Local fracture strain measurement in AHSS uniaxial flat tensile tests considering specimen geometry and fracture morphology

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Abstract. The local formability of AHSS sheet steels can be estimated by means of the relative average reduction of cross section area (or thickness) at fracture in flat tensile specimens. A 2D/3D characterization of tensile fracture shapes is performed with an optical stereo microscope for various typical fracture shapes. The initial width to thickness ratio (w0/t0) of flat tensile samples quantifies their non-proportionality behavior. A charpy like lower and upper shelf region with a highly scattered transition zone in between at a critical w0/t0 ratio is observed when plotting the fracture area or thickness reduction versus w0/t0 ratio. The higher the w0/t0 ratio of tensile specimens (samples wider, material thinner) the higher the local fracture strain level. The higher the material work hardening ability (n-value), the higher the critical w0/t0 ratio below which high scattering in thickness - and area reduction occurs. The local tensile fracture strain is therefore strongly dependent on specimen thickness, width and work hardening behavior. This is a severe drawback for a broader use of such tensile test based fracture strain measurements.

1. Introduction

Interest is raising in differentiating more efficiently newly developed advanced and ultrahigh strength steels (AHSS & UHSS) with regard to their local to global formability capability as described in an updated version of the WorldAutoSteel AHSS Application Guidelines [1]. One convenient way to make a preliminary rough classification of steel grades microstructure is found in the so called local/global formability map introduced by B. Hance [2]-[4]. The global formability being expressed as true uniform elongation (n-value at uniform elongation), the local formability being derived from the relative reduction of area at fracture (RA, “Z-value”) as local true fracture strain (TFS) in tensile direction. This has found some positive resonance within the steel and automotive industry [5]-[8]. Much more work is however needed prior to a possible implementation of such local formability properties in current automotive material standard like for instance VDA239 [9]. Test specifications for thickness- and area reduction measurement on broken tensile specimens are rather vague in current tensile standards ISO6892-1 [10] and JIS Z 2241 [11]. ASTM E8 [12] prescribes three local thickness and width measurement with a weighted average from roughly defined “middle” and “corner” positions. A more robust method is proposed in [4] with a 5 points arithmetic average thickness measurement or alternatively with a 10 points integrated polygonal fracture area calculation with image analysis tools.

The influence of sample geometry is not been found predominant up to now on local formability measurement in [7]. This somehow contradicts results in [4] and [6] showing a significant dependency
of thickness - and area reduction with the initial width to thickness ratio of tensile samples [6]. A strong correlation between thickness - and area reduction in tensile test is mostly seen in [5]-[7]. Therefore the need for some more sophisticated projected fracture area measurement without additional information is questioned in [7],[8]. Anisotropy effects depending on tensile testing direction have been found especially for hot rolled steels in [7]. A reasonable correlation of tensile thickness reduction at fracture with ISO16630 conical hole expansion ratio [13] has been found for cold rolled steels in [3],[5],[7],[8]. For hot rolled steels this correlation is less obvious as reported in [7]. Issues about the measurement of thickness - and area reduction on broken AHSS tensile samples are investigated such as: optical artefacts of various fracture shapes, scattering, width to ratio dependency, fracture angle, anisotropy, edge cracks.

2. Experimental procedure

The investigation focuses on three cold rolled commercially available AHSS grades CR330Y590T-DP (DP600), CR590Y980T-DP or CR700Y980T-DP (DP1000) and CR780Y980T-CP (CP1000) steels in the thickness range 0.7 to 2.3 mm. Three different specimen geometries (N\textsuperscript{a}1,2,3) with three replicates have been used as described in DIN EN ISO 6892-1, Annex B, exhibiting widths of 12.5 mm, 20 mm, and 25 mm, and gage length of 50, 80 and 50 mm respectively (4.10\textsuperscript{3}/s, 20°C, optical strain measurement) [10]. With all three geometries the longitudinal direction has been tested according to VDA239 standard [9], the transverse direction only for type 2 sample (20 mm initial width). Basic measures of local ductility were derived from the (projected) fracture surface of the tensile specimens:

\[ Z = (A_0 - A_f)/A_0 \]  
\[ e_1 = (\delta_0 - \delta) / \delta_0 \]  
\[ e_2 = (w_0 - w) / w_0 \]

with \( \delta_0, w_0 \) and \( A_0 \) (initial) and \( \delta, w \) and \( A_f \) (fracture) thickness, width and cross section area.

The % reduction of area, average thickness and width at fracture shown later on in this investigation have been integrated directly based on the digitalized coordinates X-Y from the principal axes of the contour plot surrounding the fracture zone. The area within the contour line has been integrated pixel by pixel, the average thickness and width have been determined from cross lines intersection with the fracture contour plot in vertical and horizontal directions along the whole thickness and width profiles. Such averaged values are thought to be more stable and objective. The projected area and width normal to tensile direction have then been determined via the average fracture angle \( \alpha \) (Figure 1). The fracture angle \( \alpha \) is defined against horizontal direction, \( \theta \) is the complementary angle vs. vertical tensile axis.

![Figure 1](image)

Figure 1: (a): Definition of fracture angle and fracture area calculation; (b): Fracture angle variety.

3. Experimental artifacts

Figure 2 shows the local morphology of typical tensile fracture shapes with a 3D Keyence VH6000 stereo microscope. The full focus image stitching modus is used in X-Y as well as \( Z \) direction with a high 2.25\( \mu \)m/pixel resolution at 100x magnification. A mix of normal ductile concave/convex and shear ductile fracture modes are observed in thickness direction. Some transition between those modes may also be observed. The fracture shape in thickness and width direction are closely related.
As shown in Figure 3 such transition in fracture shape curvature along sample width may result in local irregularities or edge breakout affecting local thickness appearance. A measurement of both halves of the sample should average out such local fracture edge irregularities. The assumption of minimum thickness at mid-width of the sample is not necessarily fulfilled. Thickness measurement at left and right corners are subjective and not representative with abnormal “fish tail” fracture type, Figure 3. Measurement with ≤0.3 mm thickness left at fracture are challenging even at 100 X magnification.

Figure 4a shows the differences in necking zone formation and width measurement challenges for a DP600 with a cross shape shear band formation with fracture initiation in the centre after significant width necking followed by shear band on the left and right side or for a CP1000 with a tendency of lateral shift prior to fracture and straight shear band formation with almost no lateral width necking. This behaviour resulting from a competition between leading and second necking lines with a subsequent diagonal groove formation has been well described in [14] for similar steel grades.

Figure 4b illustrates the necessity of cautious sample manipulation and some cleaning of broken tensile samples before optical fracture surface analysis. Zinc coating deposits and burr like filaments may also complicate fracture edge determination in spite of previous pressured air cleaning.
Figure 4: (a): DP600 (X shape fracture) vs. CP1000 (shear band localized fracture with lateral shift); 
(b): Examples of sample damage & contamination which affects the local thickness measurements.

Figure 5 draws some attention on edge crack phenomena on standard milled edges observed mostly for high strength DP grades with atypical fracture propagation path in width direction and odd thickness profile shape. This premature edge cracking may significantly reduce the observed fracture area and thus jeopardize the whole meaning for local formability measurement from tensile tests.

Figure 5: Edge cracks - atypical fracture shapes in AHSS tensile tests.

4. Experimental results
All results for integrated fracture area, average thickness and average width reduction according to equations (1)-(3) have been collected for DP600, DP1000 and CP1000 steel grades for type 1/2/3 ISO6892 samples for both testing directions (longitudinal for types 1/2/3, transverse only for type2).

The dependency of fracture area, thickness, width reduction and fracture angle vs. sample thickness (Figure 6a-c) or vs. initial sample width to thickness ratio \(\frac{w_0}{t_0}\) (Figure 6d-f) is shown for DP600, DP1000 and CP1000 respectively. The thicker the material (especially above 1.5 mm) or the lower the \(\frac{w_0}{t_0}\) ratio (below a critical \(\frac{w_0}{t_0}\) ratio) the lower the fracture thickness - and area reduction and the higher the fracture width reduction.

CP1000 shows the most stable and highest level for thickness - and area reduction around 60-70%. DP600 and DP1000 show a wider range around 40-70% and 30-60% respectively for thickness - and area reduction. The width reduction at fracture is the highest for DP600, intermediate for DP1000 and very low for CP1000. While width reduction at fracture nearly corresponds to global ductility level (n-value), the fracture thickness - and area reduction (local ductility) do not correlate with tensile strength, CP1000 showing consistently better values than DP600 or DP1000.

For a better understanding of those results, the average fracture angle \(\alpha\) as defined in Figure 1 has been introduced. Fracture angle together with fracture area and width reduction are shown versus reduction of thickness at fracture in Figure 7a-c. The fracture thickness - and area reduction closely correlate, especially for DP1000 and CP1000 steel grades. The fracture angle \(\alpha\) increases over a wide range 0-30° for DP600 and DP1000 while remaining constant at a 30° high level for CP1000.
The fracture area, thickness and width reduction are shown versus fracture angle $\alpha$ in Figure 7(d-f) for DP600, DP1000 and CP1000 respectively. The higher the fracture angle, the higher those local ductility values, the fracture width reduction on the other hand is reduced especially above 15° fracture angle. The scattering of thickness and area reduction values is not negligible. This stochastic scattering noise (±5-10 %) is in many way similar to the one observed for ISO16630 hole expansion ratio. This inherent local material scattering has however to be added to a larger systematic $w_0/t_0$ geometric superposed fracture angle dependency with a lower and upper shelf level. The fracture thickness reduction reacts much more sensitive to the $w_0/t_0$ ratio in comparison to area reduction, especially for DP1000 steel. The fracture angle $\alpha$ can be described as a function of $w_0/t_0$ as follows:

$$\alpha=90^{\circ}-\theta=\alpha_{\text{max}}/2\left[1+\tanh(S(w_0/t_0 - w_0/t_0 \text{ critical}))\right]$$

(4)

with $\alpha_{\text{max}}$: maximum saturation level of fracture angle at upper shelf level, S shape factor: transition zone width between lower and upper shelf level and $w_0/t_0 \text{ critical}$: critical width to thickness ratio at 50 % of the transition zone ($w_0/t_0 \text{ critical}=13/10/5$ for DP600/DP1000/CP1000 according to Figure 6d-f).
Figure 7: (a-c): Fracture area - & width reduction vs. reduction of thickness at fracture; (d-f): Fracture area - thickness - & width reduction vs. fracture angle \( \alpha \); for DP600, DP1000, CP1000 respectively.

Figure 8a shows exemplarily the fracture angle transition \( \alpha \) vs. width to thickness ratio for DP600 fairly accurately described by equation (4). Below a certain level of width to thickness ratio \( (w_0/t_0 \text{ transition } \approx 17) \) there is a sudden stochastic scatter in fracture angle, which is also reflected in a decrease in local ductility values. Figure 8b illustrates correspondingly the rather limited thickness range for DP600 above which scattering in fracture angle occurs for a given type 1/2/3 tensile sample geometry \((0.75, 1.2, 1.5 \text{ mm respectively})\). The wider the sample, the broader the thickness range which can be tested in the upper shelf stable region at maximum fracture angle (and thickness/area reduction) level.

Figure 9a shows the fracture area - thickness - and width reduction dependency vs. tensile fracture elongation for DP600 (transverse/longitudinal direction, type 1/2/3 samples with 50/80/50 mm gage length all mixed together). No particular dependency can be observed vs. fracture elongation.

Figure 9b shows exemplarily for DP600 1.4 mm the scattering of area - thickness - width reduction and fracture elongation vs. fracture angle, all samples from a single sheet location with 30/15 replicates in longitudinal/transverse direction for type 2 sample \((80 \text{ mm gage length, } 20 \text{ mm width})\). The \( w_0/t_0 \) ratio \((14) \) lies according to Figure 8 within the upper critical transition zone with large systematic
possible shift in fracture angle from 0 to 25°. This is confirmed in Figure 9b with one outlier suddenly found at around 0° fracture angle, with all other samples at ≥15° fracture angle. This particular sample delivers abnormally low thickness and area reduction values. On the opposite the width reduction is also much higher for this outlier, which is typical for low fracture angles. The lower the fracture angle, the higher the width reduction and the lower the thickness reduction. Fracture area reduction balances both opposite effects and behaves more stable. Figure 9b shows also a weak anisotropy of DP600 thickness - and area reduction values around 5% absolutely lower in transverse than in longitudinal direction.

Thus scattering arises from two separate sources to be distinguished, on the one hand the stochastic between replicates (in Figure 9b actually quite low below ±2-3% absolute variation around best fit lines), on the other hand from the largely dominant stochastic of fracture angle, which determines the upper and lower shelf level of area- and thickness reduction values at 55-65% & 40-60% respectively.

Some physical explanation is proposed in [14] by relating fracture angle and principal stress ratio $\xi=\sigma_2/\sigma_1$. Assuming a non-null value for transverse stress $\sigma_2$ leads to higher fracture angle values than the theoretical value reported in the literature $\theta=54.74^\circ$ ($\xi=0, \alpha=35.26^\circ$) up to $\theta=90^\circ$ ($\xi=1/2, \alpha=0^\circ$):

$$\theta = 90 - \alpha = \tan^{-1}\left(\sqrt{(2-\xi)/(1-2\xi)}\right) \text{ with } 0 \leq \xi \leq 1/2$$

It can be assumed that the wider the sample and/or the thinner the sample (w0/t0 higher), the lower the $\sigma_2$ (and $\sigma_1$) component value and the more the fracture angle approaches the theoretical $\theta_{min}=55^\circ$ value ($\alpha_{max} \approx 35^\circ$). A lowering of the strain hardening capability has the same effect, triggering an early shear band formation along a “zero elongation necking line” without pronounced diffuse necking.

Figure 8: (a) Fracture angle vs. width to thickness ratio for DP600; (b) Critical thickness above which excessive scattering in fracture angle occurs for a given type 1/2/3 ISO6892 tensile sample geometry.

Figure 9: (a) Fracture area, thickness and width reduction vs. tensile fracture elongation for DP600; (b) Fracture area, thickness, width reduction & tensile elongation vs. fracture angle $\alpha$ for DP600 1.4 mm in transverse vs. longitudinal direction.
5. Conclusions
The local formability of AHSS can be robustly assessed with integrated average reduction in area and thickness at fracture. Local thickness measurement are prone to more subjective scattering and less recommended. Samples should be manipulated cautiously and contamination free. Testing in transverse direction is slightly more conservative than in longitudinal direction. Edge cracks are however a major issue even with milled edges, which decrease the area- and thickness reduction at (premature) fracture.

The 3D fracture morphology is linked to shear band formation at local necking initiation. The width reduction and fracture angle allow some better understanding of local formability measures variations.

Scattering originates both from the inherent microstructure inhomogeneity as well as from variations in the average fracture angle. The fracture angle drives the level of local formability values for a given material. There is a critical width to ratio below which the scattering in fracture angle begins to deeply increase. This also affects the area - and especially the thickness reduction values. The higher the initial width to thickness ratio (the thinner for a given width or the wider for a given thickness) the higher and the more stable the area - and thickness reduction, the higher the fracture angle and the lower the width reduction at fracture. JIS 25 mm wide tensile samples behave therefore most stable.

None of the current standard tensile samples however entirely fulfills the need to exceed a critical width to thickness ratio for any material thickness. Notched (waisted) R5 plane strain tensile samples commonly used for crash damage model calibration [15],[16], deliver a defined normal fracture angle and may be an alternative sample geometry. Tensile samples have namely more degree of freedom in comparison to notched samples for crack propagation path and resulting fracture angle.

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