Edge crack sensitivity versus tensile local ductility of AHSS sheet steels

P Larour*, J Freudenthaler, M Kerschbaum, D Dolzer
voestalpine Stahl GmbH, voestalpine-Straße 3, A-4020 Linz, Austria.

E-mail: patrick.larour@voestalpine.com

Abstract. There is a growing interest in correlating usual tensile testing results with edge crack sensitivity testing from punched ISO16630 hole expansion ratio HER (10mm shear cut hole, 12% clearance, conical expansion tool). A new kind of tensile local ductility parameter has been developed lately based on broken sample surface of tensile specimens after testing. Reduction in area or thickness at fracture are more sensitive than conventional fracture elongation with a 50 to 80m gage length to characterize the local ductility potential of sheet steels. A representative amount (300 different sets of samples) of cold rolled sheet steels have been tested in the tensile strength range 600-1200MPa and thickness range 1-2mm with 3 replicates in the transverse and longitudinal direction with ISO 6892-1, type 2, A80 tensile samples. Correlation levels of ISO16630 HER values with conventional tensile mechanical properties such as uniform & fracture elongation, yield & tensile strength, n- & r-values or derivatives are disappointing low for the investigated AHSS grades. There is however a massive improvement in the empirical statistical correlation when using local ductility properties based on fracture area or thickness reduction measurements on broken tensile samples. Logarithmic local ductility strains correlate generally linearly with logarithmic hole expansion ratio. Logarithmic true local ductility values are proving more suitable than engineering strains for correlations. Transverse direction improves slightly the correlation quality vs. longitudinal direction. The correlation is also higher for thickness reduction in comparison to reduction of area based properties.

1. Introduction
There is some long lasting need to correlate tensile test mechanical properties with conical hole expansion ratio HER from ISO16630 ISO conical hole expansion tests HET [1], which are usually used for edge crack sensitivity characterization. A broad literature is available on the topic with mixed predictive correlation accuracy [2]-[9], the usual correlation method consisting in plotting individual basic properties such as sheet thickness, yield strength Rp0.2, tensile strength Rm, uniform elongation A5, fracture elongation Ax, strain hardening rate (n-value), plastic strain ratio (r-value) for a specific direction or averaged in 0/45/90° direction (nm, rm) [2]-[4],[7] or even strain rate sensitivity m [8],[9].

Combinations of such properties such as yield ratio Rp0.2/Rm, n*r [5], Ax*rm [2],[3], r/n [4] or postuniform strain Ax-Ax [7]-[9] as well as logarithmic postuniform width strain [7] have also been proposed. The r-value should have a positive effect on hole expansion level by postponing local thinning. This may be especially true for milled condition for bulk material testing and thicker HSLA hot rolled steels [2],[4]. In punched condition however the random shear cut pre-damage along the hole edge may reduce the influence of the r-value alone.
Some integrated multifit hybrid models have been developed including thickness, tensile properties as well as material chemistry information such as sulphur content [3]. Different models have also been proposed for punched vs. machined milled hole edge condition [2]. Nonlinear dependencies instead of linear assumptions have also been proposed in [3],[6]. Such models need however to be updated constantly for AHSS-UHSS both for cold and hot rolled multiphase steel grades.

A recent decisive improvement may be brought by local area & thickness reduction measurement on flat sheet samples according to Hance test methodology and derivatives for local ductility assessment on broken surface of (milled) flat tensile test samples [10]-[16]. A strong correlation has been found between hole expansion ratio HER and reduction of area at fracture [11]. Alternatively the average percentage or logarithmic thickness reduction at fracture is also correlating well with the ISO16630 hole expansion ratio [12]. The logarithmic fracture thickness reduction at minimum thickness location has also proven valuable for local formability characterization and edge crack sensitivity prediction [14],[15]. The concept of postuniform log. thickness strain is also introduced in [10], for which the true uniform thickness strain is deduced from the total thinning at fracture. This may enable more accurate postuniform local ductility assessment and tensile test-HET correlations.

The hole expansion ratio may correlate even better with fracture toughness and essential work of fracture [8],[9],[16],[17]. There is an open debate whether tensile local ductility from bulk undamaged material can be correlated at all with the crack resistivity behavior of a shear cut pre-damaged hole expansion test [16],[17]. Punched tensile test may be an alternative option to clarify this issue [18],[19].

The present investigation delivers a correlation between conventional milled tensile test with punched ISO16630 hole expansion ratio on a much wider statistical basis than in previous investigations (300 correlation points in total for a wide variety of AHSS-UHSS cold rolled steel grades in the tensile strength range 600-1200MPa and thickness range 1mm to 2mm). The final aim is to reduce the amount of conical hole expansion testing with a deeper big data based correlation knowledge with tensile tests.

2. Experimental procedure
The reduction of area, thickness and width at fracture shown later on in this investigation have been determined based on the digitalized contour plot surrounding the fracture zone, the tensile sample broken surface being tilted flat under the microscope as previously described in [12],[13]. The area within the contour line has been integrated pixel by pixel, the thickness (average, mid & min location) as well as the width at fracture have then been derived as shown in Figure 1. The projected fracture area and width normal to tensile direction have been determined via the average fracture angle $\alpha$ (Figure 1).

![Image]

Figure 1: Test set up, local tensile ductility test parameters definition & methodology.
A set of equation formulas is given as follows for engineering and logarithmic local ductility parameters definition plotted later on in the diagrams with $t_0$, $w_0$ and $A_0$ (initial) and $t_f$, $w_f$ and $A_f$ (fracture) thickness, width and cross section area. $W_f$ and $A_f$ are projected in the plane normal to tensile direction according to the procedure described in Figure 1, [12],[13]. $t_f$ is measured either as average thickness over the whole fracture area or at mid sample center or at min thickness location. This delivers the corresponding average/mid/min thickness reduction.

Following abbreviations are used in the following investigation: $R_{0.2}$: yield strength, $R_{m}$: tensile strength; $A_g$: uniform elongation, $A_{80}$ fracture elongation from tensile test (gage length $L_0$=80mm). $r$-value and $n$-value are determined at uniform elongation $A_g$. $L/T$ stand for longitudinal and transverse tensile testing directions. The hole expansion ratio (HER) vs. local tensile ductility at fracture conversion from log-log to %-% is highly nonlinear as shown in equations (21)-(30). The conversion equations are identical for reduction of area in equations (21)-(25) as for thickness reduction parameters in equations (26)-(30). Equations (26)-(30) are valid for any kind of thickness reduction at fracture considered, calculated either from sample average, middle or min thickness location.

Width and thickness strain or logarithmic are defined in this investigation as positive (absolute) values. Postuniform logarithmic values are derived by subtracting the log. strain at uniform diffuse necking from the total local strain (only logarithmic strains are additive not the engineering strains).

| n-value at uniform elongation $n_{Ag}$: | $n_{Ag} = \ln(1 + A_g)$ | (1) |
| r-value at uniform elongation $r_{Ag}$: | $r_{Ag} = \frac{2A_g}{E Ag}$ | (2) |
| % Reduction of area at fracture $Z_{Ag}$: | $Z_{Ag} = 100 \cdot (A_0 - A_f)/A_0$ | (3) |
| Log. True Fracture Strain TFS$_{log}$: | $TFS_{log} = \frac{\ln(A_0/A_f)}{L}$ | (4) |
| Log. postuniform True Fracture Strain TFS$_{PU,log}$: | $TFS_{PU,log} = TFS_{log} - \ln(1 + A_{Ag}/100)$ | (5) |
| % Fracture thickness reduction $e_{3f,log}$ (>0): | $e_{3f,log} = 100 \cdot (t_0 - t_f)/t_0$ | (6) |
| Log. thickness reduction at fracture $e_{3f,PU,log}$ (>0): | $e_{3f,PU,log} = \frac{\ln(t_0/t_f)}{L}$ | (7) |
| Log. postuniform thickness reduc. at fracture $e_{3f,PU,log}$ (>0): | $e_{3f,PU,log} = \frac{\ln(t_0/t_f)}{L} - \ln(1 + A_{Ag}/100)/(r_{Ag} + 1)$ | (8) |
| % Width reduction at fracture $e_{2f,log}$ (>0): | $e_{2f,log} = 100 \cdot (w_0 - w_f)/w_0$ | (9) |
| Log. width reduction at fracture $e_{2f,PU,log}$ (>0): | $e_{2f,PU,log} = \frac{\ln(w_0/w_f)}{W}$ | (10) |
| Log. postuniform width reduction at fracture $e_{2f,PU,log}$ (>0): | $e_{2f,PU,log} = \frac{\ln(w_0/w_f)}{W} - \ln(1 + A_{Ag}/100)/(r_{Ag} + 1) . \ln(1 + A_{Ag}/100)$ | (11) |
| Log. width strain at fracture at $A_{80}, e_{2f,Ag,log}$ (>0): | $e_{2f,Ag,log} = \frac{TFS_{log}}{r_{Ag}} . \ln(1 + A_{Ag}/100)$ | (12) |
| Log. postuniform width strain at $A_{80}, e_{2f,PU,Ag,log}$ (>0): | $e_{2f,PU,Ag,log} = \frac{\ln(r_{Ag} - t_{Ag})}{r_{Ag} + 1} . \ln(1 + A_{Ag}/100)$ | (13) |

**HER$_{g}$ to HER$_{log}$.**

| HER$_{log}$ | $HER_{log} = \ln(1 + HER_{g}/100)$ | (14) |
| HER$_{log}$ to HER$_{g}$. | $HER_{g} = 100 \cdot \exp(HER_{log} - 1)$ | (15) |

**TFS$_{log}$ to $Z_{Ag}$.**

| $Z_{Ag} = 100 \cdot (1 - \exp(-TFS_{log}))$ | (16) |
| $e_{3f,log}$ to $e_{3f,PU,log}$. | $e_{3f,PU,log} = \ln(1 + A_{Ag}/100)/(r_{Ag} + 1)$ | (17) |

**Fit HER$_{log}$ vs. TFS$_{log}$.**

| HER$_{log} = K \cdot TFS_{log} \approx 0.5 \cdot TFS_{log}$ with $K=0.5$ | (18) |

**Fit HER$_{g}$ vs. TFS$_{log}$.**

| HER$_{g} = 100 \cdot \{\exp(TFS_{log})^{K} - 1\}$ | (19) |

**Fit HER$_{g}$ vs. $Z_{Ag}$.**

| HER$_{g} = 100 \cdot \{\exp(-K \cdot \ln(1 - Z_{Ag}/100)) - 1\} = 100 \cdot [1 - Z_{Ag}/100]^{-K} - 1$ | (20) |

**Fit HER$_{log}$ vs. $e_{3f,log}$.**

| HER$_{log} = K \cdot e_{3f,log} \approx 0.5 \cdot e_{3f,log}$ with $K=0.5$ | (21) |

**Fit HER$_{g}$ vs. $e_{3f,log}$.**

| HER$_{g} = 100 \cdot \{\exp(K \cdot e_{3f,log}) - 1\} = 100 \cdot \{\exp(e_{3f,log})^{K} - 1\}$ | (22) |

**Fit HER$_{log}$ vs. $e_{3f,PU,log}$.**

| HER$_{log} = K \cdot e_{3f,PU,log} \approx 0.5 \cdot e_{3f,PU,log}$ with $K=0.5$ | (23) |

**Fit HER$_{g}$ vs. $e_{3f,PU,log}$.**

| HER$_{g} = 100 \cdot \{\exp(K \cdot e_{3f,PU,log}) - 1\} = 100 \cdot \{\exp(e_{3f,PU,log})^{K} - 1\}$ | (24) |

**Fit HER$_{log}$ vs. $e_{3f,PU,log}$.**

| HER$_{log} = K \cdot e_{3f,PU,log} \approx 0.5 \cdot e_{3f,PU,log}$ with $K=0.5$ | (25) |

**Fit HER$_{g}$ vs. $e_{3f,PU,log}$.**

| HER$_{g} = 100 \cdot \{\exp(K \cdot e_{3f,PU,log}) - 1\} = 100 \cdot \{\exp(e_{3f,PU,log})^{K} - 1\}$ | (26) |

**Fit HER$_{log}$ vs. $e_{3f,log}$.**

| HER$_{log} = K \cdot e_{3f,log} \approx 0.5 \cdot e_{3f,log}$ with $K=0.5$ | (27) |

**Fit HER$_{g}$ vs. $e_{3f,log}$.**

| HER$_{g} = 100 \cdot \{\exp(K \cdot e_{3f,log}) - 1\} = 100 \cdot \{\exp(e_{3f,log})^{K} - 1\}$ | (28) |

**Fit HER$_{log}$ vs. $e_{3f,PU,log}$.**

| HER$_{log} = K \cdot e_{3f,PU,log} \approx 0.5 \cdot e_{3f,PU,log}$ with $K=0.5$ | (29) |

**Fit HER$_{g}$ vs. $e_{3f,PU,log}$.**

| HER$_{g} = 100 \cdot \{\exp(K \cdot e_{3f,PU,log}) - 1\} = 100 \cdot \{\exp(e_{3f,PU,log})^{K} - 1\}$ | (30) |
3. Experimental results

The correlation results with common tensile properties in longitudinal (L) and transverse (T) directions are shown in Figure 2 to Figure 7. The HER vs. new local ductility parameters on broken samples are shown later on in Figure 8 to Figure 15.

Only a poor up to non-existing correlation with hole expansion ratio HER can be achieved for yield or tensile strength (Figure 2a,b). A slight negative but not significant enough correlation is seen for uniform or tensile elongation (Figure 3a,b). Similarly a small weak negative tendency for HER vs. n-value can be observed in Figure 4a. The r-value on the contrary has rather a slightly positive effect on HER level (Figure 4b). The product n*r-value at uniform elongation does not bring any decisive input in the correlation (Figure 5a) while the ratio r/n of r-value to n-value at uniform elongation offers a clear positive significant correlation of $r^2 > 0.5$ (Figure 5b), as also seen in [4] for hot rolled AHSS CP-steels.

Figure 2: HER vs. (a) yield strength $R_{\text{p0.2}}$, L+T; (b): tensile strength $R_m$, L+T.

Figure 3: HER vs. (a) uniform elongation $A_g$, L+T; (b): fracture elongation $A_{80}$, L+T.

Figure 4: HER vs. (a) n-value at uniform elongation, L+T; (b): r-value at uniform elongation, L+T.
Figure 5: HER vs. (a) n*r-value at Ag, L+T; (b): r/n-value at Ag, L+T.

Figure 6: HER vs. (a) postuniform elongation $A_{80}-A_g$, L+T; (b): yield ratio $R_{p0.2}/R_m$, L+T.

Figure 7: HER vs. (a) Log. width strain $e_{2,80,log}$, L+T; (b): Log. postuniform width strain $e_{2,PU,80,log}$, L+T.

Figure 8: HER vs. (a) Log. width strain $e_{2,log}$, L+T; (b): Log. postuniform width strain $e_{2,PU,log}$, L+T.
The postuniform elongation $A_{80}$ which is often mentioned in the literature does not deliver any significant correlation (Figure 6a). On the contrary the yield ratio $R_{p0.2}/R_m$ brings some significant correlation with $r^2>0.5$, the correlation seems particularly good for yield ratio values over 70% (Figure 6b). The correlation with the logarithmic width reduction up to fracture elongation according to equation (15)-(16) as proposed in [7] is almost non-existent (Figure 7a). The postuniform width reduction up to fracture elongation brings no improvement either (Figure 7b).

All in all yield ratio and $r/n$-value ratio can be considered so far as helpful for HET-Tensile test correlations among conventional tensile properties. The correlation level $r^2$ around 50% is however not satisfying enough for reliable HER prediction.

No correlation for width strain measured on broken sample surfaces could be found with HER-values for total or postuniform log. fracture width strain (Figure 8a,b). This shows together with results in Figure 7 that the local necking in tensile width direction does not bring any additional information on the local formability behaviour as also argued in [14],[15].

Figure 9 shows exemplarily some randomly chosen HER-tensile correlation tests (50 sampling data sets in total in the 600-1200MPa tensile strength range). The correlation quality with HER is strikingly good for fracture % thickness reduction at min thickness location / average or Z-value (Figure 9a). The correlation with $A_{80}$ fracture elongation is not clear and even show an opposite trend to HER values (Figure 9a). The correlation of logarithmic HER with logarithmic thickness reduction (at min thickness location or average) and True Fracture Strain TFS values is also obviously equally strong (Figure 9b).

Figure 10a delivers the correlation results for all 300 data sets with the True Fracture Strain $TFS_{\text{log}}$. Figure 10b show a significant improvement of about 10% in correlation level $r^2$ when using instead postuniform $TFS_{\text{log,PU}}$ as defined in equations (5)-(6). Figure 11, Figure 12 and Figure 13 show the correlation results of log HER vs. log. thickness reduction middle or at min thickness location. As for TFS the correlations are quite linear and the postuniform local thickness reduction values deliver slightly better correlation. The correlation level with local parameters is higher ($r^2 \approx 70\%$) than with conventional mechanical properties ($r^2 \approx 50\%$). The transverse direction improves slightly the correlation level for any local ductility parameter. It is the most sensitive direction with regards to material defects stretched in rolling direction. The longitudinal direction as prescribed in VDA239 test standard is however also still suitable with acceptable fitting accuracy. $TFS_{\text{log}}$ delivers a slightly lower correlation accuracy than with log. thickness reduction parameters. This can be compensated when only considering the postuniform strain $TFS_{\text{PU,log}}$.

Correlation results for engineering strain values between HER% and % reduction of area Z (Figure 14a) or average % thickness reduction (Figure 14b) or % thickness reduction at sample middle (Figure 15a) as well as % thickness reduction at min thickness location (Figure 15b). The non-linearity of HER% vs. eng. % local ductility parameters is well captured through the chosen modelling approach.
Figure 10: Log. HER vs. log. True Fracture Strain, L+T: (a): $TFS_{\log}$; (b): $TFS_{PU,\log}$.

Figure 11: Log. HER vs. log. thickness reduction at fracture average, L+T: (a): $e_{3f,\log,\text{average}}$; (b): $e_{3f,\log,PU,\text{average}}$.

Figure 12: Log. HER vs. log. thickness reduction at fracture middle, L+T: (a): $e_{3f,\log,\text{mid}}$; (b): $e_{3f,\log,PU,\text{mid}}$.

Figure 13: Log. HER vs. log. thickness reduction at fracture min, L+T: (a): $e_{3f,\log,\text{min}}$; (b): $e_{3f,\log,PU,\text{min}}$. 
4. Conclusions

Correlations from edge crack sensitivity (ISO16630 hole expansion ratio HER) with tensile testing (ISO 6892-1, type 2 As tensile samples) have been performed based on a wide thickness, tensile strength and microstructure range. Following conclusions can be drawn:

- No particular correlation can be achieved with yield or tensile strength, uniform or fracture elongation, n- or r-value alone.
- Yield ratio and r-value to n-value ratio deliver the most promising correlation results among conventional tensile test mechanical properties.
- Correlation with tensile test in transverse direction are slightly better than in longitudinal direction.
- Correlation with true log. values both for HER and local ductility properties are strongly linear.
- Engineering values bring an artificial strong non linearity in correlation results from the true logarithmic to engineering % strain conversion, which complicates analytical correlation models. Correlations should be done in true logarithmic strain modus and converted later on in engineering % strain formulation using the set of equations given if needed. Engineering strain formulation is actually no valid for such high strain levels found in local ductility.
- Tensile width strain does not correlate well with HER. The local necking in width direction does not bring additional information on local ductility but rather on global formability.
- Fracture area based local formability correlate slightly less with HER than thickness based parameters.
- Thickness strain measured on an average integral basis, or in the middle or at the min thickness location of broken samples surfaces actually comparatively all perform well in correlation with HER.
- Subtracting the postuniform component up to uniform diffuse necking improves the statistical correlation level with HER for all local ductility values, but especially for TFS.
- It actually does not matter which local formability tensile property is used, the correlation is still much better than with any conventional tensile properties or derivatives.
• 100% correlation will never be achieved. The correlation level ($r^2$ up to 70-75%) has been optimized in the order of the inherent scattering of both local tensile and hole expansion testing. Any correlation dealing with fracture strain behavior should be based on statistical regression with a significant data amount matching the confidence level expected. It should be also considered that the scattering of the mean of 3 replicates has been investigated both for tensile and HER values. Individual test values with higher scattering have not been considered.

References

[1] ISO 16630:2017(E) Metallic Materials—Sheet and Strip—Hole Expanding Test.
[2] Comstock R J, Scherrer D K and Adamczyk RD (2006) Hole expansion in a variety of sheet steels. Journal of Materials Engineering and Performance 15 675-683.
[3] Comstock R J, Brown D and Scherrer D K (2011) Predicting Formability of Sheared Holes in a Variety of Sheet Steels. Materials Science and Technology (MS&T), Columbus, Ohio, USA.
[4] Goncalves J, Alibeigi S and Sarkar S (2019) Comprehensive understanding of effective parameters on edge cracking sensitivity of hot-rolled complex phase steels. IOP Conf. Ser.: Mater. Sci. Eng. 651 012108.
[5] Narayanasamy R, Narayanan C S, Padmanabhan P at al. (2010) Effect of mechanical and fractographic properties on hole expandability of various automobile steels during hole expansion test. Int J Adv Manuf Technol 47 365-380.
[6] Paul S K (2014) Non-linear Correlation Between Uniaxial Tensile Properties and Shear-Edge Hole Expansion Ratio. Journal of Materials Engineering and Performance 23 (10) 3610-3619.
[7] Kim J H, Kwon Y J, Lee T et al. (2018) Prediction of Hole Expansion Ratio for Various Steel Sheets Based on Uniaxial Tensile Properties. Met. Mater. Int. 24 (1), 187-194.
[8] Yoon J I, Jung J, Kim J G et al. (2017) Key factors of stretch-flangeability of sheet materials. Journal of Materials Science 52 7808-7823.
[9] Yoon J I, Jung J, Joo S H et al. (2016) Correlation between fracture toughness and stretch-flangeability of advanced high strength steels. Materials Letters 180 322-326.
[10] Hance B (2016) Advanced High Strength Steel: Deciphering Local and Global Formability. Int. Automotive Body Congress, Sept. 28-29, Dearborn, MI, USA.
[11] Hance B M (2017) Practical Application of the Hole Expansion Test. SAE 2017-01-0306.
[12] Larour P, Freudenthaler J and Weissböck T (2017) Reduction of cross section area at fracture in tensile test: measurement and applications for flat sheet steels. J. Phys.: Conf. Ser. 896 012073.
[13] Larour P, Wagner L, Felbinger A and Angel J (2019) Local fracture strain measurement in AHSS uniaxial flat tensile tests considering specimen geometry and fracture morphology. IOP Conf. Ser.: Mater. Sci. Eng. 651 012016.
[14] Heibel S, Dettinger T, Nester W et al. (2018) Damage Mechanisms and Mechanical Properties of High-Strength Multiphase Steels. Materials 11 761.
[15] Gruenbaum M, Aydin G, Dettinger T and Heibel S (2019) Local formability of AHSS: Measurement technique, specimen types and robustness. IOP Conf. Ser.: Mater. Sci. Eng. 651 012056.
[16] Denks I A, Schneider M, Westhäuser S et al. (2019) On the Correlation between Suitable Material Parameters for the Prediction of Local Formability of AHSS. Steel research int. 90 (6) 1800460.
[17] Frómeta D, Parareda S, Lara A et al. (2020) Identification of fracture toughness parameters to understand the fracture resistance of AHSS steels. Eng. Fracture Mechanics 229 106949.
[18] Yoon J, Jung J, Ryu J H et al. (2017) Development of Methodology with Excellent Reproducibility for Evaluating Stretch-Flangeability Using a Sheared-Edge Tensile Test. ExpMech 57,1349-58.
[19] Cestoni H, Anderson D (2018) Effect of Edge Quality on Formability of an AA6xxx Aluminum Alloy. IOP Conf. Series: Materials Science and Engineering 418 012065.