A critical assessment of notched tensile tests for formability mapping of AHSS sheets

L. Wagner1, P. Larour1, F. Sonlleitner1,2, A. Felbinger1,2, J. Angeli1,2

1voestalpine Stahl GmbH, voestalpine-Straße 3, A-4020 Linz, Austria.
2University of Applied Sciences Upper Austria - Campus Wels, Stelzhammerstraße 23, A-4600 Wels, Austria.

E-mail: leopold.wagner@voestalpine.com

Abstract. The influences of specimen geometry during the determination of local ductility have recently been investigated, using the fracture surfaces of standardized tensile tests specimens. Among the shortcomings of these specimens was the rather undefined strain path to failure, i.e. uniaxial tension followed by a deviation towards a more or less pronounced plane strain path, and the varying fracture angle, often hampering accurate image acquisition of the fracture surface. Notched tensile tests are currently used during damage model calibration for sheet metal for crash simulation. These samples exhibit a defined strain path to fracture and the notch triggers fracture predominantly perpendicular to the tensile direction. These kind of specimens have therefore been suggested as alternative to standardized tensile test specimens. However, several issues need to be addressed for notched tensile specimens as well, in addition to being an undesired additional test during e.g. quality control. These include again geometric considerations as well as the effect of different fracture types on the resulting measures of local fracture strain.

1. Introduction

Application specific material selection for the automotive body based on tensile test results, i.e. yield strength, tensile strength, tensile elongation, etc. has become a challenge due to variability of a wide range of AHSS/UHSS grades and their specific microstructure-based properties. Similar tensile properties might be gained by alternative material concepts, differing significantly in other tests, e.g. bending tests or hole expansion tests (HET). This has led to a demand for an additional material parameter to describe these differences.

Quite naturally, the two aforementioned tests are among the most promising candidates. The bending angle according to the VDA bending test [1] however has multiple shortcomings. Next to an inherent thickness dependency due to the fixed test setup geometry, there are also significant difficulties regarding determination of fracture according to the standard for many AHSS. Load maximum can typically no longer be associated with material failure, especially for relatively thin sheet material of $R_m \leq 800$ MPa [2-3]. So in order to apply bending angle according to VDA238-100 as a measure for local formability, additional instrumentation (e.g. DIC, acoustics, etc.) is vital to determine actual fracture and an alternative measure for bendability would have to be determined, e.g. bending strain. The second prominent candidate is the HET test [4]. This test however does not only describe the inherent material behavior, but the quality of punched hole is of paramount importance for the test results [5-7]. In addition, the resulting hole expansion ratio has to be considered at best “semi”-local, due to its...
measurement length of ~31mm, i.e. the circumference of the 10mm punched hole, and only thickness measurements at fractured edges of e.g. milled HET specimens might give insight to local formability [8] only.

An alternative which has recently been heavily investigated are fracture surfaces from uniaxial tensile tests. These have a multitude of advantages over the two aforementioned tests. Next to being readily available - since tensile tests are performed on a regular basis - there is no punched (i.e damaged) edge and the tests always lead to fracture. However, several shortcomings of standard uniaxial tensile tests have been presented, predominantly the dependency on tensile specimen geometry and sheet thickness [9-15]. The resulting width to thickness ratio w/t has been identified as a parameter to look at. Different fracture types, fracture angles, strain paths to fracture, etc. and thus different local fracture strains of the same material might result from different w/t.

Addressing fracture angle and strain path to fracture directly leads to considering notched tensile tests, which are mainly used for damage model calibration [8, 16-19]. Despite the fact that the strain path to fracture is again not in ideal plane strain for each material and thickness [19], the fracture angle should not substantially deviate from 90° to the loading direction, i.e. straight across the notch, regardless of the tested material and thickness, simplifying subsequent image acquisition. Different types of notched tensile specimens are currently used with notch radii typically ranging from 4mm up to 20mm [8, 16-19].

Studying a potential influence of notched specimen geometry requires three parameters, i.e. notch radius, notch width and sheet thickness. However, the influence of sheet thickness on measures of local fracture strain always contains both the geometric effect of a thickness variation, i.e. a varying width-to-thickness ratio and stress state at fracture, and the effect of possible microstructural differences of the same material produced in a different thickness [15]. Therefore, we choose again the opposite way of keeping the sheet thickness constant and varying the specimen geometry [11]. In order to achieve a fully scaled specimen in the notch region, not only the notch width has to be scaled, but also the notch radius and the gage width outside the notch.

Herein, the effect of differences in local fracture strain depending on the type of notched tensile specimen is investigated with ISO 6892 Type 2 specimen as reference. Formability mapping is attempted from results of notched tensile tests and compared to corresponding data from standard tensile tests. The results are discussed with respect to different types of fracture for all tested specimens. Varying the width-to-thickness ratio for notched tensile tests has been performed in order to study possible effects of w/t.

2. Materials and Methods

2.1. Materials tested

The four investigated materials are hot dipped galvanized AHSS grades, namely CR330Y590T- DP (DP600) in 1.0 and 2.0mm, CR700Y980T-DP (DP1000) in 1.0 and 1.5mm, CR780Y980T-CP (CP1000) in 1.0 and 2.0mm as well as CR900Y1180T-CP (CP1200) in 1.5 and 2.0mm.

2.2. Tensile testing

Tensile tests were performed using the standardized tensile test specimen Type 2 in ISO 6892 (ISO, see [20]), as well as notched tensile specimens. A commonly used notched specimen exhibiting a notch radius $R_{\text{NOTCH}}$ of 5mm and a notch width $W_{\text{NOTCH}}$ of 10mm (NR5) [8,16,18] was used, i.e. a geometry with $2R_{\text{NOTCH}} = W_{\text{NOTCH}}$. Sealed versions of this sample were tested to increase the $w_0/b_0$ range, having been scaled by 0.6 (NR3) and 1.5 (NR7.5), i.e. resulting in notch radii of 6mm and 15mm, respectively (Figure 1a-c). All tests were conducted in transverse direction.

2.3. Definitions of global and local formability

In the light of the many different descriptions of local and global formability in recent publications [9-15], clear definitions of the terms used to describe global and local formability are essential. Herein,
we use true uniform elongation from Type 2 specimen in ISO 6892 UE\textsubscript{TRUE}\textsubscript{ISO} as well as the corresponding true uniform elongations from the investigated notched tensile geometries UE\textsubscript{TRUE}\textsubscript{NRx} as measures for global formability in line with Hance formability plot original introduction \[9,14\].

Figure 1: Left: Notched tensile samples with notch radius of 3mm (NR6, a), 5mm (NR5, b) and 7.5mm (NR7.5, c) with overall sample dimensions 30 x 100mm; right: schematic illustration of (d) slant fracture across the thickness “S-Type”, as well as (e) U- or (f) V-shaped fracture across the thickness “V-Type”.

There is a multitude of possibilities to define a measure for local fracture strain, both from fracture surface or fracture thickness measurements [9-11]. Herein we use the true fracture strain TFS as well as true thickness strain TTS, following the definitions below:

\begin{align*}
\text{True Fracture Strain:} & \quad TFS = \ln(A_0/A_f) \quad (1) \\
\text{True Thickness strain}|\text{t} = \text{t}_{\text{MIN}}: & \quad TTS_{\text{MIN}} = \ln(t_{\text{MIN}}/t_0) \quad [-] \quad (2) \\
\text{True Thickness strain}|\text{t} = \text{t}_{\text{MID}}: & \quad TTS_{\text{MID}} = \ln(t_{\text{MID}}/t_0) \quad [-] \quad (3) \\
\text{True Thickness strain}|\text{t} = \text{t}_{\text{AV}}: & \quad TTS_{\text{AV}} = \ln(t_{\text{AV}}/t_0) \quad [-] \quad (4)
\end{align*}

with \(A_0\) and \(t_0\) as initial cross section and thickness as well as \(A_f\) as fracture cross section and \(t_{\text{MIN}}\), \(t_{\text{MID}}\) and \(t_{\text{AV}}\) as minimum fracture thickness, average fracture thickness within a centered quarter of the fracture surface width and average fracture thickness over the whole fracture surface width, respectively.

2.4. Determination of fracture types

Herein we do not elaborate on the details of microscopic fracture surface characterization but rather stay with a macroscopic description of the fracture surface only. We describe two different types of fracture, characterized by their appearance across the sheet thickness (Figure 1d-f). We consider slant fracture across the thickness, typically coinciding with relatively moderate necking prior to fracture (Figure 1d), as well as fracture showing a U- or V-shape (Figure 1e-f), typically coinciding with pronounced local necking prior to fracture. The latter two will be considered as V-Type whereas slant fracture will be addressed as S-Type. While S-Type clearly coincides with shear fracture, such a classification is more difficult for V-Type, since V- and U-shapes may represent both normal and shear fracture to some extent. The classification of individual samples is challenging based on microscopic imaging alone. However, with the additional indicators to the predominant fracture type, such as the aforementioned necking or the fracture angle, a classification for percentage of S- and V-Type within each fracture surface has been performed.

3. Results and Discussion

3.1. Evaluation of different local strain measures

As indicated above, many different measures of local fracture strain can be defined on a fracture surface of a uniaxial tensile specimen.
If thickness based measures $TTS_{\text{MIN/MID/AV}}$ are compared to a surface based measure $TFS$, one can observe that (Figure 2):

(a) $TTS_{\text{MIN}}$ is almost consistently higher than the corresponding $TFS$ for NR5 samples whereas this observation is only valid for DP1000, CP1000 and CP1200 for ISO samples. This can be explained by the higher work hardening of DP600, resulting in a pronounced width reduction prior to fracture for ISO specimens. This leads to a higher $TFS$, in contrast to the NR5 specimens, where width reduction is much less pronounced.

(b) for NR5 samples $TTS_{\text{MID}}$ vs. $TFS$ almost falls onto the 1:1 relation, whereas $TTS_{\text{MID}}$ is consistently lower than $TFS$ for all ISO samples.

(c) the correlation between $TTS_{\text{AV}}$ and $TFS$ shows the smallest scatter and lies in parallel to the 1:1 relation. The reason for the offset is the width reduction prior to fracture, which is relatively small for ISO and NR5 samples of DP1000, CP1000 and CP1200 – mainly due to their small $UE_{\text{ISO}}$ and the less pronounced width reduction of NR5 samples. Here, the ISO samples of DP600 again show a higher offset due to the high work hardening of DP600.

The comparison of thickness based measures to each other shows:

(d) that $TTS_{\text{MIN}}$–$TTS_{\text{MID}}$ (i.e. the often described symmetric parabolic shape of the fracture surface) is only valid for NR5 samples of DP1000 and CP1200. All other samples and materials show larger $TTS_{\text{MIN}}$ as compared to $TTS_{\text{MID}}$, resulting from the $t_{\text{MIN}}$ not being in the center of the specimens (e.g. ISO samples of DP600 and DP1000) or $t_{\text{MIN}}$ being a standout local minimum of a thickness profile (e.g. ISO and NR5 samples of CP1000).

(e) that – as expected – $TTS_{\text{AV}}$ is consistently smaller than $TTS_{\text{MIN}}$, which is most pronounced for “fish-tail” like fracture surface edges of CP1000 in 1.0mm.

![Figure 2](image-url)

**Figure 2:** Comparison of thickness based measures $TTS_{\text{MIN}}$ (a), $TTS_{\text{MID}}$ (b) and $TTS_{\text{AV}}$ (c) to area based measure $TFS$ as well as comparison of $TTS_{\text{MID}}$ (d) and $TTS_{\text{AV}}$ (e) to $TTS_{\text{MIN}}$ for all investigated steel grades; ISO (filled) and NR5 (empty) samples shown only.

3.2. **Comparison of ISO and notched NR5 geometries for formability mapping**

Formability mapping for the investigated steel grades is attempted using different combinations of global and local parameters (Figure 3). It has to be stated that global fracture strain values from the notched specimens cannot represent global formability, since the notch – restraining width reduction during the test – forces these specimens into almost instantaneous necking upon the start of plastic deformation (Figure 3a). Thus only $UE_{\text{ISO}}$ is used for further discussion of the results (Figure 3b-c) The
comparision of local fracture strain measures for ISO specimens and the corresponding NR5 specimens reveals big differences in the resulting strains for some of the investigated materials. While most prominent for CP1200 and DP1000, where - for TTS$_{MIN}$ and TFS - differences of a factor of ~2 between NR5 and ISO samples can be observed (Figure 3). CP1000 shows almost no differences between NR5 and ISO samples for TTS$_{MIN}$ and TFS, whereas the results of DP600 show a pronounced difference for TFS only (Figure 3).

This can be explained by the higher work hardening of DP600, resulting in a pronounced width reduction prior to fracture for ISO specimens. This leads to a higher TFS, in contrast to the NR5 specimens, where width reduction is much less pronounced. The width reduction has previously been identified as detrimental to the determination of local fracture strains, since the majority of width reduction typically occurs prior to local necking, and should therefore be rather related to the global formability of a material [17]. When purely thickness related measures – as TTS$_{MIN}$ – are compared, differences between NR5 and ISO samples for DP600 practically disappear (Figure 3c). However, the factor of ~2 between results from ISO and NR5 samples in general are in stark contrast to the findings in [15], where the reported differences did not exceed 20%. There might be several reasons for these differences, some of which will be discussed in the following.

Figure 3: Formability mapping of the investigated materials using TFS vs. UE of each test (also UE of the notched tensile tests – a), TFS vs. UE$_{ISO}$ (b), and TTS$_{MIN}$ vs. UE$_{ISO}$ (c); one thickness shown for each grade only (1.0mm for DP600, DP1000 & CP1000, 1.5mm for CP1200).

Figure 4: TFS and TTS$_{MIN}$ vs. width-to-thickness ratio w/t for DP600 (a), DP1000 (b), CP1000 (c) and CP1200 (d).
3.3. Influence of Geometry

Firstly, the previously investigated w/t ratio has to be addressed. It differs by a factor of 2 between ISO and NR5 samples. So for the grades with a factor of 2 between the investigated thicknesses (i.e. DP600 & CP1000) a direct comparison for constant w/t between ISO and NR5 samples is possible (Figure 4a,c). However, as stated above, for these two grades no substantial differences of TTS_{MIN} was observed between ISO and NR3 samples. Using the NR6 and NR7.5 samples, this comparison is also possible for the two other grades (i.e. DP1000: \( w_{ISO}/1.5mm = w_{NR15}/1.0mm \); CP1200: \( w_{ISO}/2.0mm = w_{NR15}/1.0mm \); Figure 4b,d). It can be seen that the differences in local fracture strain (TTS_{MIN} or TFS) between ISO and notched samples remain, even for the same w/t ratios.

3.4. Influence of fracture type

Considering the fracture type across the thickness might give further insight to the observed differences in local fracture strains between ISO and NRx samples (Figure 5).

One can observe that the results of the 1.0 and 2.0mm samples of DP600 remain separated in terms of TFS and TTS_{MIN}, even when considered with their respective fracture type (Figure 5a), and no distinct increase or decrease of TTS_{MIN} and TFS with increasing %V-Type can be seen.

The results of CP1000 can be grouped together for both thicknesses again and no distinct trends of TTS_{MIN} and TFS with increasing %V-Type can be seen for this grade as well. In general the majority of the results for these two grades lie above 50% V-Type. However, there is one NR7.5 sample of CP1000 2.0mm which lay separated in terms of TTS_{MIN} and TFS (Figure 4c), which can now be explained, since it is the only sample for CP1000 showing 0% V-Type fracture (Figure 5c).

For DP1000, NRx samples can be found from 0% to 100% V-Type (Figure 5b), with decreasing TTS_{MIN} and TFS with decreasing %V-Type. However the ISO samples remain separated in terms of TTS_{MIN} and TFS despite similar %V-Type. A possible explanation might be the different strain path to fracture initiation for these specimens. While it is well known that the strain path for uniaxial tensile tests diverts from uniaxial tension towards plane strain tension during diffuse and local necking [21], the extent of this deviation prior to fracture – and the implications of a strain path change on the damage tolerance – remain geometry and material specific. However, this does not necessarily mean, that the stress state at fracture initiation for ISO and NR5 samples become similar, since strain path deviations towards biaxial tension prior to fracture have also been reported for notched tensile tests [19].

![Graph](image_url)

**Figure 5:** TFS and TTS_{MIN} vs. percentage of V-type fracture within the fracture surface for DP600 (a), DP1000 (b), CP1000 (c) and CP1200 (d).
While ISO and NR5 samples might have the same %V-Type, they will typically show a different strain path to fracture initiation, e.g. their strain paths both cross the fracture limit for shear fracture well before that one for normal fracture but different strain paths lead to different stress states and accordingly to different fracture strains.

The only steel grade investigated which shows a consistent trend of TTS$_{\text{MIN}}$ and TFS for all samples, i.e. ISO and NRx, is CP1200 (Figure 5d).

For both DP1000 and CP1200, TTS$_{\text{MIN}}$ and TFS seem to decrease with decreasing %V-Type until ~50%V-Type, after which there seems to be a plateau, i.e. no further decrease until 0% V-Type (or 100% S-Type).

4. Conclusions

In addition to the disadvantage of having to perform an additional test instead of the typically already available standardized tensile tests, the notched tensile specimen has several other shortcomings as well. There is no access to meaningful global formability parameters based on notched tensile tests alone. So if notched tests are used to determine local fracture strains, a standard tensile test has to be performed as well in order to gain global formability parameters.

It is definitively worth to inspect the fractured surfaces of the samples used for formability mapping for their respective fracture type. This is the only way to clarify the observed differences between sample types and thicknesses for the same material, which may reach a factor of 2. However, fracture type does not fully explain differences seen between ISO and NRx samples with same w/t. The fracture type classification might not be fully adequate. V-Shape might also be attributed to shear fractures to some extent, i.e. two crossing shear slopes across the thickness as compared to a single slope in S-Type.

Other effects which might contribute to the observed differences may be the different strain path to fracture, triggering the same fracture mode earlier during the tensile test and thus yielding lower local fracture strains.

However, assessing local fracture strain measures of notched tensile tests might still be useful in order to keep track of the variation of damage model parameters for forming and crash simulation. A once calibrated damage model for a sheet material might be scaled according to the actual plane strain fracture strain during process robustness analyses.

References

[1] VDA 238-100:2010: Plate bending test for metallic materials, Verband der Automobilindustrie E.V., 2010.

[2] Wagner L, Larour P, Dolzer D, Leomann F, Suppan C (2020) Experimental issues in the instrumented 3 point VDA238-100 bending test. IOP: Mater. Sci. Eng. 967 012079.

[3] Noder J, Dykeman J, Butcher C (2021) New methodologies for fracture detection of automotive steels in tight radius bending: application to the VDA 238-100 V-bend test. Experimental Mechanics 61 367-394.

[4] EN ISO 16630: Metallic materials – sheet and strip – hole expansion test, European Committee for Standardization (CEN), 2017.

[5] Larour P, Pauli H, Freudenthaler J, Lackner J, Leomann F, Schestak G (2016) Experimental artefacts on ISO 16630 hole expansion ratio. In: Proceedings of the 35th International Deep Drawing Research Group Annual Conference (IDDRG2016), June 12-15, 2016, Linz, Austria.

[6] Larour P, Freudenthaler J, Eßbichl R, Kerschbaum M, Horinek H, Samek L (2017) Influence of shear cut edge condition on conical hole expansion ratio. In: Proceedings of the 5th International Conference on Steels in Cars and Trucks (SCT2017), June 18-22, 2017, Noordvijkerhout, Netherlands.
[7] Atzema E, Seda P (2017) Effect of zinc coating and time on edge ductility. In: Proceedings of the 5th International Conference on Steels in Cars and Trucks (SCT2017), June 18-22, 2017, Noordvijkerhout, Netherlands.

[8] Wagner L, Berger E, Larour P, Pauli H (2018) Forming fracture limits of AHSS sheets as related to different characterization tests. In: Proceedings of the 11th Forming Technology Forum, July 2-3, Zurich, Switzerland.

[9] Hance BM (2016) AHSS: Deciphering Local and Global Formability. In: Proceedings of the International Automotive Body Congress, Sept. 28-29, Dearborn, MI, USA.

[10] Larour P, Freudenthaler J, Weissböck T (2017) Reduction of cross section area at fracture in tensile test: measurement and applications for flat sheet steels. Journal of Physics: Conference Series 896 012073.

[11] Wagner L, Larour P (2018) Influence of specimen geometry on measures of local fracture strain obtained from uniaxial tensile tests of AHSS sheets. IOP: Mater. Sci. Eng. 418 012074.

[12] Larour P, Wagner L, Felbinger A, Angeli J (2019) Local fracture strain measurement in AHSS uniaxial flat tensile tests considering specimen geometry and fracture morphology. IOP: Mater. Sci. Eng. 651 012016.

[13] Westhäuser S, Schneider M, Teschner M, Denks IA (2019) Local ductility – key parameter for predicting formability of AHSS. IOP: Mater. Sci. Eng. 651 012049.

[14] Hance BM, Link TM (2019) Effects of fracture area measurement method and tension specimen type on fracture strain values of 980 class AHSS. IOP: Mater. Sci. Eng. 651 012061.

[15] Grünbaum M, Aydin G, Dettinger T, Heibel S (2019) Local formability of AHSS: Measurement technique, specimen types and robustness. IOP: Mater. Sci. Eng. 651 012056.

[16] Till ET, Hackl B (2013) Calibration of plasticity and failure models for AHSS sheets. In: Proceedings of the 32nd International Deep Drawing Research Group Annual Conference (IDDRG2013), June 2-5, 2013, Zurich, Switzerland p.119-124.

[17] Heibel S, Dettinger T, Nester W, Clausmeyer T, Tekkaya EA (2018) Damage mechanisms and mechanical properties of high-strength multiphase steels. Materials 11 761.

[18] Wagner L (2019) Towards consistent parameter identification tests for damage model calibration of sheet metal. In: Proceedings of the International Symposium on Impact Engineering (ISIE2019), July 2-5, Gmunden, Austria.

[19] Peshekhodov I, Dykiert M, Vucetic M, Behrens B-A (2016) Evaluation of common tests for fracture characterization of advanced high-strength sheet steels with the help of the FEA. IOP: Mater. Sci. Eng. 159 012014.

[20] EN ISO 6892:2017: Metallic materials – Tensile testing – Part 1: Method of test at room temperature, European Committee for Standardization (CEN), 2017.

[21] Hu SJ,Marciniak Z, Duncan JL (2002) Mechanics of Sheet Metal Forming. Elsevier.