Local formability assessment of AHSS steels with shear cut tensile tests

P Larour¹*, J Freudenthaler¹, H Pauli¹, M Kerschbaum¹, L Wagner¹, A Felbinger¹,², F. Sonnleitner¹,², J Angeli¹,²

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

E-mail: patrick.larour@voestalpine.com

Abstract. As an alternative to the ISO16630 hole expansion test, the punched tensile test is increasingly popular for edge crack characterization of AHSS advanced high strength steels. In this investigation the reduction of area as well as thickness reduction at fracture in the vicinity of left/right sample edge fracture sides has been determined by means of light optical microscopy according to the Hance local formability test methodology for 10% to 40% cutting clearance in (both sided) sheared cut vs. spark eroded or milled edge conditions. An edge crack index has been defined based on the tensile sample fracture shape. Local formability tensile properties based on area reduction or average thickness reduction are more sensitive to edge condition than Aₓₓ fracture elongation values. The determination of the reduction of area at fracture is however challenging due to projection issues. The % thickness reduction at minimum thickness as well as at left/right thickness in cut edge vicinity may offer some additional information about edge crack initiation and final fracture. The shear punch edge quality (punch and die tool wear, target vs. actual clearance) should be closely monitored for accurate reproducible testing results.

1. Introduction

Literature review punched tensile test:
Edge crack sensitivity investigations are commonly run by means of ISO16630 conical hole expansion test (HET) [1]. This test covers only the edge strain loading case out of plane. In industrial practice however a significant part of edge crack issues occur without holes while stretch flanging of cut edges of a blank for which hole expansion testing not necessarily reproduces the loading state as well as cutting pre-damaged edge condition. An alternative testing strategy consists therefore in comparing milled and punched edge conditions on commonly used tensile test samples for sheet steels [2]-[25].

The type of fracture (from the punched edge or from necking in the bulk material or mixed type) can be analyzed for an edge crack sensitivity assessment based on tensile fracture morphology [2]-[4],[8]-[9],[13],[18],[22],[24]. The difference in fracture strain between milled and punched conditions quantifies the edge crack sensitivity. Fracture strain is usually defined as the Aₓₓ fracture elongation with extensometer gage length in the parallel sample section. Postmortem local strain analysis on electro-etched 1-2mm grid have also been performed in [4],[15],[16],[22] or more recently using digital image correlation (DIC) with stochastic speckle patterns [9],[20]-[25].

Tensile test samples are easier to handle and simulate in comparison to HET. This is a frictionless test,
with in plane uniaxial loading of the sample cross section (until necking). It can be analyzed with simple 2D/3D DIC devices, without strain gradient effects in radial or thickness directions as compared to ISO16630 HET. Without a predefined notch, the edge crack however can occur randomly anywhere along the parallel cut length, which makes the use of shorter downsized tensile sample parallel length - mostly around 50mm - more advantageous. DIC also delivers the onset of localized necking in punched vs. milled edge condition as additional abort or failure criteria [21]. Such a local necking abort criteria may be more suitable than local fracture strain for industrial practice and FE simulations.

In comparison to axisymmetric punched HET, shear cut tensile tests allow an easier and industrially more relevant investigation of parameters such as:

- testing direction [13],[14],[16]-[18]
- cutting clearance [3],[4],[7]-[9],[11]-[14],[17],[18],[20],[21],[24],[25]
- tool wear [3],[18],[20],[21]
- pre-cutting (shaving) [2]
- open vs. close cut conditions as well as single vs. multistage cutting with variable blank geometry and open cut scrap width [21],[25]
- improved scrap support trimming techniques [3],[4],[18]
- oblique shear cutting angle [13],[14],[24]

The influence of laser and water jet cutting condition (often used in prototyping) in comparison to milled condition (or hand polishing, grounding with file and sand papers or EDM wire cutting) can be also tested [10],[14],[24],[34]. The influence of strain rate (edge cracks in components crash loading) as well as temperature (heat assisted component forming for edge crack prevention) on edge crack sensitivity may also be easier investigated with usual tensile test set up.

Some correlation between DIC failure strain from punched tensile tests and the ISO16630 hole expansion ratio HER have been found in [7],[12],[17],[20],[23]. The absence of strain gradients, a different gage length as well as earlier necking on tensile samples lead to more conservative fracture strain values in punched tensile tests, in comparison to hole expansion test [17]. These values are however more representative for in-plane edge crack types found in blank holder regions or in stretch flanged walls [16]. The burr height is usually higher for open cutting lines in comparison to close cutting conditions as present in hole expansion tests. Stretch flanging of blank edges (line cut) and hole flanging - both industrially relevant forming processes - may therefore behave fundamentally differently due to different initial cut edge conditions [17]. The cutting clearance of tensile test cutting tools is also easier to adjust via spacers, clearance active elements or set of shims [11],[22] as compared to the need for new tools each time for HET tests [4].

There is a wide range of punched tensile sample manufacturing methods. The easiest way consists in punching rectangular strips with straight edges for tensile tests [4]-[6],[12]-[18],[20],[22]. Either both straight sides are punched [5],[6],[15],[16],[20] or one side is hand polished after punching [17],[18],[22] or lightly milled after shearing [13],[14] to remove the shear affected zone. Strip tests usually do not break in the clamps with gage length to width ratios larger than 2 [12] and for steels with sufficient work hardening capability [4] and such as DP500 [18] or DP600/DP800 [12] or DP1000 [12],[22]. This may no longer apply for low n-value advanced or ultrahigh strength steels AHSS-UHSS.

An alternative testing geometry consists in asymmetric half dog bone shape, one side straight punched with precision shearing tools and the opposite side milled [3],[4],[10],[11],[17],[19]. Symmetric dog bone tensile samples can also be punched on both sides in a ready to test condition [2],[7]-[9]. An innovative flexible tool for symmetric dog bone sample is shown in [21],[25] with one side being milled first and the opposite side then being punched with variable initial blank geometry and scrap width and variable open vs. close cut conditions. In comparison to half dog bone samples, dog bone samples have a symmetric loading condition similar to usual standard tensile tests. Some tools punch both edges on one sample at once, other tools punch one side after another with two samples punched together. Figure 1 summarizes the various competing tensile sample types with punched edges found in the literature, with increasing complexity from strip up to half and full dog bone geometries.
Figure 1: Punched tensile sample types, literature overview (red sample edge: punched with a definite clearance, black sample edge: milled/EDM/Laser cut/ground).

Shear cut tensile test local formability vs. ISO16630 HER:
Considering fracture elongation for edge fracture sensitivity assessment makes sense on a phenomenological level. DIC local strain measurements are mostly suitable for robust determination of the onset of localized necking in tensile test, which is useful as a material failure criteria for FEM purpose. DIC fracture strain is however strongly dependent on a variety of measurement settings such as virtual gage length and time resolution (frame rate) dependency as well as unclear element formulation right at blank edges, which lead to a strong underestimating of the intrinsic local ultimate material fracture strain measurement, especially for low n-value AHSS-UHSS steel grades. As proposed in [12], an alternative fracture strain analysis method focuses on ultimate “0 gage length” local edge fracture strain (Sheared Edge Limit Strain SELS) through thickness measurement in crack vicinity. This is quite promising from a material characterization point of view, since such thickness based postmortem properties are truly gage length and frame rate independent materials properties. The idea of local thickness or area reduction measurement on flat sheet samples has recently grown increasingly popular according to the Hance methodology for local ductility assessment based on fracture surfaces of tensile test samples [26]. A strong correlation has been found between hole expansion ratio HER and reduction of area [27] as well as thickness reduction at fracture [28],[29]. This correlation is anyway much higher as compared to correlations with standard tensile properties such as fracture elongation, uniform elongation or post uniform elongation [30].

HER may correlate even better with fracture toughness and essential work of fracture [31],[32]. There is an ongoing debate whether tensile-based local ductility measures from the bulk undamaged material can be correlated at all with the crack resitvity behavior of a shear cut pre-damaged hole expansion test [32],[33]. This question may be clarified by using punched tensile tests to include the shear cut pre-damage [23]. The dependency of reduction of area with varying cutting clearance has been indeed recently investigated for aluminum, however encountering some experimental difficulties in determining the projected reduction of area with irregular edge crack fracture shapes as well as dealing with burr affected and chamfered sample edges [34]. The recently gained knowhow in experimental measurement of reduction of area (and thickness reduction to avoid such projection issues) for AHSS steels may here be beneficial in overcoming such experimental challenges [35]-[36]. The entire broken sample surface shape includes the history of the crack propagation, either starting the usual way through sample necking in center or rather from the edge or in a mixed necking and edge crack pattern.

The edge crack sensitivity thematic is also quite related to the topic of hydrogen embrittlement of shear cut pre-damaged material, for which punched tensile test testing standards are currently developed as for example according to VDA 238-202 specification [37]. The characterization methods for shear punched edges for both topics are actually the same, so that both research communities should interact and benefit more from each other [39]-[40].

The aim of this study is to show the advantages of local formability measurement based on tensile test fracture surfaces in punched vs. milled/EDM condition in order to characterize more accurately the edge crack sensitivity of AHSS grades.
2. Experimental procedure

Investigated materials: 1.5mm thick dualphase (drawing type) and multiphase (bending type) AHSS steels with tensile strengths between 600 and 1200MPa have been investigated together with mild steel and HSLA steel reference grades (Table 1).

Table 1: Transverse mechanical properties of the investigated steels (ISO 6892-1 type 2).

| Steel grade      | Delivery condition | Product type | Thickness [mm] | $R_{p,0.2}$ [MPa] | $R_m$ [MPa] | $A_y$ [%] | $A_{90}$ [%] |
|------------------|-------------------|--------------|----------------|-------------------|------------|-----------|-------------|
| Mild steel       | CA mild           | dualphase    | 1.47           | 165               | 287        | 24        | 45          |
| HSLA340          | HDG microalloyed  | dualphase    | 1.47           | 373               | 434        | 14        | 27          |
| DP600            | CA dualphase      | multiphase   | 1.47           | 362               | 642        | 15        | 25          |
| DP800            | CA+ELO dualphase  | multiphase   | 1.50           | 533               | 812        | 11        | 17          |
| CP800            | HDG multiphase    | multiphase   | 1.49           | 663               | 812        | 19        | 16          |
| DP1000           | CA+ELO dualphase  | multiphase   | 1.44           | 705               | 997        | 8         | 12          |
| AHSS1000MPa      | CA+ELO multiphase | multiphase   | 1.55           | 721               | 1036       | 11        | 14          |
| CP1000(1)        | CA+ELO multiphase | multiphase   | 1.49           | 940               | 1020       | 4         | 7           |
| CP1000(2)        | HDG multiphase    | multiphase   | 2.00           | 911               | 1011       | 4         | 7           |
| CP1200           | CA multiphase     | multiphase   | 1.59           | 1082              | 1266       | 3         | 6           |

CA: continuous annealed / ELO: electrogalvanized / HDG: hot dip galvanized

Punched tensile test set-up: ISO6892-1 type 2 tensile samples (Figure 2) have been manufactured with punched edges on both sides with a defined cutting clearance between 5% and 45% (0.1 to 0.6mm cutting gap). EDM (electrical discharge machined) wire cut and milled samples are also tested as reference. All tensile tests are performed at $4 \times 10^{-3}$s$^{-1}$ constant strain rate in transverse direction.

Figure 2: ISO 6892-1 tensile sample geometry, punched clearances and fracture type.

Punching tool: A tool has been designed for cold rolled steels in order to punch 2 tensile test samples at once, one side switched after another from initial milled 30 x 250mm rectangular strips. Only the parallel length section $L_c=120$mm as well as radii (R35) have been punched to 20mm gage width with an elongated hole die at cutting clearances between 0.1 and 0.6mm (Figure 3). Special care was put on sharp punching tools to avoid irregular cut edge conditions and excessive burr (Figure 4). A comparison between nominal target tool clearance and actual clearance has been performed from metallographic cross sections at 6 different positions on each sample (left/right edges, upper/middle/lower gage length
zones) for a mild and DP600 steel in Figure 5. The clearance tolerance is around ±30-40µm (Figure 5a), which translates into an acceptable ±2-3% clearance tolerance (Figure 5b) for 1.5mm investigated materials. The burr formation is triggered strongly after 15-20% clearance (Figure 5c).

Figure 3: Punching tool test setup for both sided punched tensile test ISO 6892-1 sample. 0.1; 0.15; 0.2; 0.25; 0.3; 0.4; 0.5; 0.6mm cutting clearance.

Figure 4: Cut edge quality vs. cutting punch quality (a): edge-sharp punch; (b): edge-worn out punch.

Figure 5: Actual vs. nominal clearance (a): absolute values; (b): relative values; (c): burr vs. clearance.

Edge crack fracture characterization: Typically edge cracks propagate 90° to the tensile direction across the sample width, until they merge with another edge crack emerging from the opposite side or with a locally necked zone. Virtually all configurations between 0% to 100% edge crack length along fracture area can be found as shown for a wide range of cold rolled AHSS (tensile strength 600-1200MPa, thickness ≈ 1.5mm) in Figure 6. This allows the definition of a fracture morphology based edge crack index for a ranking of AHSS steel grades with regard to edge crack sensitivity with pre-damaged shear cut tensile test sample edges. As shown in Figure 7, it is clear that shear band formation originates from sample edge and no more from sample center in the case of punched sample edges. This is a competitive process with multiple edge crack forming in the same time.

High speed video (100 000! frames/second) as well as high speed infrared camera (≈1kHz lower frame rate) have been used during quasistatic tensile testing for milled sample edges (Figure 8) as well as shear punched edges (Figure 9). The whole fracture occurs almost instantaneously within <60µs which requires at least a challenging 100kHz frame rate with powerful LED spotlights to obtain around 5 useful pictures along fracture progress. The much slower infrared camera is more suitable to capture the shear band formation and localized necking prior to fracture initiation.

The fracture clearly initiates from sample center in case of milled edges with no edge cracks (mode 1 fracture). With shear cut edges the fracture starts from one or both edges like an indent notch growing perpendicularly to the tensile test direction. The extent to which it grows as such until localized
necking finally occurs in the torn up remaining sample width section defines the edge crack sensitivity degree. The edge crack propagates in a shear mode across thickness without localized necking. The higher the cutting clearance to higher the edge crack index moves from a mixed mode 2+1 towards 100% (mode 2 fracture). The thickness profile of fracture surface across sample width gives also a good indication on edge crack existence. Asymmetric thickness profiles with higher thickness plateau level correlate well with shear slant fracture in the edge crack propagation region (Figure 8, Figure 9).

Figure 6: Punched tensile fracture morphology with increasing 90° edge crack proportion along fracture area. Edge crack index definition 0-100%. Cold rolled 1.5mm, AHSS 600-1200 MPa.

Figure 7: Edge crack and shear band formation examples on AHSS punched tensile samples. (a): DP600, 1.4mm, milled edges Z-shape fracture start from sample center. No edge crack. (b): CP1000(2), 2.0mm, milled edges, shear band fracture start from center & edges. No edge crack.

Figure 8: Milled tensile samples, fracture starting from sample center without edge cracks. FEM simulation; high speed & infrared Videos; Keyence 2D/3D microscope with thickness profile.
Figure 9: Punched AHSS1000MPa tensile tests, fracture starting from cut edge high speed videos, Keyence 2D/3D microscope with thickness profile (a),(b): 10% clearance; (c): 20% clearance.

**Local ductility measurement:** Figure 10 shows the digital microscope setup (Keyence VHX-6000) used for postmortem optical fracture surface analysis of the tensile samples. Those are placed vertically under the microscope (Figure 10a) for direct projected measurement of thickness and fracture area.

A scan is performed in Z-direction through the focal range of a sample in order to build a fully-focused image with a large working distance (depth of field \(\approx 25\)mm). The pre-selected X-Y area is then scanned delivering a 2D/3D stitched image. The projection is done in accurate manner directly by the hardware without additional need for horizontal tilting testing sample and fracture angle measurement (Figure 10b) previously described in [28],[35]. When dealing with irregular asymmetric edge crack fracture shapes, this is the most efficient way for accurate image projection for reduction of area determination. The local thickness measurement is however not affected and can still be determined in the usual horizontally tilted 2D manner (Figure 10b). The average thickness measurement using fracture contourplots may be affected by the sample tilting if the thickness and fracture angle distribution is not symmetric along sample width, producing strong projection distortion effects [34] (Figure 11).

Figure 10: Keyence digital microscope set up. Tensile sample in vertical / tilted / flat position.

Figure 11: Projection distortion issues depending on sample axis angle rotation under microscope.
Alternatively, local thickness strain measurements based on minimum thickness location as well as thickness in the vicinity of punched edges - where edge crack begins - may be an effective and robust alternative. In order to determine the projected area it is necessary to calculate the projected width \( b \) as shown in Figure 12. The microscope view delivers a “wrong” apparent sample fracture width \( L_{\text{app}} \).

A double projection correction is then actually necessary in the general case to take into account the angle \( \alpha \) between microscope and tensile sample vertical axes as well as the average fracture angle \( \gamma \) between \( X \) sample surface width and horizontal direction. An integrated piecewise linear projection procedure may be necessary in case of very irregular asymmetric fracture angle pattern.

In this investigation the particular case with both microscope and sample vertical axes aligned (\( \alpha = 0 \)) is chosen (\( b = L_{\text{app}} \) directly). The surface area projection has been directly performed by the Keyence 3D stereo microscope hardware in this investigation. Figure 13 shows the determination method for \% thickness and contourplot area reduction from fractured samples.

Figure 14a shows some example of burr formation, which has to be included in contourplot area measurement. Figure 14b shows some edge cracks which also happen occasionally when testing FLC tensile samples too.
Engineering stress strain curves vs. cutting clearance: The interpretation of engineering stress strain curves from tensile tests in the punched condition differ significantly from the reference milled condition. A sharp bend in the engineering stress strain curve before, at or after uniform elongation $A_g$ indicates some edge crack initiation. The curve is prolonged straight to much lower stress level in a $45^\circ$ angle which is unusual for tensile tests (Figure 15). This is due to the edge crack propagating perpendicular to tensile direction acting like a wedge with a linear decrease in sample cross section. This discontinuity occurs sooner for more severe edge cracks, which prevent a proper necking in width direction as shown in Figure 15a,b. The determination of fracture elongation is severely perturbed and may be not reliable. The beginning of edge crack can only be determined manually. Usual software only deliver the elongation at final rupture, which is not the same. Due to such kinked stress-strain curves, the fracture elongation of punched samples may be even higher than for milled edges (Figure 16a)!

Some unusual elastic springback may also occur during edge crack propagation (Figure 16b). The fracture elongation in tensile tests may be therefore misleading in quantifying edge crack sensitivity.

Figure 15: Engineering stress strain curves vs. clearance (a): AHSS 800MPa; (b): HX340LAD.

Figure 16: Engineering stress strain curves vs. clearance: experimental artefacts, AHSS 1000MPa.

3. Experimental results

Figure 17 shows the edge crack index defined according to Figure 6 from broken tensile test samples vs. cutting clearance. The clearance is varied between 0.1 and 0.6mm, which corresponds to a relative clearance of 6 to 42%. The edge crack index is given vs. increasing clearance, ranging from 0% (no edge cracks), 0-25% (moderate edge cracks) up to 25-100% (severe edge cracks). CP1000 & CP1200 steels are not edge crack sensitive at all (edge crack index=0%) and CP800 is only very slightly edge crack affected. DP800 & DP1000 steels are sensitive at clearances $\geq 7$ and 14% respectively. DP600 is also affected at clearances $\geq 27%$. Edge cracks are also observed for HSLA340 steel at clearances $\geq 21%$. Even mild steel shows some edge crack indications at clearances $\geq 34%$. 
Figure 17: Tensile edge crack index classification vs. clearance for the investigated steel grades.

The dependency of uniform $A_g$ and fracture elongation $A_{80}$ vs. cutting clearance is shown in Figure 18a and Figure 18b respectively. Only a low sensitivity to edge condition can be seen based on such tensile test mechanical properties. CP-grades are not affected by cutting clearance, while DP grades are to some extent, with a pronounced decrease in $A_{80}$ mostly above 15-20% clearance. Even mild steel and HSLA steel show some clearance dependency, not just AHSS. Fracture elongation is generally more sensitive than uniform elongation to edge condition.

The % reduction of area $Z$ and % thickness reduction at fracture based on average thickness from broken samples are shown in Figure 19a and Figure 19b respectively. The % thickness reduction based on minimum thickness is shown in Figure 20a. The thickness reduction based on the thickness in the vicinity of punched edges (minimum thickness left or right on sample area) is shown in Figure 20b. All of these local ductility measures point out edge crack sensitive behavior for DP600/800/1000 steels to some extent. A decrease in % thickness reduction based on minimum thickness is a strong evidence for edge crack occurrence. Thickness measurements in the vicinity of punched sample edges (slightly away from eventual edge burr) are also quite sensitive to edge crack occurrence and deliver the initial fracture thickness strain at edge crack initiation. The integrated average thickness or contourplot area is more an indicator of the whole energy absorbed for crack initiation and propagation. The smaller the difference between edge and average thickness strain, the more edge crack sensitive the material.

Figure 21a shows the % width reduction at fracture vs. cutting clearance. Edge crack occurrence is generally linked to a decrease in width reduction within the disturbed necking zone, especially for high elongation materials [12]. Figure 21b shows the ISO16630 hole expansion ratio (HER) values vs. cutting clearance for the investigated steel grades together with EDM/milled references. The HER values in punched condition are significantly lower than in EDM/milled conditions. The HER values decrease steadily with increasing clearance for mild and HSLA340 steels. For CP-steels a maximum in HER is reached around 15% clearance. The HER values for DP800/DP1000 steels are the lowest. A similar ranking in edge crack sensitivity is seen between conical hole expansion and punched tensile testing.

Figure 18: (a): Uniform elongation $A_g$ vs. clearance; (b): Fracture elongation $A_{80}$ vs. clearance.
Figure 19: (a): % Reduction of area Z vs. clearance; (b): Average % thickness reduction vs. clearance.

Figure 20: % Thickness reduction vs. clearance (a): at min thickness; (b): at left/right sample edge.

Figure 21: (a): % Width reduction vs. clearance; (b): Conical expansion HER vs. clearance.

Figure 22 shows the edge crack sensitivity factor defined here exemplarily on % average thickness reduction vs. cutting clearance. The edge crack sensitivity factor can be defined as absolute (Figure 22a) or relative (Figure 22b) ratio of punched to reference EDM/milled values. Absolute ratio deviations below 80% or relative deviation higher than 20% in comparison to reference level can be considered as a pronounced edge crack sensitivity indication [25]. Actually any kind of mechanical property Ag, A80, thickness reduction, area reduction, thickness reduction at min thickness or at edges etc., can be used to define the edge crack sensitivity factor.
4. Conclusions

Punched tensile testing is a suitable complementary / alternative testing method to classical ISO16630 conical hole expansion tests. The both sided shear cut edge quality (punch and die tool wear, target vs. actual clearance) should be however closely monitored for accurate reproducible testing results.

The tensile fracture shape allows also for the definition of an edge crack index for a quick ranking of AHSS edge crack sensitivity. Post processing of broken tensile sample surfaces yields valuable data about local fracture ductility deterioration vs. pre-damage by both-sided shear cutting in comparison to milled or EDM wire bulk material edge conditions.

The reduction of area and thickness at fracture are more sensitive measures for the characterization of AHSS edge crack sensitivity in comparison to uniform or fracture elongation from tensile test. Projection issues may however affect the integrated average thickness and area measurement in case of peculiar fracture shapes with asymmetric thickness and fracture angle distributions. Edge crack occurrence is also linked to a decrease in width reduction at fracture, since edge crack prevents the proper development of post uniform localized necking.

A decrease in % thickness reduction at minimum thickness is a strong evidence for edge crack occurrence. Thickness measurements in the vicinity of punched sample edges (slightly away from eventual edge burr) are also quite sensitive to edge crack occurrence and deliver the initial fracture thickness strain at edge crack initiation. The integrated average thickness or contourplot area is more an indicator of the whole energy absorbed for crack initiation and propagation. The smaller the difference between edge and average thickness strain, the more edge crack sensitive the material.

All of these local ductility measures point out an edge crack sensitive behavior for DP600/800/1000 steels to some extent in comparison to multiphase CP800/1000/1200 steels.

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