Effects of fracture area measurement method and tension test specimen type on fracture strain values of 980 class AHSS

B M Hance\(^1\)* and T M Link\(^2\)

United States Steel Corporation, USA
\(^1\) Automotive Center, 5850 New King Court, Troy, MI 48098
\(^2\) Research & Technology Center, 800 E. Waterfront Drive, Munhall, PA 15120

*bhance@uss.com

Abstract. With increasing focus on “local formability” and fracture behavior of advanced high strength steels (AHSS), the effects of tension test specimen type and fracture area measurement method on fracture strain values were examined. Three 980 class AHSS and three standard tension test specimens with various widths were evaluated. Fractures types were grouped into three categories according to appearance and thickness profile “shape”—Type 1: Perpendicular to the tensile axis (across specimen width) with a V-shape thickness profile; Type 2: Irregular transition from Type 1 to Type 3 with a W-shape thickness profile; and Type 3: Angled across the specimen width with a U-shape thickness profile. All materials exhibited Type 1 fractures when tested with Subsize specimens. However, as the specimen width-to-thickness ratio increased, the fracture type changed from Type 1 to Type 2 or from Type 1 to Type 3. In contrasting the effects of specimen type and fracture area measurement method, specimen type (width) has a far greater impact on the consequent fracture strain value. For tension testing no clear universal relationship exists between the width-to-thickness ratio and the fracture strain. These observations suggest that, when reporting fracture strain values, the specimen type, the material thickness, and the fracture area measurement method must be indicated.

1. Introduction

Over the past two decades, fracture strain values derived from standard uniaxial tension tests have been used increasingly to evaluate automotive crashworthiness and formability of aluminium alloys [1] and advanced high strength steels (AHSS) [2]-[7]. In 2016 the foundation for a formability classification and rating system was introduced for AHSS [8], where performance expectations are distinguished by the relationships between true fracture strain (local formability) and true uniform strain (global formability) in a standard tension test. Such local/global performance mapping concepts continue to be explored by steelmakers [9]-[15], automakers [16] and international industry consortiums [17]-[18].

The “zero-gage-length” elongation at fracture \(e_0\) is a conceptual engineering strain value based on an infinitesimal gage length in a uniaxial tension test:

\[
e_0 = \frac{A_o}{A_f} - 1,
\]

where \(A_o\) and \(A_f\) are the specimen cross-section area before testing and after fracture, respectively (constant volume assumed) [19].
It follows that the true fracture strain (TFS) is the true (logarithmic) strain value associated with \( e_0 \):

\[
TFS = \ln(1 + e_0) = \ln \left( \frac{A_f}{A_o} \right) = -\ln \left( 1 - \frac{Z}{100} \right),
\]

(2)

where \( Z \) is the percent reduction of area at fracture in a tension test [11], and

\[
Z, \% = 100 \cdot \left( \frac{A_o - A_f}{A_o} \right).
\]

(3)

This analysis is focused on the influence of tension test specimen type and fracture area measurement method on the true fracture strain value. Also considered are the effects of specimen type on tensile properties, fracture appearance, fracture thickness profile, strain path to fracture and local/global formability map characteristics.

2. Materials and procedures

2.1. Materials

Three 980 class AHSS materials were included in this analysis, and basic descriptions are given in Table 1. All were produced through cold-rolling at U. S. Steel Gary Works in Gary, IN, USA and finished at the PRO-TEC Coating Company continuous annealing line in Leipsic, OH, USA.

| Material          | Thickness | Description                                                                 |
|-------------------|-----------|-----------------------------------------------------------------------------|
| 980DP             | 1.2mm     | Conventional dual-phase (DP) ferrite/martensite steel                        |
| 980HY(LCE)        | 1.5mm     | Higher yield strength (HY) version of 980DP with low carbon equivalent (LCE); Microstructural refinement achieved via microalloying with niobium (Nb) |
| 980 XG3\textsuperscript{TM} Steel | 1.4mm | Third generation advanced high strength steel (“3rd GEN AHSS” [17] or “GEN3 AHSS” [10]) with an excellent combination of strength and formability |

2.2. Tension testing

Three standardized tension test specimen types were considered. Relevant dimensions and testing parameters are summarized in Table 2. All specimens were aligned with the tensile axis in the transverse orientation (90° to the sheet rolling direction).

| Standard | Specimen type | Nominal dimensions, mm (in.) | Crosshead speed, mm/s (in./s) |
|----------|---------------|------------------------------|-------------------------------|
| Ref. [20]| Subsize       | Gage width Gage length Stage 1\textsuperscript{a} Stage 2\textsuperscript{b} |                                |
| ASTM Std | 6.35 (¼)     | 25 (1) .025 (.001) 0.20 (.008) |
| Ref. [21]| JIS No. 5     | 25 (1) 50 (2) .025 (.001) 0.43 (.017) |

\textsuperscript{a}0 to 2% elongation; \textsuperscript{b}2% elongation to fracture

2.3. Fracture area measurement methods

Figure 1 shows an idealized tension test specimen fracture surface, where five thickness measurement locations are indicated: two at the edges \((t_a, t_c)\); one at the center \((t_c)\), and two at the quarter-width positions \((t_b, t_d)\). Measured approximately at mid-thickness, \(w_f\) is the fracture width. The dashed outline is a 10-point polygon (decagon) that approximates the projected fracture surface area, where the points (corners) of the polygon correspond width-wise to the thickness measurement locations.
From the dimensions portrayed in Figure 1, four methods to determine \( A_f \) are defined in Table 3—three lineal methods and one areal method. Method A uses a single thickness measurement at mid-width. Method B uses a weighted three-thickness average (ASTM parabolic method [20]). Method C uses a five-thickness average. For Method D, \( A_f \) is determined with image analysis software as the area of a polygon as depicted in Figure 1.

### Table 3. Fracture area measurement methods

| Methods | Fracture thickness | Fracture width | Fracture area, \( A_f \) |
|---------|-------------------|----------------|--------------------------|
| Lineal A | \( t_f = t_c \) | \( w_f \) | \( A_f = t_f \cdot w_f \) |
| Lineal B | \( t_f = (\frac{1}{3}) \cdot (t_a + 4t_c + t_e) \) | \( w_f \) | \( A_f = t_f \cdot w_f \) |
| Lineal C | \( t_f = (\frac{1}{3}) \cdot (t_a + t_b + t_c + t_d + t_e) \) | \( w_f \) | \( A_f = t_f \cdot w_f \) |
| Areal D | Not applicable | Not applicable | Area of polygon |

Dimensional measurements were made with a Keyence VHX-5000 digital microscope with focal stacking capability. Note that \( t_c, w_f \) and \( A_f \) are respectively: the *projected* thickness, the *projected* width, and the *projected* area of the fracture surface. That is, to accommodate irregular, angled fracture surface features, measurements are made with respect to a virtual plane normal to the tensile axis.

### 3. Results and discussion

Tensile properties for 980DP, 980HY (LCE) and 980 XG^3™ steel are summarized in Table 4.

### Table 4. Tensile properties\(^a\)

| Material | Specimen  | YS, MPa | UTS, MPa | UE, % | TE, % | PUE, % |
|----------|-----------|---------|----------|-------|-------|--------|
| 980DP    | Subsize   | 643 (11)| 1044 (5) | 7.7 (0.4) | 13.0 (0.6) | 5.3 (0.6) |
|          | ASTM Std  | 635 (12)| 1041 (3) | 7.6 (0.2) | 12.1 (0.4) | 4.5 (0.3) |
|          | JIS No. 5 | 642 (11)| 1062 (4) | 8.1 (0.2) | 14.2 (0.8) | 6.1 (0.8) |
| 980HY (LCE) | Subsize | 787 (5) | 1059 (4) | 6.5 (0.2) | 13.6 (1.4) | 7.1 (1.4) |
|          | ASTM Std  | 784 (8) | 1052 (5) | 6.3 (0.3) | 11.4 (0.5) | 5.1 (0.3) |
|          | JIS No. 5 | 788 (14)| 1074 (7) | 6.8 (0.3) | 13.1 (0.4) | 6.3 (0.4) |
| 980 XG^3™ Steel | Subsize | 638 (1) | 1010 (3) | 16.3 (0.5) | 22.1 (0.6) | 5.8 (0.9) |
|          | ASTM Std  | 632 (5) | 1005 (2) | 16.4 (0.5) | 21.2 (0.4) | 4.8 (0.2) |
|          | JIS No. 5 | 637 (5) | 1017 (1) | 17.2 (0.2) | 25.0 (0.4) | 7.8 (0.4) |

\(^a\) Transverse orientation; Average values listed (n=5, standard deviation in *italics*); YS = yield strength (0.2% offset); UTS = ultimate tensile strength; UE = uniform elongation; TE = total elongation; PUE = post-uniform elongation (TE – UE); \(^b\) n=4

The following general observations were made from the data in Table 4: (1) For all three materials, yield strength (YS), ultimate tensile strength (UTS), total elongation (TE) and post-uniform elongation (PUE) were lowest when measured by the ASTM Std specimen; (2) For all three materials, UTS and uniform elongation (UE) were highest when measured by the JIS No. 5 specimen; (3) For 980DP and 980 XG^3™ steel, TE and PUE were highest when measured by the JIS No. 5 specimen; and (4) For 980HY(LCE), TE and PUE were highest when measured by the Subsize specimen.

As all the subject materials are 980 class AHSS (980 MPa minimum UTS designation), tensile property differences are graphically better represented by a plot of TE vs YS (Figure 2) rather than by
the customary “banana diagram” or Global Formability Diagram approach (TE vs UTS) [17]. For the 980DP baseline material, the product YS·TE ranges from about 7 to 9 GPa·%. For 980HY(LCE), YS·TE ranges from about 9 to 11 GPa·%, and for 980 XG3™ steel, YS·TE ranges from about 13 to 16 GPa·%.

![Figure 2. Relationships between total elongation (TE) and yield strength (YS). Contours represent specific values of the product YS·TE (GPa·%), as indicated. See text for details. Error bars indicate ±1 standard deviation for each specimen type (Table 4).](image)

3.1. Fracture types
Based solely on fracture appearance, three fracture types were observed in this analysis, and examples of each are shown in Figure 3. Type 1 fracture is perpendicular to the tensile axis across the specimen width; Type 2 fracture is an irregular transition from Type 1 fracture to Type 3 fracture; and Type 3 fracture is aligned at an angle across the specimen width (~50-60° from the tensile axis). All materials exhibited 100% Type 1 fracture with Subsize specimens. However, as the specimen width increased (Subsize → ASTM Std → JIS No. 5), the fracture type changed from Type 1 to Type 2 (980DP and 980 XG3™ steel) or from Type 1 to Type 3 [980HY(LCE)]. When tested with the ASTM Std specimen, 980DP and 980 XG3™ steel showed a mixture of Type 1 and Type 2 fractures, and 980HY(LCE) showed a mixture of Type 2 and Type 3 fractures. A similar fracture orientation dependence on specimen width was reported for dual-phase (DP) steels more than thirty years ago by researchers at the Colorado School of Mines [22]. Wagner and Larour [13] have since confirmed this behaviour for other AHSS types and have illustrated that the transition behaviour—in terms of critical specimen width-to-thickness ratio—is material dependent, as demonstrated in Figure 3(b).

![Figure 3. (a) Examples of each fracture type, from left to right: Type 1 fracture (Subsize specimen)—1.4mm 980 XG3™ steel; Type 2 fracture (ASTM Std specimen)—1.2mm 980DP; and Type 3 fracture (JIS No. 5 specimen)—1.5mm 980HY(LCE); (b) Fracture type summary.](image)

Figure 4 shows example Type 1 and Type 3 fractures in cross-section at the mid-width position (corresponding to $t_c$ in Figure 1). Type 1 fractures typically run at an angle through thickness (~50-55° from the tensile axis). While most of the Type 1 fractures in this analysis resemble that shown in Figure 3(a)-left and that shown in Figure 4(a), occasional through-thickness chevron profiles and “cup and
cone” [13] type fractures have been observed for Type 1 fractures. Nevertheless, Type 1 fractures are roughly symmetric about a plane normal to the sheet surface at the mid-width position.

Type 3 fractures invariably show localized necking in through-thickness cross-section as in Figure 4(b). Therefore, Type 3 fractures are roughly symmetric about a plane parallel to the sheet surface at the mid-thickness position. Type 2 fractures have both Type 1 and Type 3 characteristics at different positions across the width and thus have no overall plane of symmetry.

Although outside the scope of this analysis, various degrees of damage (void formation) were observed in through-thickness cross-sections of fractured specimens—e.g. Figure 4. The authors refer the reader to the detailed metallographic analysis of Heibel et al. [16] for more information on this topic.

Steinbrunner et al. [22] defined an angle $\Phi$ that represents the fracture orientation across the specimen width with respect to the tensile axis (TA). That is, $\Phi = 90^\circ$ means that the fracture is perpendicular to TA. Furthermore, another angle $\Phi_2$ may be defined to represent the through-thickness fracture orientation with respect to TA. These angles are shown schematically in Figure 5. From the observations above, Type 1, Type 2 and Type 3 fracture characteristics are summarized in Table 5.

![Figure 4](image-url) **Figure 4.** Examples of (a) Type 1 fracture, and (b) Type 3 fracture. Polished through-thickness cross-sections at the mid-width position. The tensile axis is horizontal.

![Figure 5](image-url) **Figure 5.** Schematic representation of the gage section of a fractured tension test specimen, where $\Phi$ and $\Phi_2$ are the angles between the fracture and the tensile axis (TA) across width and through thickness, respectively. Here, TA is the $x$ axis; the $xy$ plane is at mid-thickness, and the $xz$ plane is normal to the $xy$ plane at mid-width.

| Fracture type | Fracture orientation Across width | Through thickness | Symmetry (Figure 6: $xyz$ system) |
|---------------|----------------------------------|-------------------|----------------------------------|
| Type 1        | $\Phi \sim 90^\circ$            | $\Phi_2 \sim 50-55^\circ$ | $xz$ plane                       |
| Type 2        | Irregular                        | Irregular         | None                             |
| Type 3        | $\Phi \sim 50-60^\circ$         | Localized neck    | $xy$ plane                       |

3.2. Fracture thickness profiles
Researchers at voestalpine Stahl in Austria [11], [13], [23] have extensively analysed the effects of tension test specimen geometry on AHSS fracture characteristics. It was explained that the parabolic fracture thickness profile assumption (Figure 1) is applicable only to smaller width-to-thickness ratios—e.g. thicker, hot-rolled materials or narrow gage sections. For thinner, cold-rolled materials (or wider gage sections), there is often no clear fracture thickness minimum at the mid-width position. In some cases, a fracture thickness maximum at mid-width had been observed. Furthermore, occasional mid-thickness delamination renders volume constancy dubious—re Equation (1).

Fracture thickness profiles are shown in Figure 6 for 980DP, 980HY(LCE) and 980 XG3™ steel for each specimen type. As specimen width increased, the fracture thickness generally decreased, and the fracture thickness profile “shape” varied drastically and systematically with fracture type. Type 1 fractures have a V-shape (parabolic) thickness profile. Type 2 fractures have a W-shape thickness profile, and Type 3 fractures have a U-shape thickness profile.

![Figure 6](image.png)

**Figure 6.** Fracture thickness profiles for each specimen type. Width positions correspond to the thickness measurement locations defined in Figure 1. The dashed curves are 4th order polynomial fits to the experimental fracture thickness data. Error bars indicate ±1 standard deviation (n=5).

### 3.3. True fracture strain (TFS)

The effects of specimen type and fracture area measurement method (Table 3) on TFS value are summarized in Figure 7. The data for 980HY(LCE) and 980 XG3™ steel (earlier “980 GEN3”) were published elsewhere [10], and the data for 980DP were added to this analysis as a “GEN1 AHSS” baseline. In contrasting the effects of specimen type and fracture area measurement method, specimen type (width) has a far greater impact on TFS value, and the relationship between specimen geometry and TFS is material-dependent. Similar conclusions were drawn by Wagner and Larour [13]. For 980DP and 980 XG3™ steel, TFS decreased as specimen width increased, while for 980HY(LCE), TFS generally increased as specimen width increased. For Method A (single mid-width thickness measurement), TFS is relatively high in contrast to that determined by other methods—especially for narrower specimens where “parabolic” or V-shape fracture thickness profiles are prominent. For the Subsize specimen type, Methods B and D result in similar TFS values (low width-to-thickness ratio), and for the ASTM Std specimen type, Methods C and D gave similar results (intermediate width-to-thickness ratio).

Method D measurements were not made for the JIS No. 5 specimens, as the fracture surfaces were too wide to fit within the field of view with the Keyence system at 20X magnification (lowest setting available). For Methods A, B and C, fracture width (\(w_f\)) measurements for the JIS No. 5 specimens were made on a separate measuring microscope with a dial indicator precision of 0.0005 in. (0.013 mm). The microscope was continually manually re-focused to ensure true projected lineal measurements.
3.4. True thinning strain at fracture

Heibel et al. [16] have suggested that the true thinning strain at fracture ($\varepsilon_{3f}$) is a more intrinsic measure of local formability:

$$\varepsilon_{3f} = \ln\left(\frac{t_f}{t_0}\right) = \ln\left(\frac{t_0}{t_f}\right),$$

(4)

where $t_0$ is the initial sheet thickness, and $t_f$ is the sheet thickness at fracture. Note that, by convention $\varepsilon_{3f}$ is positive and represents the absolute value of the true thickness strain at fracture (a negative value). It was argued that other fracture strain values (e.g. TFS, Z) are based on fracture area measurements and thus include specimen width change information, for better or for worse. The influence of specimen width-to-thickness ratio on TFS and $\varepsilon_{3f}$ is illustrated in Figure 8, where the fracture thickness ($t_f$) was measured by Method C (Table 3). For all materials the difference between TFS and $\varepsilon_{3f}$ decreased as specimen width increased.

Figure 7. Effects of specimen geometry and fracture area ($A_f$) measurement method on true fracture strain (TFS). Error bars indicate ±1 standard deviation (n=5).

Figure 8. Effects of tension test specimen width-to-thickness ratio on true fracture strain (TFS) and true thinning strain at fracture ($\varepsilon_{3f}$)—Method C (Table 3). Error bars indicate ±1 standard deviation (n=5).
3.5. Fracture forming limit diagram (FFLD)

Figure 9 is an alternative representation of the data shown in Figure 8, where major and minor strain values are plotted on a so-called fracture forming limit diagram (FFLD). In this context, the major strain at fracture (ε1f) is equivalent to TFS, and the minor strain is the true width strain at fracture (ε2f), where 

\[ ε_{2f} = ε_{3f} - \text{TFS} \] (constant volume).

Recall that by convention, ε3f is the absolute value of the true thinning strain at fracture. As the specimen width increased, the effective strain-path-to-fracture veered away from the “uniaxial tension” (UT) strain path and toward plane strain. For the UT strain path, normal isotropy was assumed—that is, the plastic strain ratio R is assumed equal to 1 (not measured for this analysis). Various studies [4]-[7] have shown good correlation between TFS and the hole expansion ratio \( λ \) measured by the ISO Standard 16630 hole expansion test [24]. At the edges of pierced-and-extruded holes, for example, deformation occurs approximately along the UT strain path [7], [25]. Consequently for this type of process, Subsize specimens (Type 1 fractures) may provide the best indicator of intrinsic local formability, as the strain-path-to-fracture is nearest to the UT strain path.

\[ \text{Figure 9. Fracture forming limit diagram (FFLD), where TFS is the major strain (ε}_{1f}, and the true width strain at fracture is the minor strain (ε}_{2f}). \text{See text for details. Error bars indicate ±1 standard deviation (n=5).} \]

3.6. Local/global formability map

As a convenient measure of overall formability expectation, the formability index (F.I.) represents an intermediate strain value between the true uniform strain (εu) and true fracture strain [8], [10], where

\[ \text{F.I.} = \sqrt{ε_u \cdot \text{TFS}}, \] (5)

and \( ε_u \) is the true strain value associated with percent uniform elongation (UE, Table 4):

\[ ε_u = \ln \left( 1 + \frac{\text{UE}}{100} \right). \] (6)

Furthermore, the local/global strain ratio indicates the relative preponderance of local formability to global formability and is defined as:

\[ \frac{\text{Local/Global Strain Ratio}}{ε_u} = \frac{\text{TFS}}{ε_u}. \] (7)

These concepts were used to construct the local/global formability map (or “Hance diagram” [9], [18]) shown in Figure 10, and a summary is given in Table 6. For both 980DP and 980 XG3\textsuperscript{TM} steel, the formability map coordinates are relatively insensitive to tension test specimen type, while that of 980HY(LCE) is more sensitive. Recall that, for 980HY(LCE), the Subsize specimen (Type 1 fracture) resulted in a substantially lower fracture strain value in contrast to the ASTM Std and JIS No. 5 specimens (Type 2 and Type 3 fractures). This effect was so strong that the formability character was nearly moved from the “Local” region of the map to the “Balanced” region of the map, and the
formability level was nearly reduced from Good to Fair [10]. This example highlights the importance of specimen type in the practical application of fracture strain values derived from uniaxial tension tests.

![Local/global formability map](image)

**Figure 10.** Local/global formability map. Contours represent specific values of the formability index (F.I.) as indicated [Equation (5)]. See text for details. Error bars indicate ±1 standard deviation for each specimen type.

| Material          | Formability character | Formability level [10] |
|-------------------|-----------------------|------------------------|
| 980DP             | Balanced: 5 ≤ TFS/εu < 10 | Fair: 0.1 ≤ F.I. < 0.2 |
| 980HY(LCE)        | Local: TFS/εu ≥ 10    | Good: 0.2 ≤ F.I. < 0.3 |
| 980 XG3™ Steel    | Global: TFS/εu < 5    | Very Good: ≥ 0.3       |

### 4. Summary and conclusions

The effects of tension test specimen type (width) and fracture area measurement method on fracture strain values were examined for three 980 class advanced high strength steels (AHSS). Included were:

1. 980DP (conventional dual-phase steel);
2. 980HY(LCE) (micro-alloyed multi-phase steel with high yield strength and low carbon equivalent); and
3. 980 XG3™ steel (third generation AHSS).

Various fracture area measurement methods were considered, and three standard specimen types were evaluated: Subsize, ASTM Std, and JIS No. 5. The following conclusions were drawn from this analysis:

1. Three distinct fracture types were observed:
   - Type 1: Perpendicular to tensile axis (across width) with a V-shape thickness profile
   - Type 2: Irregular transition from Type 1 to Type 3 with a W-shape thickness profile
   - Type 3: Angled across specimen width with a U-shape thickness profile
2. All materials exhibited Type 1 fractures with Subsize specimens (narrow gage width).
3. As the specimen width-to-thickness ratio increased, the fracture type changed from Type 1 to Type 2 (980DP and 980 XG3™ steel) or from Type 1 to Type 3 (980HY(LCE)).
4. Specimen type (width) has a far greater impact on the consequent fracture strain value in contrast to the effect of fracture area measurement method.
5. It is advised that, when reporting fracture strain values derived from tension tests, the specimen type, the material thickness, and the fracture area measurement method be clearly indicated.

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