} * \tan\left( \alpha_{\text{Rigid}}/2 \right)
\]

(7)

The horizontal displacements of rolls \( \Delta X_{\text{Roll, Exp}} \) are taken from experiments in Figure 6a [9] in this case for DP600_2mm and HX340LAD_1.75mm. An average linear spring stiffness \( K \) of the bending roll support is determined from experimental data over all steel grades data (half of setup simulated):

\[
K_{\text{Spring}} = F_{\text{Rollx, Rigid}} / \Delta X_{\text{Roll, Exp}} / 2
\]

(8)

The simulation of compliant setups is then carried out fixing the rolls on a horizontal spring with stiffness \( K \). Altering the horizontal compliance enables to arbitrarily shift the bending angle at maximum force. The higher the tool rigidity the higher the bending angle at maximum force until it disappears with the standard rigid tool configuration (Figure 6b). The test setup bending roll transverse stiffness must therefore be taken into account for reliable bending test FE simulation. A nonlinear spring might be able to better describe the horizontal deformation behaviour of the rolls [9]. The bending stiffness of the rolls should be ideally increased in such a way to minimize this issue. In any way the \( \alpha_{F_{\text{max}}} \) values are rather meaningless and even highly test setup dependent if no material failure occur.

4. Experimental results on mixed bending curves with/without cracks

A multitude of bending tests show some cracks with the bending punch in longitudinal direction but no cracks in transverse direction as for DP600 in Figure 7a (test interrupted at maximum load) or for DP800 in Figure 7b (test up to 160° but with roll distance 2xthickness instead of 2xthickness+0.5mm). Longitudinal/transverse directions in Figure 7 and Figure 8 mean that the bending punch line is longitudinal/transverse to rolling direction according to VDA238 nomenclature convention. Note in Figure 7b that when reducing the roll distance to 2xthickness (as prescribed in the older VDA238 specification draft before 2010) the bending curves show no maximum force and a continuous steady load increase in spite of crack initiation at some point during bending test.
This indicates that the maximum force VDA238 criteria is mainly dependent on the prescribed bending roll distance. Figure 8a shows a deviation in differential bending slope for DP800 20° after maximum load in longitudinal direction. Figure 8b confirms the usefulness of comparing longitudinal and transverse bending curves. Some deviation from ideal Finite Element simulated plasticity behaviour (Abaqus explicit, CPE8R plane strain 2D shell elements, Hill48, no damage model, no friction) is a strong indicator for damage initiation. Transverse curves follow longer the ideal plasticity path than the longitudinal curves (Figure 8b). Figure 9a and Figure 9b show examples of crack detection with Acoustic Emission respectively for DP1000 and CP1200 with cracks beginning 15 to 40° beyond maximum load. The thinner the material the larger the discrepancy between $\alpha_{\text{Fmax}}$ and $\alpha_{\text{Acoustic crack initiation}}$.
The particular case of bending curves with sample-punch lift-off occurring with or without material failure should be considered. Punch lift off leads to a shift from 3 point to 4 point bending loading and a sudden secondary increase in bending load (“two humps” bending curves, Figure 5f & Figure 10a). As shown in Figure 10b the effect of roll distance on bending curve shape can also be simulated in FE simulations (Abaqus explicit, CPE8R plane strain 2D shell elements, Hill48, no damage model, no friction). An increase in thickness results in an increase in bending roll distance according to VDA238 specification ($d_{\text{roll}}=2\times\text{thickness}+0.5\text{mm}$). The lower the bending roll distance, the more a continuous increase in bending load is seen without properly defined load maximum ($\alpha_{\text{Fmax}}=160^\circ$, Figure 11a) and a material failure which is hidden within the increasing bending curve. The bending load drop from material failure superpose on top of it, which leads to a rather unpredictable load curve depending on crack propagation rate thus preventing a proper $\alpha_{\text{Fmax}}$ analysis and even definition (Figure 11b). The 3 point bending loading state is also no more fulfilled when punch lift off occurs and cracks may be triggered prematurely, which is not representative of the true material bendability [13].

Figure 10: CP1000 bending curves (a): Experiment vs. thickness; (b): FE simulation vs. roll distance.

Figure 11: CP1000: (a) Crack initiation vs. roll distance; (b): Bending curves with/without cracks.

5. Acoustic fracture analysis on AHSS bending curves
A wide selection of Cumulated Acoustic Emission CAE testing is shown in the 1000MPa tensile strength range (Figure 12a) and more generally for typical cold rolled steels in the tensile strength range 600-1200MPa and thickness range 1-2mm (Figure 12b). The test setup characteristic crack-free base line of each CAE curve seems surprisingly to be quasi-independent on material strength, thickness or steel sheet coating with free bending rolls and can be fitted with a 2nd order polynomial vs. bending angle (equation 2, Figure 12b) and subtracted later on from total CAE signal (CAE*), which gives an opportunity for a crack detection method. A significant deviation from the known crack-free CAE behaviour will then give a strong indication on macroscopic failure start. How soon and how fast the friction-free CAE* amount grows is a valuable information with regard to the fracture toughness of the investigated microstructure in bending loading condition.
Some selected examples for accumulated acoustic emission CAE are shown with total experimental data in Figure 13a as well as corrected from the friction contribution in Figure 13b. The postuniform bending slopes with or without friction PUBS-CAE / PUBS-CAE* (equation 4&5) are also valuable physical crack propagation related properties. Such acoustic characteristics may be more reliable than load based PUBS-F postuniform bending slope (equation 6) for crack propagation speed analysis. While PUBS-CAE is based on accumulated acoustic energy, the PUBS-F postuniform bending slope may be only largely dependent on geometric effects and test setup compliance concealing the material-related information. Alternative plots based on the distribution of Acoustic Emission peaks in form of histograms may also be of interest to distinguish the damage behaviour of different microstructure in plane strain bending conditions.

Table 1 shows the postuniform bending properties based on Figure 13. A much better differentiation can be reached with acoustic properties (CAE160, CAE160*, PUBS-CAE, PUBS-CAE*) in comparison to PUBS-F from bending curve postuniform slope between \( F_{\text{max}} \) and inflection point. Note the distinction between \( a_{F_{\text{max}}} \) (at absolute load maximum) and \( a_{F_{\text{max}}-30N} \) (from VDA238 specification 30N below \( F_{\text{max}} \) for cold rolled steels) which are often mixed up. In this case there is up to 6° difference between \( a_{F_{\text{max}}} \) and \( a_{F_{\text{max}}-30N} \). \( AE_{\text{crack initiation}} \) matches better with \( a_{F_{\text{max}}-30N} \) than with \( a_{F_{\text{max}}} \) for the selected materials.

| Material | \( a_{F_{\text{max}}} \) | \( a_{F_{\text{max}}-30N} \) | \( a_{\text{inflection}} \) | \( a_{\text{crack initiation}} \) | \( F_{\text{max}} \) | \( F_{\text{inflection}} \) | | | \( AE_{160} \) | \( AE_{160}^{*} \) | \( \text{PUBS-CAE} \) | \( \text{PUBS-CAE}^{*} \) |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material 1 | 127 | 133 | 142 | 15 | 136 | 2397 | 1841 | 37 | 17718 | 10140 | 433 | 422 |
| Material 2 | 90 | 96 | 122 | 32 | 100 | 3470 | 2490 | 31 | 5096 | 3656 | 67 | 61 |
| Material 3 | 69 | 73 | 99 | 30 | 73 | 4648 | 3003 | 55 | 2519 | 1009 | 19 | 12 |
6. Conclusions
Whatever strength level considered up to 1200MPa there is always a counterexample to be found for which the VDA238 assumption maximum bending load $F_{\text{max}} = \text{crack initiation}$ is contradicted. A non-negligible amount of tests show a crack initiation way after $F_{\text{max}}$ or even no cracks at all (run out) in spite of a well-defined load maximum in the bending curve, thus $\alpha_{f_{\text{max}}}$ largely underestimating the true bendability of the investigated steel grades. Transverse test are more affected than longitudinal ones (VDA nomenclature). The thinner the material, the lower the strength level and the lower the strain hardening, the more this problem of invalid test may also occur. This is a major obstacle for a widespread use of this bending testing method for AHSS-UHSS characterisation based on load measurement alone. Unless each sample is checked visually for crack occurrence at $F_{\text{max}} - 30\text{N}$, the results cannot be trusted.

A significant improvement involves the use of online passive acoustic emission sensor for post-mortem crack detection analysis. This is however time and know how intensive and rather subjective since many test set up specific noise sources superpose to the actual crack events. Ideally some video instrumentation would complete the load and acoustic emission instrumentation to deliver a more robust assessment on crack initiation and propagation rate. Video instrumented crack detection is however also subjective depending on lightning contrast as well as spatial and temporal image resolution when focusing on a constantly moving punch bending line. Bending test instrumentation is therefore quite a challenging task with no ready to go commercial application.

More over the bending curve maximum force in the absence of material failure is directly dependent on the test set up support roll stiffness and would therefore vary arbitrarily from test lab to test lab, delivering actually misleading information on the bending behaviour. The sample-punch lift off topic for steels with low n-value challenges also the very definition of $\alpha_{f_{\text{max}}}$ which is no more defined in case of a double hump bending curve.

Based solely on load instrumentation the VDA238 bending test therefore needs to be interpreted with special care taking into account the tested material, in order to avoid misleading results. Unless significant instrumentation improvement is made, the VDA238 bending test should remain in the field of martensitic press-hardened steels for which $F_{\text{max}} \approx \text{crack}$ is arguably fulfilled.

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