Predicting the Bending-Affected Fracture in Sheet Forming

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IABC
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Outline

1. Background – Shear Fracture, 2006

2. DBF Results & Simulations, 2011
   Intermediate Conclusions

3. Practical Application, 2012
   Ideal DBF Test
   Recommended Procedure

4. No Ideal Test?
   Results,
   Recommended Procedure
1. Background – Shear Fracture, 2006
Shear Fracture of AHSS – 2005 Case

Jim Fekete et al, AHSS Workshop, 2006
Shear Fracture of AHSS - 2011

Unpredicted by FEA / FLD

CAE Prediction for DP780

Stoughton, AHSS Workshop, 2006
Shear Fracture: Related to Microstructure?

**Ferrite-Martensite DP**
- Ferrite
- Martensite

**TRIP**
- Ferrite
- Martensite
- Bainite
- Retained Austenite

Ref: AISI AHSS Guidelines
Shear fracture...
- is unique to AHSS (maybe only DP steels)
- occurs without necking (brittle)
- is related to coarse, brittle microstructure
- is time/rate independent

Notes:
- All of these based on the A/SP stamping trials, 2005.
- All of these are wrong.
- Most talks assume that these are true, even today.
2. DBF Results & Simulations, 2011


DBF Failure Types

**Type I:** Tensile failure (unbent region)
**Type II:** Shear failure (not Type I or III)
**Type III:** Shear failure (fracture at the roller)
DBF Test: Effect of R/t

DP 780 - RD
V_1 = 51 mm/s
t = 1.2 mm

UTS = 861 MPa

UTS, ΔUF ↑ as R/t ↑.
“H/V” Constitutive Eq.: Large-Strain Verification

**Graph Description:**

- **Graph Title:** "H/V” Constitutive Eq.: Large-Strain Verification

- **Axes:**
  - Y-axis: Effective Stress (MPa)
  - X-axis: Effective Strain

- **Data Points and Lines:**
  - **DP590(B), RD**
    - Strain Rate: $10^{-3}$/sec
    - 25°C

- **Lines:**
  - **Hollomon $\sigma = 4\text{MPa}$**
  - **H/V $\sigma = 1\text{MPa}$**
  - **Bulge Test (r=0.84, m=1.83)**
  - **Voce $\sigma = 1\text{MPa}$**
  - **Tensile Test**

- **Fit Range:** Extrapolated, Bulge Test Range
FE Simulated Tensile Test: H/V vs. H, V

Experiment (D-B)

Voce  H/V model  Hollomon

DP590(B), RD
Strain Rate=10^{-3}/s
100^{\circ}C, Isothermal
Predicted $e_f$, H/V vs. H, V: 3 alloys, 3 temperatures

<table>
<thead>
<tr>
<th></th>
<th>Hollomon</th>
<th>Voce</th>
<th>H/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP590</td>
<td>0.05 (23%)</td>
<td>0.05 (20%)</td>
<td>0.02 (7%)</td>
</tr>
<tr>
<td>DP780</td>
<td>0.03 (18%)</td>
<td>0.04 (22%)</td>
<td>0.01 (6%)</td>
</tr>
<tr>
<td>DP980</td>
<td>0.04 (30%)</td>
<td>0.03 (21%)</td>
<td>0.01 (5%)</td>
</tr>
</tbody>
</table>

Standard deviation of $e_f$: simulation vs. experiment
FE Draw-Bend Model: Thermo-Mechanical (T-M)

- Abaqus Standard (V6.7)
- 3D solid elements (C3D8RT), 5 layers
- Von Mises, isotropic hardening
- Symmetric model

\[ h_{\text{metal,air}} = 20 \text{W/m}^2\text{K} \]
\[ \mu = 0.04 \]
\[ h_{\text{metal,motoral}} = 5 \text{kW/m}^2\text{K} \]

Kim et al., IDDRG, 2009
Front Stress vs. Front Displacement

Measured

T-M

Isothermal
Solid, Shell

DP780-1.4mm, RD
$V_1 = 51 \text{mm/s, } V_2/V_1 = 0$
$R/t = 4.5$
Displacement to Maximum Front Load vs. \( R / t \)

- Type I
  - Isothermal, Solid
  - Isothermal, Shell
  - T-M, Solid

- Type III
  - Measured

- DP780-1.4mm, RD
  - \( V_1 = 51\, \text{mm/s}, V_2/V_1 = 0 \)
Is shear fracture of AHSS brittle or ductile?
Fracture Strains: DP 780 (Typical)
Fracture Strains: TWIP 980 (Exceptional)
Directional DBF : DP 780 (Typical)

DP 780
\( t = 1.2 \) mm
\( \frac{R}{t} = 5.2 \)
\( \Delta U_F = 45 \pm 3 \) (mm)

\( \frac{R}{t} = 2.5 \)
\( \Delta U_F = 35 \pm 2 \) (mm)
Directional DBF Formability: DP980 (Exceptional)

![Graph showing elongation to fracture vs. angle to RD for DP980 with R/t = 3.3.](image-url)
Interim Conclusions

• “Shear fracture” occurs by plastic localization.

• Deformation-induced heating dominates the error in predicting shear failures.

• Brittle cracking can occur. (Poor microstructure or exceptional tensile ductility, e.g. TWIP).

• T-dependent constitutive equation is essential.

• Shear fracture is predictable plastically.
  (Challenges: solid elements, T-M model.)
3. Practical Application - 2012
DBF/FE vs. Industrial Practice/FE

Ind.: Plane strain
High rate
~Adiabatic

FE: Shell
Isothermal
Static

DBF: General strain
Moderate rates
Thermo-mech.

FE: Solid element
Thermo-mech.
Ideal DBF Test: Plane Strain, High Rate
Ideal Test Results - Stress

![Graph showing the relationship between peak engineering stress (MPa) and bending ratio (R/t) for DP780-1.4mm material. The graph indicates an analytical PS result and marks the ultimate tensile strength (UTS) at (R/t)*.]
Ideal Test Results - Strain

Analytical PS Results
DP 780 - 1.4mm

True Strain

Bending Ratio, R / t

(R/t)*

Outer Strains
Center Strains (Membrane)
Inner Strains

FLD₀
How to Use Practically: Bend, Unbend Regions

Type “B” (Bending)

Type “U” (Unbending)
Practical Application of SF FLD – (1) Direct

For each element in contact

Known: $R$, $t \rightarrow \varepsilon^\text{membrane}$

Predicted Fracture: $\varepsilon^\text{FEA} > \varepsilon^*\text{membrane}$
For each element drawn over contact

Known: \((R, t)_{contact} \rightarrow P_{max} \rightarrow \sigma^*_{PS \text{ tension}} \rightarrow \varepsilon^*_{PS \text{ tension}}\)

Predicted Fracture: \(\varepsilon_{FEA} > \varepsilon^*_{PS \text{ tension}}\)

Example: von Mises Yield, Hollomonon Hardening

Von Mises: \( \sigma^*_{PST} = \frac{\sqrt{3}}{2} \frac{P_{max}}{A} \)

Hollomon: \( \sigma = K \varepsilon^n \)

So: \( \sigma^*_{PST} = \frac{\sqrt{3}}{2} K \varepsilon^*_{PST} n \rightarrow \varepsilon^*_{PST} = \frac{2}{\sqrt{3}} \left( \frac{\sigma^*}{K} \right)^{1/n} \)
1. Use adiabatic law in FEA, use rate sensitivity

2. Classify each element based on X-Y position (tooling)
   a) Bend (plane-strain)
   b) After bend (plane-strain)
   c) General (not Bend, not After)

3. Apply 4 criteria:
   a) FLD (Bend, After)
   b) Direct SF (Bend)
   c) Indirect SF (After)
   d) Brittle Fracture* (All?)
4. No Ideal Test?
(What to do?)
What is Needed?

\[ P_{\text{max}} = f(R/t) \]
(PS, high-speed DBF)

\[ \varepsilon^{\text{membrane}} = f(R/t) \]
(PS, high-speed DBF)
FE Plane Strain DBF Model

- Abaqus Standard (V6.7)
- Plane strain solid elements (CPE4R), 5 layers
- Von Mises, isotropic hardening
- Isothermal, Adiabatic, Thermo-Mechanical

\[ U_2, V_2 = 0 \]

\[ \mu = 0.06 \]
Adiabatic Constitutive Equation

\[
\bar{\sigma}_{\text{adiabatic}}(\bar{\epsilon}, \dot{\bar{\epsilon}}) = \bar{\sigma}(\bar{\epsilon}, \dot{\bar{\epsilon}}, \Delta T)
\]

\[
\Delta T = \frac{\eta}{\rho C_p} \int_0^{\bar{\epsilon}} \bar{\sigma} d\bar{\epsilon}
\]

DP980(D)-GA-1.45mm

d\epsilon/dt=10^{-3}/s
Peak Stress, Plane-Strain: DP980

Peak Engineering Stress (MPa) vs. $R/t$

- PS FE Model, $m=0, \mu=0$
- Analytical Model, Plane Strain
- UTS
- DBF measured (RD, TD)

$\text{DP980-1.43mm}$
Membrane Strains at Maximum Load

![Graph showing membrane strains at maximum load for different bending ratios.

- DP590
- DP780
- DP980

True Membrane Strain vs. Bending Ratio, \( R / t \)

Analytical Adiabatic Model Stopped at Maximum Load
Analytical Model: Model vs. Fit

Analytical Adiabatic Model Stopped at Maximum Load

\[ \varepsilon_s \left( \frac{t}{R} \right) = \varepsilon_s^o \left( \frac{t}{R_{max}} \right) + S \left( \frac{t}{R} - \frac{t}{R_{max}} \right) \]

- **DP980**
  - \( S = 0.221, \varepsilon_s^o = 0.088 \)
- **DP780**
  - \( S = 0.198, \varepsilon_s^o = 0.101 \)
- **DP590**
  - \( S = 0.167, \varepsilon_s^o = 0.138 \)
Analytical Adiabatic Model
Stopped at Maximum Load

Analytical Model: Model vs. Fit

\[ \varepsilon_s \left( \frac{t}{R} \right) = \varepsilon_s^0 \left( \frac{t}{R_{\text{max}}} \right) + S \left( \frac{t}{R} - \frac{t}{R_{\text{max}}} \right) \]

- DP590: \( S = 0.168, \varepsilon_s^0 = 0.138 \)
- DP780: \( S = 0.198, \varepsilon_s^0 = 0.101 \)
- DP980: \( S = 0.221, \varepsilon_s^0 = 0.088 \)
Conclusions

- Shear fracture is predictable with careful testing or careful constitutive modeling and FEA.

- “Shear fracture” occurs by plastic localization.

- “Shear fracture” is an inevitable consequence of draw-bending mechanics. All materials.

- Brittle fracture can occur, but is unusual. (Poor microstructure or v. high tensile limit, e.g. TWIP).

- T-dependent constitutive equation is essential for AHSS because of high plastic work. (But probably not Al or many other alloys.)
Thank you.
References


