Reduction of cross section area at fracture in tensile test: measurement and applications for flat sheet steels

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Abstract. This contribution deals with the use of maximum thinning and reduction of sample cross section area at fracture after tensile testing and applications for industrial flat sheet steels. Although included in all usual tensile testing standards, this mechanical property (“Z-value”) has long been neglected for flat sheet materials. It happens however to include some most valuable information on local ductility at fracture of sheet steels. This is increasingly needed for a more suitable description and ranking of newly developed advanced high strength sheet steels with regard to local ductility (stretch-flangeability, bendability, crash-ability) versus global ductility (deep-drawability). It is shown in this investigation that the ISO16630 punched and milled hole expansion ratio correlates linearly with the relative thickness reduction at fracture. A classification of cold rolled AHSS-UHSS sheet steels is attempted by plotting the relative thickness & area reduction at fracture vs. uniform and fracture elongation.

1. Introduction
Driven by worldwide lightweight autobody requirement, a multitude of new advanced and ultra high strength sheet steels (AHSS/UHSS) have been developed recently. Material designations based on microstructure as for example low/high yield dualphase (DP), multiphase (MP), complexphase (CP) microstructures have led to a multitude of specific brand names. A differentiation based on industrial application is also found as for example deep drawing (DP-like) vs. bending type (CP-like), low/balanced/high λ steel, improved bending and flanging (IBF) steel categories etc… Worldwide a growing confusion arises for OEM’s, stampers and even for steel producers themselves. Some work is therefore being currently undergone to differentiate steels based on their global vs. local ductility [1]. Global ductility is understood as the resistance against the beginning of localized necking (instability) and deep drawability. The local ductility on the other side refers to the resistance against crack initiation and propagation (damage, thoughness), which drives stretch flanging, bending and crash ability. This contribution shows some results about the predicting ability of local thickness fracture strain to assess the edge crack sensitivity of AHSS. A local vs. global ductility mapping of AHSS is also performed.

2. Literature review, definitions

2.1. Z-value applications in literature
The concept of fracture strain (“0 gauge length elongation”), although known long ago for round bar tensile tests in the form of Z-value, has been recently (re)introduced to classify flat steels according to
their local vs. global ductility behavior [2],[3]. The reduction of area in tensile testing has been used for 3rd generation AHSS development such as for AHSS 980 grades [2]-[3], for high martensite DP980 steel [4], for DP1000/1200 steels [5], for TRIP-aided and DP-steels [6] and Medium-Mn steels [7]. It was also used to show the positive effect of bake hardening on AHSS crush behavior [8].

The Z-value could be successfully correlated with the stretch flangeability in conical hole expansion test for AHSS 980 MPa steels [2]-[5], for DP steels [8] and hot rolled mild / HSLA steels [9] (1970!). Local fracture strain from punched notched and hole tensile sample has been used for edge crack prediction in [10] for 600-1000MPa AHSS. ISO16630 hole expansion ratio has been well correlated with the tensile thickness fracture strain for cold & hot rolled AHSS [11]. The stretch flangeability has been investigated in [12] vs. local tensile fracture strain from digital image correlation for hot & cold rolled 800MPa AHSS. In [13] the fracture strain in milled vs. punched tensile tests are compared with DP/CP1000 steels. The anisotropy of fracture strain has also been investigated in [17].

Some increasing effort is also being put in order to correlate the bendability of AHSS with local tensile fracture strain. The limiting bend ratio has been investigated vs. n-value and local fracture strain for AHSS in [2],[8]. Such bendability vs. tensile test correlations are based on Datsko work [14] (1960!) and have been used for hemming ability estimation of aluminum [15],[16]. With the development of AHSS with limited bendability, such approach is also being increasingly considered within the steel industry. The axial and side impact crash ability has been assessed in relation with the Z-value of AHSS/UHSS in [8],[17],[18] as well as for press-hardening grades with notched tensile samples in [19].

Due to the major difficulties encountered to generate a reproducible cut edge condition according to ISO16630 hole expansion testing standard [20],[21], a growing interest arises in alternative Z-values to quantify objectively the local ductility from widespread tensile testing. The overall issue of postuniform damage failure strain beyond forming limit curve (FLC) vs. triaxiality has to be considered [13],[22].

2.2. Local ductility
According for example to ISO 6892 [23] and ASTM E8 [24] tensile testing standards, the percentage reduction of area Z is defined as the difference between the original cross-sectional area $S_0$ and the minimum cross-sectional area $S_f$ after fracture expressed as a percentage of the original area $S_0$:

$$Z = \frac{S_0 - S_f}{S_0}$$

(1)

The absolute percentage thickness strain $\varepsilon_3$ between original thickness $t_0$ and at fracture $t_f$ is:

$$\varepsilon_3 = \frac{t_0 - t_f}{t_0}$$

(2)

The absolute logarithmic thickness strain ($\varepsilon_{3,log} > \varepsilon_3$) is defined based on $|\ln(t_f/t_0)|$ as follows:

$$\varepsilon_{3,log} = -\ln(1 - \varepsilon_3)$$

(3)

With the assumption of volume constancy the necking zone, the Z-value is converted to a percentage local fracture strain $A_0$ (zero-gage-length elongation) for infinitesimal gage length at fracture [2],[25]:

$$A_0 = \frac{Z}{1-Z}$$

(4)

A mild steel with Z=90% yields somehow unrealistic $A_0=900\%$ according to equation (4)! The true logarithmic fracture strain TFS ($\varepsilon_0$) is then rather given as:

$$TFS = \ln(1 + A_0)$$

(5)

The “true fracture elongation” TFE is similarly defined based on percentage fracture elongation $A_{90}$:

$$TFE = \ln(1 + \frac{A_{90}}{100})$$

(6)
Although not directly measurable, the local engineering fracture strain can be calculated indirectly simply by measuring the projected fracture area \( S_f \) under optical microscope (Figure 1a) as described in [2] based on ASTM E8 (chapter 7.12: reduction of area) [24]. The ASTM assumes a parabolic fracture shape with a minimum thickness in the sample middle (Figure 1b,c). This is mostly the case for thicker hot rolled sheets. For cold rolled UHSS however there is no clear thickness minimum, so some best fit lines are used for fracture area determination. Often tensile samples fail with a minimum thickness clearly outside the middle axis (Figure 1e,g), the thickness may even be maximum in the center zone of samples (Figure 1f). Delamination may also occur as shown in Figure 1d, questioning whether volume constancy can still be assumed up to fracture and the validity of such area measurement.

\[ n = \ln(1 + \frac{UE}{100}) \]  
\[ \frac{d\sigma}{d\epsilon} = \sigma \]  
\[ \varepsilon_{1,\text{local necking}} = 2n \]  
\[ \frac{d\sigma}{d\epsilon} = \frac{\sigma}{2} \]  
\[ \varepsilon_{2,\text{w at fracture}} \approx \ln \left( \frac{W_f}{W_o} \right) \]  
\[ \varepsilon_{2,\text{w}} = -2n \frac{R}{R+1} \]
The ratio between fracture width $W_f$ and initial with $W_0$ can then be calculated as follows:

$$\frac{W_f}{W_0} = \exp\left(-2n \frac{R}{R + 1}\right) \tag{13}$$

Ongoing investigations may show some better accuracy using following empirical law (Figure 2):

$$\frac{W_f}{W_0} \approx \exp\left(-2.5n \frac{R}{R + 1}\right) \tag{14}$$

![Figure 2](image_url)

**Figure 2.** Calculated vs. measured tensile sample fracture width for 2n vs. 2.5n necking criteria.

2.3. **Global ductility**

Global ductility is usually defined with percent uniform elongation UE (Ag) according to equation (7). It corresponds to the n-value at true uniform elongation. The n-value determination for AHSS/UHSS however is quite subjective depending on the strain range considered. With regard to uniform strain, the elastic strain is not negligible for low Ag values below 5%, a plastic strain correction should be therefore performed, which is usually not considered in daily practical testing [27].

In case of a low n-value in combination with a pronounced upper yield strength a determination of uniform elongation is even almost impossible ($R_{um}=R_m$). The n-values for UHSS in the early strain range 2-4% also cannot be compared with n-values in the stabilized upper strain range above 10%, as done for mild and HSLA or DP600 steels. Uniform elongation may scatter less than fracture elongation and be independent from gage length, it brings however other issues to be addressed.

Recent investigations have also successfully correlated the forming limit curve FLC with fracture elongation rather than uniform elongation and thickness for a wide range of sheet steels [28]-[30]. The formability in FLC is namely understood and measured with the Bragard or strain rate dependent method as the beginning of local instability, which is closer to fracture elongation than uniform elongation.

3. **Local ductility applications**

3.1. **Local vs. global ductility after bake hardening**

The percentage thickness strain is plotted versus tensile fracture strain $A_80$ in Figure 3 for some cold rolled steels in the as delivered and bake hardened conditions (170°C/20min) with/without 2% previous pre-straining ($BH_0$, $BH_2$). After a $BH_2$ bake hardening heat treatment, there is almost no fracture elongation left for CR780Y980T-CP steel, but the local thickness strain at fracture remains on a high level around 60%. Bake hardening is not detrimental to the local ductility, it even improves it as well as the crash damage performance [8].
3.2. ISO16630 hole expansion ratio (HER) vs. tensile thickness strain at fracture

Figure 4a and Figure 4b show the linear dependency of percentage/logarithmic ISO16630 HER-value with percentage/logarithmic thickness tensile fracture thickness strain for cold rolled AHSS-UHSS steels in the tensile strength range 600-1200MPa. The percentage fracture thickness strain is calculated according to equation (2). The logarithmic fracture thickness strain is determined with equation (3). A maximum percentage thickness strain of 70% in Figure 4a leads therefore according to equation (3) to a logarithmic thickness strain of around 1.2 in Figure 4b. Both in milled and punched condition a fairly good correlation ($R^2$>0.6) can be found. Given the high inherent scattering of HER, any correlation coefficient $R^2$ above 0.5 can already be considered as statistically relevant. The correlation results may be improved by considering transverse instead of longitudinal tensile direction. Both HET and tensile tests deliver a thinning fracture strain under uniaxial loading and should therefore correlate [3],[5].

3.3. Local vs. global ductility mapping of AHSS

Tensile tests in longitudinal direction have been performed (3 replicates) according to ISO 6892 standard with 80mm gage length (20mm original width). Representative averaged results are summarized from a broader investigation involving around 500 tensile tests and tedious manual optical fracture strain measurements as previously described in Figure 1. It allows some first rough estimation of the local ductility of AHSS grades, however with limited statistical reliability and no industrial production
relevance. Figure 5 to 7 show respectively the percentage fracture thickness strain, the percentage area reduction at fracture and the local percentage fracture strain $A_0$ vs. percentage uniform (a) and fracture elongation (b). Figure 8 and Figure 9 show respectively the true fracture thickness strain and true fracture strain versus true uniform (a) & true fracture elongation (b). A redundancy of information is observed between all diagrams. A representation versus uniform elongation differs only very slightly from the one versus fracture elongation. Thickness strain contains the most relevant information about local ductility. A graphic representation as in Figure 8a/9a is often seen in literature for formability mapping. Such results seem to be very promising to achieve a classification of newly developed AHSS/UHSS grades. The outstanding local formability of CP steel grades can be clearly seen in such diagrams. DP grades on the contrary lie on a lower local formability and higher global elongation level. Current material development towards some balanced AHSS grades can be clearly ranked with such diagrams.

Figure 5. Percentage fracture thickness strain vs. percentage uniform (a) and fracture elongation (b).

Figure 6. Percentage reduction of area $Z$ vs. percentage uniform (a) and fracture elongation (b).

Figure 7. Percentage local fracture strain vs. percentage uniform (a) and fracture elongation (b).
4. Conclusions
Within this investigation it could be shown that the ISO16630 hole expansion ratio in punched and milled condition correlate quite well with the thickness strain at fracture from tensile tests. Some work is currently undertaken to understand the connection between bendability and fracture thickness strain, which is not that straight forward as for stretch flangeability.

The fracture thickness reduction can be measured with a cheap optical microscope relatively easily. The (challenging) measurement of fracture width or reduction of area is not considered as essential for local ductility assessment. An update of tensile testing standards may be necessary for AHSS without parabolic but rather erratic fracture shapes and no clear minimum thickness location. The suitability of such local ductility measurement in daily practice has yet to be further developed. Fracture strain from plane strain notched tensile samples could be more suitable for bendability & crash prediction.

The local ductility can be quantified by means of the (percentage or true) thickness strain or derivatives like reduction of area or true fracture strain in tensile direction. The global ductility may be both characterized based on (true) tensile uniform or fracture elongation. Advantages and drawbacks of those assessment methods are open to discussion. New possibilities are created for a ranking of AHSS steel grades according to their local, balanced or global ductility performance behavior.

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