ON TRUE FRACTURE STRAIN (TFS) OF AHSS SHEETS: MEASUREMENT AND DERIVATION

Jun Hu, PhD
Cleveland-Cliffs Inc.
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FROM TE VS. UTS ...

Engineering Stress-Strain Curves

Steel Strength-Ductility Diagram
True Stress-Strain Curves

Local-Global Formability Diagram
(Fracture vs. Necking Resistance)

([Diagram showing TFS vs. UE with annotations])

Estimation of $n_{\text{terminal}}$ from Keeler-Brazier equation leads to FLC
TFS FOR MAT. SELECTION & COMPARISON

- TFS from uniaxial tension test results of various 800-1700 MPa grades
- TFS from notch sample tension test results of various 800-1700 MPa grades

**ISO 16630**

**VDA 238-100**
TFS FOR MODELING & SIMULATION

GISSMO: Generalized Incremental Stress-State dependent damage Model in LS-DYNA®

\[ \dot{D}_f = \frac{n}{\varepsilon_f} D_f^{1 - \frac{1}{n}} \tilde{\varepsilon}_p \]

Damage evolution

Failure curve

Damage regularly overestimated for linear damage accumulation!!

REMARKS & SCOPE OF WORK

TFS for material selection & comparison
- Forming performance
- Uniaxial tension test results mainly
- Represented by: $A_f$, $\varepsilon_{1f}$, $\varepsilon_{tf}$, $\overline{\varepsilon}_f$

TFS for modeling & simulation
- Forming + crash performance
- Various stress states: shear, tensile, plane strain, & equi-bixial
- Represented by: $\varepsilon_f^p$ ($\approx \overline{\varepsilon}_f$ for steels)

How to measure-derive TFS?
- On uniaxial tensile test samples
- On other stress states samples
TARGET MATERIALS

GI-Q&P980 vs. GI-DP980LCE

- Nominal thickness: 1.2 mm
- UTS × TE (GPa·%): ~20 vs. ~10 (Gen3 vs. Gen1)
- UE (L/D/T, %): ~19/18/18 vs. ~6/5/4
- TE (L/D/T, %): ~25/23/23 vs. ~11/10/8

Conclusion 1:
‘Formability’: Q&P980 > DP980LCE
Tested:
ε_{xx}, ε_{yy}, ε_{xy}

Derived:
ε_{1}, ε_{2}, ε_{t}, \bar{ε}_{VM}

ε_{1} + ε_{2} + ε_{t} = 0

Volume constancy

\bar{ε}(VM) \approx \sqrt{\frac{2}{3} (\varepsilon_{1}^2 + \varepsilon_{2}^2 + \varepsilon_{t}^2)}
12 longitudinal ASTM-E8 tensile samples of each grade were tested at 0.001/s at room temperature.

Conclusion 2:
‘Formability’: Q&P980 ≈ DP980LCE
TFS FROM DIC: EFFECTS OF FRAME RATE

The DIC-based TFS result is based on the last image before fracture.

DIC frame rates: Sample 1-3, 1 Hz; Sample 4-6, 10 Hz; Sample 7-9, 100 Hz; Sample 10-12, 500 Hz

*Some steels exhibit pronounced sensitivity
TFS FROM FRACTURE AREA (FA) OPTICAL

- **Parabolic approximation (Optical (P), ASTM E8):**
  \[ t_f = \frac{1}{6} (t_1 + 4t_2 + t_3) \]

- **Area of polygon fit (Optical (A)):**

\[ \bar{\varepsilon}(\text{vM}) \approx \varepsilon_{1f} = \int_{l_0}^{l_f} \frac{dl}{l} = \ln \left( \frac{l_f}{l_0} \right) = \ln \left( \frac{A_0}{A_f} \right) = \ln \left( \frac{w_0 t_0}{w_f t_f} \right) \]

Volume constancy
Without parabolic approximation, the Optical (A) results are comparatively more accurate.

Conclusion 3:
‘Formability’: Q&P980 < DP980LCE
DIC VS. FA-OPTICAL RESULTS

**DIC Results**

- (1) Q&P980_DIC
- (2) DP980LCE_DIC

**FA-Optical Results**

- (1) Q&P980_Optical(P)
- (2) Q&P980_Optical(A)
- (3) DP980LCE_Optical(P)
- (4) DP980LCE_Optical(A)

Fracture Strain (VSGL0.5mm) vs. Sample ID
DISCREPANCY ANALYSIS: THINNING

\[ t_0 \approx 1.2 \text{mm} \]

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_t \approx 0 \]

\[ t_0 \approx 1.2 \text{mm} \]

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_t < 0 \]
DISCREPANCY ANALYSIS: FRAC. SURFACE
DISCREPANCY ANALYSIS: VOIDS

Q&P980

DP980LCE
DISCREPANCY ANALYSIS: REMARKS

• The volume constancy assumption is mainly responsible for the discrepancy and deviation.
• Either the DIC method or the FA-optical measurement is based on and affected by the volume constancy assumption. Yet the impact on the FA-optical results is comparatively less.
• The deviation induced by the volume constancy assumption is material-dependent.
• An alternative method should avoid such an assumption.
ALTERNATIVE: HYBRID METHOD

Use the DIC results \((\varepsilon_1, \varepsilon_2)\) + measured thickness strain \((\varepsilon_t)\) to derive the effective strain \(\bar{\varepsilon}\) at fracture \(\rightarrow\) avoid the volume constancy assumption

*Limitation: synchronization deviation

\[
\bar{\varepsilon}(vM) \approx \sqrt{\frac{2}{3} (\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_t^2)}
\]
## DIC VS. FA-OPTICAL VS. HYBRID

<table>
<thead>
<tr>
<th>Complexity</th>
<th>DIC</th>
<th>FA-Optical</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>Complex</td>
<td>Simple</td>
<td>Most complex</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Sometimes largely deviated</td>
<td>Some deviations</td>
<td>Most accurate</td>
</tr>
<tr>
<td>Applicability</td>
<td>All stress states</td>
<td>Mainly tensile</td>
<td>All stress states</td>
</tr>
</tbody>
</table>

**Recommended**
- DIC: Recommended for mat. selection & comparison
- FA-Optical: Recommended for modeling & simulation
DIC VS. HYBRID: FRACTURE LOCI

Q&P980

Fracture Strain

Triaxiality Ratio

DIC-MM C
Hybrid-MM C
DIC-Test
Hybrid-Test

DP980LCE

Fracture Strain

Triaxiality Ratio

DIC-MM C
Hybrid-MM C
DIC-Test
Hybrid-Test
CONCLUSIONS

• TFS (fracture resistance) ≠ UE/FLC (necking resistance)
• A material can exhibit high TFS and low UE/FLC, or vice versa.
• TFS measurement-derivation is not straightforward.
• The TFS from the default DIC method is questionable due to the volume constancy assumption and may underestimate the local formability of some materials.
• The TFS from the fracture area optical measurement is good enough for material selection & comparison. The results can already reveal the goodness of the local formability, despite some inaccuracy.
• As an alternative, a hybrid method is proposed mainly for fracture modeling and simulation, though the synchronization issue still affects the accuracy.
FOR MORE INFORMATION

Jun Hu, PhD
Cleveland-Cliffs Inc.
Jun.Hu@clevelandcliffs.com

Grant Thomas, PhD
Cleveland-Cliffs Inc.
Grant.Thomas@clevelandcliffs.com

Cynthia Campbell
Cleveland-Cliffs Inc.
Cynthia.Campbell@clevelandcliffs.com

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