Draw-Bend Fracture Prediction with Dual-Phase Steels

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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?

Ref: AISI AHSS Guidelines
Conventional Wisdom, 2006

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
References: DBF Results & Simulations


**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 \( R/t \)

**Graphical Data**

**DP 780 - RD**

- \( V_1 = 51 \, \text{mm/s} \)
- \( t = 1.2 \, \text{mm} \)

**UTS** = 861 MPa

- UTS, \( \Delta UF \) ↑ as \( R/t \) ↑.

- Failure Type:
  - 3
  - 1

**Stress (MPa)** vs. **\( \Delta U \) (mm)**
“H/V” Constitutive Eq.: Large-Strain Verification

- **Effective Stress (MPa)**
  - **Effective Strain**
  - **H/V $\sigma = 1$MPa**
  - **Hollomon $\langle \sigma \rangle = 4$MPa**
  - **Voce $\langle \sigma \rangle = 1$MPa**
  - **Bulge Test ($r=0.84, m=1.83$)**

**Material:**
- DP590(B), RD

**Conditions:**
- **Strain Rate** = $10^{-3}$/sec
- **Temperature** = 25°C

**Tests:**
- **Tensile Test**
- **Bulge Test**

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

Engineering Stress (MPa) vs. Engineering Strain

Experiment (D-B)

Voce, H/V model, Hollomon

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

Standard deviation of $e_f$: simulation vs. experiment

<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>
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</tbody>
</table>
FE Draw-Bend Model: Thermo-Mechanical (T-M)

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

\[ h_{\text{metal,air}} = 20 \text{W/m}^2\text{K} \]

\[ \mu = 0.04 \]

\[ h_{\text{metal,metal}} = 5 \text{kW/m}^2\text{K} \]

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

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

TW 980

- 51 mm/s
- 2.54 mm/s

Fracture Strain

Bend Ratio R/t

0.7 2.6 5.3 6.6

Tensile Test, RD

εu, Tension
Directional DBF : DP 780 (Typical)

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

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

Elongation to Fracture (mm)

Angle to RD (degree)

DP980
R/t = 3.3
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

**DBF**: General strain
Moderate rates
Thermo-mech.

**FE**: Solid element
Thermo-mech.

**Ind.**: Plane strain
High rate
~Adiabatic

**FE**: Shell
Isothermal
Static
Ideal DBF Test: Plane Strain, High Rate
Ideal Test Results - Stress

Peak Engineering Stress (MPa) vs. Bending Ratio, R / t

Analytical PS Result

DP780-1.4mm

(R/t)*

(UTS)
Ideal Test Results - Strain

Analytical PS Results
DP 780 - 1.4mm

- True Strain
- Bending Ratio, $R / t$

Lines:
- (R/t)*
- Outer Strains
- Center Strains (Membrane)
- Inner Strains

Notation:
- FLD
- $R / t$
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: $\varepsilon_{\text{FEA}} > \varepsilon_{\text{membrane}}$
Practical Application of SF FLD – (2) Indirect

For each element drawn over contact

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

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

Example: von Mises Yield, Hollomonon Hardening

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

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?

\[ P_{\text{max}} = f(\frac{R}{t}) \]

(PS, high-speed DBF)

\[ \varepsilon^{*}_{\text{membrane}} = f(\frac{R}{t}) \]

(PS, high-speed DBF)

![Graph of Peak Load vs. Bending Ratio, R / t](image)

![Graph of Membrane Strain vs. Bending Ratio, R / t](image)
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

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

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

DP980(D)-GA-1.45mm

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

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

Graph showing the peak engineering stress (MPa) vs. \( R/t \) for DP980-1.43mm.
Membrane Strains at Maximum Load

$\varepsilon_s$, True Membrane Strain

Bending Ratio, $R / t$

Analytical Adiabatic Model
Stopped at Maximum Load

DP590
DP780
DP980
Analytical Model: Model vs. Fit

Analytical Adiabatic Model Stopped at Maximum Load

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

- 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

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

DP590: 
\[ S = 0.168, \varepsilon_s^o = 0.138 \]

DP780: 
\[ S = 0.198, \varepsilon_s^o = 0.101 \]

DP980: 
\[ S = 0.221, \varepsilon_s^o = 0.088 \]
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 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


Extra Slides
DP Steels

Engineering Stress (MPa) vs. Engineering Strain (%)

- DP590(B)-1.4mm
- DP780(D)-1.4mm
- DP980(D)-1.45mm

Strain Rate: $10^{-3}$/sec
Room Temp.
Rolling Direction
“H/V” Constitutive Framework

\[
\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T) = f(\varepsilon, T) \cdot g(\dot{\varepsilon}) \cdot h(T)
\]

**Special:**

\[
f(\varepsilon, T) = \alpha(T) f_{Hollo} + (1 - \alpha(T)) \cdot f_{Voce}
\]

\[
\alpha(T) = \alpha_1 - \alpha_2 (T - T_{RT}) \quad f_{Hollo} = K \varepsilon^n \quad f_{Voce} = A[1 - B \exp(-C \varepsilon)]
\]

**Standard:**

\[
g(\dot{\varepsilon}) = \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{a[\log \dot{\varepsilon}] + b}
\]

\[
h(T) = (1 - D \cdot (T - T_{RT}))
\]

Sung et al., *Int. J. Plast.* 2010
Simulated D-B Test: Effect of Draw Speed

DP980(D)  
R/t=4.4, V₂/V₁ = 0

Front Displacement (mm)

F/F_{UTS}

- Adiabatic
- Isothermal
- 51mm/s (dε/dt=2.5/s)
- 13mm/s (0.6/s)
- 2.5mm/s (0.13/s)
- 0.001mm/s (5x10⁻³/s)
DBF Formability: DP980(A), RD vs. TD (Typical)

* Directional Formability: TD = RD

![Graph showing directional formability with R/t values and U_f values for RD and TD in DP980(A).]

- DP980(A)
- $V_1 = 51$ mm/sec
- $V_2 / V_1 = 0$
DBF Formability: DP980(D), RD vs. TD (Exceptional)

* Directional Formability: RD > TD

![Graph showing directional formability comparison between RD and TD for DP980(D) with specific velocities and R/t ratios.](image-url)
Analytical Model – Curvilinear Derivation

Neutral line

\[ \varepsilon_\theta = \ln \left( \frac{r}{r_n} \right) \]
\[ \bar{\varepsilon} = \frac{2}{\sqrt{3}} \varepsilon_y \]
\[ \bar{\varepsilon} = \frac{2}{\sqrt{3}} \ln \left( \frac{r}{r_n} \right) \]

\[ \sigma_{\theta\theta}(r) = \int_r^{R+K} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) dr + \frac{2}{\sqrt{3}} \bar{\sigma}(r) \quad r > r_n \]

\[ \sigma_{\theta\theta}(r) = \int_{r_n}^{R+K} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) dr - \int_r^{r_n} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) dr - \frac{2}{\sqrt{3}} \bar{\sigma}(r) \quad r < r_n \]

Materially embedded coordinate \( \xi \) :

\[ dr = \lambda_r d\xi = \frac{r_n}{r} d\xi \]
\[ \sigma_{\theta\theta}(\xi) = \int_{\xi_n}^{R+K} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) \frac{\partial r}{\partial \xi} d\xi + \frac{2}{\sqrt{3}} \bar{\sigma}(\xi) \quad \xi > \xi_n \]
\[ \sigma_{\theta\theta}(\xi) = \int_{\xi_n}^{R+K} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) \frac{\partial r}{\partial \xi} d\xi - \int_{\xi}^{\xi_n} \left( \frac{2}{\sqrt{3}} \bar{\sigma} \right) \frac{\partial r}{\partial \xi} d\xi - \frac{2}{\sqrt{3}} \bar{\sigma}(\xi) \quad \xi < \xi_n \]

\[ T = \int_{R}^{R+K} \sigma_{\theta\theta} dr = \int_{R}^{R+K} \sigma_{\theta\theta} \frac{\partial r}{\partial \xi} d\xi \]

Fracture Criterion: Fracture occurs at \( T_{\text{max}} \) for given \( R, t_o \)
DBF Interpretation: Plane-strain vs. Tension

- **Simplified FE Model, m=0, μ=0**
- **Analytical Model, Plane Strain**

Graph showing the relationship between Peak Engineering Stress (MPa) and R/t for DP780-1.4mm.
Inner and Outer Strains at Maximum Load

Analytical Adiabatic Model Stopped at Maximum Load

True Strain

Bending Ratio, $R / t$

Inner Strains

Outer Strains

DP590

DP780

DP980
Membrane Strains (R/t Affected Only)

Analytical Adiabatic Model
Stopped at Maximum Load

$\Delta \varepsilon_s$, True Membrane Strain

Bending Ratio, R / t
R/t-Affected Membrane Strains vs. t/R

Analytical Adiabatic Model
Stopped at Maximum Load

$\Delta \varepsilon _s$, True Membrane Strain

1 / Bending Ratio, t / R

DP590
DP780
DP980
Forming Limit Diagram

Ref: Hosford & Duncan
PS T-M Model: Model vs. Fit

Plane Strain Thermo-Mechanical Model Stopped at Maximum Load

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

- DP590
  - \( S = 0.753, \varepsilon_s^o = 0.149 \)

- DP780
  - \( S = 0.330, \varepsilon_s^o = 0.123 \)

- DP980
  - \( S = 0.051, \varepsilon_s^o = 0.133 \)
PS T-M Model: Model vs. Fit

Plane Strain Thermo-Mechanical Model Stopped at Maximum Load

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

DP590

\[ S = 0.753, \varepsilon_s^o = 0.149 \]

DP780: \[ S = 0.330, \varepsilon_s^o = 0.123 \]

DP980: \[ S = 0.051, \varepsilon_s^o = 0.133 \]
Draw-Bend Fracture Test (DBF): $V_1$, $V_2$ Constant

$V_2 = \alpha V_1$

Specimen width: 25mm

Tool radius choices:
2/16, 3/16, 4/16, 5/16, 6/16, 7/16, 9/16, 12/16 inch
3.2, 4.8, 6.4, 7.9, 9.5, 11.1, 14.3, 19 mm

$\alpha = \frac{V_2}{V_1}$: 0 and 0.3

Wagoner et al., Esaform, 2009
AHSS vs. HSLA

Ref: AISI AHSS Guidelines