Local ductility – key parameter for predicting formability of AHSS

S Westhäuser, M Schneider, M Teschner, I A Denks
Salzgitter Mannesmann Forschung GmbH, Eisenhüttenstraße 99, 38239 Salzgitter
s.westhaeuser@sz.szmf.de

Abstract. In order to be able to make targeted use of the advantages of AHSS grades in forming processes it is necessary to determine local material properties. Hence, in addition to edge crack sensitivity measures, such as hole expansion ratio according to ISO 16630 (HERISO), it is currently intensively discussed whether measures, that assess the local ductility of the material, should also be specified in material specifications. One representative is given by the parameter true fracture strain (TFS) that is based on the measurement of the fracture area of a cracked flat tensile specimen. By means of 16 different cold- and hot-rolled steel batches, the relation between the parameters TFS and HERISO was investigated. The outcome is that these parameters do not correlate to a satisfying degree when considering all materials and consequently are regarded as representatives of different material properties. Thus, the issue of the reliability of the measures is considered separately. For the regarded steel grades, the overall scattering of TFS, i.e. neglecting the sample orientation, is found to be 13 – 44 % and the scattering of HERISO is within 5 – 35 %. The high scattering of TFS is mainly caused by the anisotropy of the materials. In case of parallel measurements of the same batch the relative standard deviations of TFS and HERISO are on the same level for cold-rolled strips, whereas in case of hot-rolled strips the relative standard deviation of HERISO is significantly higher. By investigating the influence of the tensile specimen shape for a bainitic hot-rolled strip numerically, it could be shown that the width-to-thickness ratio, that takes the hole fracture area into account, influences the TFS value directly.

1. Introduction and motivation
In general, three different levels of testing are applied to a material before used for a serial part. These test levels are indirect testing, simulative testing and direct testing (Figure 1) [1]. Generally, the complexity and the costs are increasing by the consecutive levels. For this reason, a high predictability of the material’s performance in simulative and direct testing is aimed.

Regarding indirect testing, basic material parameters like uniform elongation as well as n- and r-values are considered. They might be called global ductility parameters. “Basic” material parameters are intended to be independent from other parameters and geometry. Simulative tests are used to estimate the formability of a material. In contrast to indirect tests, geometries and forming operations are used that are closer to the component manufacturing such as the Nakajima test. In case of deep-drawing grades or dual-phase steels, which transfer the strain over a comparatively large material region before the onset of necking, the global formability of the material can be predicted satisfactorily by global ductility parameters. A continuous predictability up to direct testing, i.e. component manufacturing in laboratory or in press shop, is possible.
In order to reduce the sheet thickness and to realize more complex geometries for lightweight constructions, AHSS grades have been developed and are nowadays available. Many of these grades can be severely deformed locally and thus have a so-called high local formability. Typically, the local formability is determined by tests like bending according to VDA238-100 and hole expanding that belong to the simulative testing level. The predictability of the local formability based on indirect test measures is subject of various recent studies. For example, the linear correlation between edge crack sensitivity (i.e. hole expansion ratio) and local ductility parameters like true fracture strain (TFS) is propagated for cold-rolled steel grades in many current publications [2, 3]. In [4, 5] it could be shown that such a correlation is only weak when hot strip grades are taken into account additionally. Investigations on the relation of global and local ductility to edge crack sensitivity measure lead to the conclusion that these three measures do not correlate in general [4, 5]. For this reason, in [4] it is proposed to introduce a third parameter at the level of indirect testing, which gives an indication of the crack resistivity of the material. Measures like true fracture strain of shear cut edges (TFS$_{SC}$) from hole expansion test with Nakajima punch [6] or essential work of fracture (EWF) [7] are possible parameters for quantifying the crack resistivity. However, these tests are not established yet. In [4] it is shown that all investigated materials possess a specific combination of global ductility, local ductility and crack resistivity. It is proposed to consider these three material properties from the basic indirect tests to predict the material’s performance in simulative tests such as ISO 16630 hole expansion ratio (HER$_{ISO}$). The independence of these material properties is visualized by means of a formability triangle and the relation of these properties to HER$_{ISO}$ as a representative of local formability is illustrated in Figure 2.

Thus, local ductility parameters play a central role in the predictability of simulative tests. Besides the prediction of the local formability by means of local ductility and a crack resistivity parameter, the knowledge of the local ductility of a material in combination with the global ductility is important for a satisfying prediction of the global formability of current steel grades. Due to the lack of real component comparisons, particularly with regard to HER, the predictability of direct testing is currently to be assessed as limited.

The determination of TFS is currently not defined in any standard. Based on the measurement of the fracture area of cracked flat tensile specimen, different evaluation methods are proposed. These methods differ mainly in whether the entire fracture surface area (TFS-A) or only individual sheet

![Figure 1. Material testing levels and temporal development of the characteristic values.](image-url)
thicknesses such as the maximum thinning (TFS-T) are determined and used for the calculation (see chapter 3).

![Diagram](image)

**Figure 2.** “Formability triangle” defined by global ductility, local ductility and crack resistivity.

The presented studies focus on the main topics:

1. Validation, by means of a larger database of the statement, found in [4, 5], that a linear correlation of the parameters TFS and HERISO is not generally valid
2. Numerical investigation of the influence of the sample shape on the TFS parameter
3. Assessment of the scattering of TFS and HERISO

2. **Material and its mechanical properties**

The investigations are carried out on the following 16 different combinations of material (6 hot- and 10 cold-rolled batches) and thickness (Table 1):

- Ferritic-bainitic hot-rolled strip containing approximately 80% bainite and 20% ferrite: HR-BS800 in 2.0 mm and 4.0 mm sheet thickness (3 batches)
- Ferritic-bainitic hot-rolled strip containing approximately 20% bainite and 80% ferrite: HR-FS800 in 2.0 mm and 4.0 mm sheet thickness (3 batches)
- Dual phase steel (cold-rolled strip): CR-DP600 and CR-DP800 between 1.0 mm and 2.0 mm sheet thickness (10 batches)

**Table 1.** Mechanical properties of investigated materials.

| Material    | Yield strength $R_{p0.2}$ (MPa) | Tensile strength $R_m$ (MPa) | Total elongation $A_{50}^* / A_{55}^{**}$ (%) |
|-------------|---------------------------------|-----------------------------|---------------------------------------------|
| HR-BS800    | $\geq 680$                      | 800 - 980                   | $\geq 10^* / \geq 12^{**}$                  |
| HR-FS800    | $\geq 700$                      | 750 - 950                   | $\geq 10^* / \geq 12^{**}$                  |
| CR-DP800    | 450 - 560                       | 780 - 900                   | $\geq 14^*$                                 |
| CR-DP600    | 340 - 420                       | 600 - 700                   | $\geq 20^*$                                 |

3. **Experimental procedures**

Tensile tests were carried out on test pieces transvers, diagonal and parallel to the rolling direction. For all materials equal or thinner 3.0 mm a non-proportional tensile specimen with an initial gauge length of 80.0 mm and a width of 20.0 mm ($A_{so}$ samples, shape H [9]) was used. In case of materials with 4.0 mm thickness proportional tensile tests ($A_5$ samples, shape E [9]) were performed with an initial
gauge length of 35.0 mm and a width of 10.0 mm. For all batches, four individual specimens were investigated for each combination of thickness and orientation to the rolling direction. The uniform elongation is taken as a measure for the global ductility, see chapter 3.1.1. [8, 9].

In order to determine the local ductility, two approaches are followed using a light optical microscope with 5.5x magnification:

1. Measurement of reduction of sample cross section area at fracture according to [5, 10]
2. Measurement of maximum thinning of sample cross section area at fracture according to [2, 5]

The hole expanding test according to ISO 16630 as one representative of local formability is conducted in order to quantify the edge crack sensitivity by the hole expansion ratio ($\text{HER}_{\text{ISO}}$) [11, 12]

4. Results and discussion

4.1. Global and local ductility

In accordance to the formability classification and rating system proposed in [10] for all 16 materials the TFS-A, TFS-T and $\varepsilon_u$ parameters are presented in Figure 3 for standard tensile specimen shapes (in each case longitudinally, transversely and diagonally to the rolling direction).

![Figure 3. TFS-A and TFS-T as function of true uniform strain standard tensile specimens according to [2, 10].](image)

The investigated steels show a specific combination of $\varepsilon_u$ and TFS. However, the scattering is large and differs for the samples and the evaluation methods. For instance, CR-DP800 (TFS-A from 0.63 to 0.88) reveals only approximately a third of the scattering compared to CR-DP600 (TFS-A from 0.69 to 1.43). The scattering of the individual samples of HR-BS800 is approximately three times in TFS-T compared to TFS-A. One reason might be that the effects of the sample orientation is more pronounced in TFS-T than in TFS-A.

In order to compare both local ductility evaluation methods, TFS-A is plotted versus TFS-T in Figure 4. The table shows the coefficient of determination for the adaptation of a unit line with respect to the rolling direction. The linear correlation can be considered in any case as reasonable and consequently TFS-A and TFS-T can be interpreted as equal (all coefficients are higher than 0.68).
Figure 4. left: Comparison of TFS-A and TFS-T for standard tensile specimens by means of a unit line; right: Table for coefficient of determination for the adaptation of a unit line for different rolling direction.

4.2. Correlation between local ductility and HER

In Figure 5, TFS-T versus true HER$_{ISO}$ is shown for all 16 materials. The left diagram presents the results of cold-rolled materials and the right diagram the corresponding results of hot-rolled materials. HER$_{ISO}$ is the mean value of 10 individual measurements.

Figure 5. TFS-T as function of true HER$_{ISO}$ for cold-rolled materials (left diagram) and hot-rolled materials (right diagram).

The cold-rolled dual phase steel samples are located at a TFS-T to true HER$_{ISO}$ ratio of approximately 2:1 to 3:1. Two groups of CR-DP600 can be identified. One group consists of 3 batches and has both high HER$_{ISO}$ and high TFS values. The other group comprises two different CR-DP600 batches, that show HER-values similar to the level of the CR-DP800. The five different CR-DP800
cold-rolled strips show no significant differences with respect to TFS-T as well as HER\textsubscript{ISO}. In-between one sample orientation the cold strip samples show a linear correlation between TFS-T and HER\textsubscript{ISO} (e.g. longitudinal to rolling direction: $R^2 > 0.8$). HR-FS800 shows ratios at around 4:1 and can be clearly distinguished from HR-BS800 with regard to both parameters. TFS-T to HER\textsubscript{ISO} ratios of HR-BS800 ranges from 2:1 to 3:1. As $R^2$ is between 0.3 and 0.65 depending on the sample orientation a sufficient linear correlation between TFS-T and HER\textsubscript{ISO} is not discernible in case of hot-rolled strips.

Significant differences in TFS-T with respect to the testing direction can be identified for all hot-rolled materials as well as for the most CR-DP600 samples. The highest TFS-T values are obtained in longitudinal direction for each material except CR-DP600. In case of CR-DP600, this applies to samples in longitudinal and diagonal direction. Neglecting the influence of the sample orientation and the thickness, the scattering of the TFS values, i.e. the relative deviation of the mean values of each batch from the mean value of the respective steel grade, is in the range of 13 - 44 % and the scattering of the HER\textsubscript{ISO} values in the range of 5 - 35 %. However, considering only one sample orientation, for instance longitudinal to rolling direction, scattering of TFS is reduced to 6 - 27 %.

5. Numerical simulation of tensile specimen

The numerical experiment aims to understand the geometrical influence on the TFS value without being subject to the influence of batch variation as in the experimental investigations. Accordingly, different width/thickness ratios (w/t ratios) of the tensile specimens are considered in the simulation. For a sheet thickness of 4.0 mm, the widths 4, 6, 10 and 20 mm are taken into account and in case of 2.0 mm thickness a width of 20 mm.

5.1. Model and material description

All virtual tensile specimens are modelled in LS-DYNA with under-integrated solid elements (elform 1). The initial edge lengths of the elements are 0.05 x 0.1 x 0.1 mm ($x$, $y$, $z$-direction), where $x$-direction corresponds to the loading direction of a longitudinal tensile test. With this configuration, it is achieved, that the elements are close to the ideal cubic shape over a larger range of strain.

For the numerical investigations the HR-BS800 with a thickness of 4.0 mm is selected. This steel has an anisotropic hardening behaviour which is described by the material model *MAT\_TABULATED\_JOHNSON\_COOK\_ORTHO\_PLASTICITY. The extrapolation of the hardening curves for 0°, 45° and 90° to the rolling direction is controlled by an inverse optimization [13]. The method of the smallest error squares is used to match the experimental and numerical stress-strain curves. The material behaviour is validated by comparing the numerical strain concentration in the necking area with experimental results measured with an optical strain analysis system. In order to determine the TFS value, the fracture surface is realized by using a MMC (Modified Mohr-Coulomb) failure model for the selected steel [14].

5.2. Results of the numerical investigation

Figure 6 (left) shows the superposition of the resulting fracture area from the numerical model in case of an initial width of 20.0 mm and thickness of 4.0 mm as well as the contours of the experimental tests of the HR-BS800. Regarding the small deviations in the thickness profile, width and maximum thickness reduction, the compromise in accuracy and computing time is regarded to be reasonable.

The virtual experiments show a strong dependence of the TFS-A and the TWS value (true width strain) on the specimen geometry (Figure 6 right) under consideration of different w/t ratios, especially at small ratios. This confirms the experimental results of Wagner [15]. The TFS-T value based on thickness reduction shows only a slight reduction with increasing w/t ratios.
Figure 6. Comparison of the fracture surface from virtual and experimental tests with initial width of 20.0 mm and thickness of 4.0 mm (left) and the TFS values related to w/t ratios from the virtual experiments (right).

The reason why the TFS-A value forms a constant plateau at w/t ratios of 5 to 10 is shown by comparing the section cuts taken instantly before cracking (solid line) with the initial rectangular section cuts (dotted line) (Figure 7). For all tensile specimen shapes, a similar thickness reduction occurs in the middle of the specimen due to necking under plane strain condition. With increasing w/t ratios, the material flow from the width is prevented geometrically. This is resulting in a decreasing TWS value, which has a direct influence on the TFS-A value (Figure 6).

Figure 7. Comparison of section cuts of virtual tensile specimens in initial condition (dotted line) and shortly before cracking (solid line).

Figure 8 shows the comparison of the stress states of the considered w/t ratios. The Lode angle parameter is plotted over the triaxiality for the elements which failed in the virtual tensile test. Each data point represents one element that is deleted to realize the fracture in the simulation. Figure 9 shows the stress ratios at the beginning of the necking (left) and one time step before the first element failed (right). The Lode angle parameter is required for the usage of damage modelling in the 3D application [14]. At a value of 1 it describes a tensile load, at 0 shear load and at -1 compression load. As expected, at the beginning of the necking (Figure 8 left) all specimen shapes are subjected to uniaxial tension. In case of specimens with large w/t ratios, it changes into a shear load during necking (Figure 8 right). This in turn confirms the results of Wagner [15]. Beyond a critical w/t ratio, the shear load increases to such an extent that the fracture behaviour changes from cup and cone type of fracture to shear type of fracture. The consideration of a further increase of the w/t ratio leads to the expected shear fracture in the virtual tensile tests (Figure 9).
Figure 8. Lode angle parameter related to triaxiality of the elements which failed for both at the beginning of necking (left) and the end of necking (right).

Figure 9. Influence of w/t ratios on development of fracture type (from cup cone to shear) using 1/4 tensile specimen due to high computing time. In case of w/t = 30 the complete specimen is used for simulation.

6. Comparison of relative standard deviations for parallel measurements
Figure 10 shows the standard deviations related to the corresponding mean values of the parameters TFS-A, TFS-T with sample orientation longitudinal to rolling direction and true HER_{ISO}. In the vast majority TFS-T has a larger standard deviation than TFS-A both for cold- and hot-rolled strips. This can be explained by the number of measures. In case of TFS-T the thickness of the fracture surface is only measured once whereas in case of TFS-A the effective sheet thickness is calculated by averaging three thickness measurements at different positions as described in chapter 3.

A comparison of the relative standard deviations of all measures with respect to cold-rolled and hot-rolled steel grades reveals the following differences. On average the standard deviations of both TFS parameters are smaller in case of hot-rolled strips. A reason might be the lower relative error for samples with higher thicknesses when using a microscope with fixed optical resolution. However, the relative standard deviation of true HER_{ISO} is on average higher for hot-rolled than for cold-rolled samples. Consequently, the relative standard deviation of the characteristic values TFS and true
HER\textsubscript{ISO} for cold-rolled strips are in most cases at a similar level (batches 1 to 10) whereas the relative standard deviation of true HER\textsubscript{ISO} is consistently significantly higher than of TFS for hot-rolled strips.

![Figure 10. Comparison of the relative standard deviations of the parameters TFS-A, TFS-T with sample orientation longitudinal to rolling direction and HER\textsubscript{ISO}.](image)

7. Summary and conclusion
Based on 10 cold- and 6 hot-rolled materials the local ductility and local formability as well as their relation were investigated. The local ductility parameter TFS was calculated using two different methods. The methods are based on the measurement of the fracture surface and the maximum thinning of the cracked tensile specimens, respectively. The edge crack sensitivity is represented by the local formability measure “hole expansion ratio” determined according to ISO 16630.

The most important outcomes of the studies are:

- Regarding all steel grades, the correlation between the parameters TFS and HER\textsubscript{ISO}, i.e. between local ductility and local formability, is not observed to a sufficient degree. For cold-rolled steel grades, a linear correlation of TFS and HER\textsubscript{ISO} is discernible (e.g. longitudinal to rolling direction: $R^2 > 0.8$).
- For the regarded steel grades, the overall scattering of TFS is found to be 13 – 44 % and the scattering of HER\textsubscript{ISO} is within 5 – 35 %. The high scattering of TFS is mainly caused by anisotropy of the materials.
- The TFS values depend significantly on the orientation of the tensile specimen. The most severe effect is observed in the examined hot-rolled specimens and in the 600 MPa strength class of dual-phase steel.
- The TFS-A value shows a strong dependence on the width/thickness ratio, whereas the TFS-T value fluctuates only slightly with increasing width/thickness ratios. The numerical simulation of TFS-A proofs that an increase in width/thickness ratio from 1 to 10 results in a drastic decrease of TFS-A from 1.43 to 0.81.
- On average the relative standard deviations of TFS-A, TFS-T and HER\textsubscript{ISO} are on the same level for cold-rolled strips. Consequently, using the measures TFS and HER\textsubscript{ISO} synonymously, as suggested for cold-rolled steels in [2] and [3], does not offer any advantages with regard to the variation of the characteristic values. In case of hot-rolled strips the relative standard deviations of HER\textsubscript{ISO} are significantly higher.
8. Outlook
Based on the presented results it is recommended to consequently distinguish between local ductility and crack resistivity when predicting local formability. The method of evaluation local ductility (i.e. TFS) needs to be refined in order to reduce inherent scattering. Subsequently, a standardization of the TFS determination is to be aimed. In order to determine the crack resistivity of steel sheets, a suitable test technique must be qualified.

References
[1] Emmens W C 2011 Formability Springer Berlin Heidelberg DOI 10.1007/978-3-642-21904-7.
[2] Larour P, Freudenthaler J and Weissböck T 2017 Reduction of cross section area at fracture in tensile test J. Phys.: Conf. Ser. 896 DOI: 10.1088/1742-6596/896/1/012073.
[3] Heibel S, Nester W, Clausmeyer T and Tekkaya A E. 2016 Damage characterization of high-strength multiphase steels IOP Conf. Ser.: Mater. Sci. Eng. 12013 159 DOI: 10.1088/1757-899X/12013/1/012013.
[4] Denks I A, Schneider M, Westhäuser S and Lesch C 2019 On the relation of global and local ductility to edge crack resistivity of advanced high strength steel sheets Steel Research International DOI: 10.1002/srin.201800460.
[5] Westhäuser S, Schneider M and Denks I A Local Ductility and Edge Crack Resistivity of Advanced High Strength Steel Grades, International Conference on „New Developments in Sheet Metal Forming” ISBN 978-3-947085-01-9
[6] Schneider M, Peshekhodov I, Bouguecha A, Behrens B-A 2016 A new approach for determination of formability of a steel sheet sheared edge Production Engineering - Research and Development Volume 10, Issue 3, pp 241–252 DOI: 10.1007/s11740-016-0677-4
[7] Casellas D et al. 2016 Fracture Toughness to Understand Stretch-flangeability and Edge Cracking Resistance in AHSS x, The Minerals, Metals & Materials Society and ASM International Volume 48, Issue 1, pp 86–94 DOI: 10.1007/s11661-016-3815-
[8] N.N. 2009 DIN EN ISO 6892-1 Metallische Werkstoffe-Zugversuch-Teil 1: Prüfverfahren bei Raumtemperatur Beuth Verlag.
[9] N.N. 2016 DIN 50125 Prüfung metallischer Werkstoffe-Zugproben
[10] Hance B 2016 Advanced High Strength Steel: Deciphering Local and Global Formability International Automotive Body Congress
[11] N.N. 2009 International Standard ISO 16630 Metallic Materials – Sheet and Strip – Hole Expanding Test
[12] Schneider M and Eggers U 2011 Investigation on Punched Edge Formability International Deep Drawing Research Group
[13] Schneider M, Teschner M and Westhäuser S Analysis of stress states during experimental determination of cut-edge formability LS-DYNA Anwenderforum
[14] Bai Y and Wierzbicki T 2008 A new model of metal plasticity and fracture with pressure and Lode dependence International Journal of Plasticity 24 (6) Volume 24, Issue 6, Pages 1071-1096 DOI 10.1016/j.ijplas.2007.09.004.
[15] Wagner L and Larour P Influence of specimen geometry on measures of local fracture strain obtained from uniaxial tensile tests of AHSS sheets International Deep Drawing Research Group 37th Annual Conference IOP Conf. Series: Materials Science and Engineering 418 DOI: 10.1088/1757-899X/418/1/012074