Dynamic Considerations in Prediction of Fracture of Ultra High-Strength Steel During Crash

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Overview

- High strain rate response of automotive alloys (tensile + shear characterization):
  - DP980 (SMDI), DP600
  - Fully quenched Usibor® 1500-AS, Ductibor® 500-AS

- Effect of strain rate on fracture?
  - Shear conditions (zero triaxiality)
  - Positive triaxiality conditions

- Weld failure characterization – “spot weld groups”
Shear Testing

- Achieves shear strains easily on the order of unity with relatively constant triaxiality of zero
- Appropriate for high rate testing in Hopkinson bar or high speed hydraulics (1-1000/s)


Issue today lies in the majority of fracture characterization for crash CAE being done at quasi-static rates...

Potential sources of rate effects:

- Elevated strain rates
- Temperature increase through adiabatic heating (~90% of plastic work converted to heat) *
- Inertial effects

* Temperature increase also important for constitutive behaviour and not commonly considered in today’s crash CAE...
Dynamic Fracture

Quasi-static loading

Effect of dynamic loading on failure strain?

DP980 (SMDI) TD
MMC Fracture Loci

Equal Biaxial Tension

Shear

Uniaxial Tension

Plane Strain

Dynamic Fracture

Fracture Loci: MMC Model

DP980 - Transverse Direction
Rate Effects – Shear (DP600)

- Rate sensitivity is initially positive, but becomes negative at large strains
- Promotes earlier localization under shear loading*

Onset of shear cracking is determined as the point where the hardening rate is exhausted\(^1\).

Repeatable and eliminates the need to detect fracture based on visible cracking\(^2\).

\(^1\)Zener and Hollomon, Journal of Applied Physics, 15, 22-32, 1944.

Effect of strain rate on failure strain

Earlier localization at higher strain rates due to thermal instability promotes lower fracture strain (DIC measurements)
Failure in Uniaxial Tension versus Shear – Rate Effect

In tension, positive rate sensitivity promotes higher failure strains as strain rate increases.

In shear, thermal localization reduces failure strain (as measured using DIC) with increasing strain rate.
At microstructural level, gain rotation can be used to estimate the local shear strains within the shear band (gives shear angle, $\alpha$)

$$\varepsilon_{eq}^{VM} = \frac{2}{\sqrt{3}} \varepsilon_1 = \frac{2}{\sqrt{3}} \sinh^{-1}(\gamma/2)$$

$$\gamma = \tan(\alpha)$$
Local Strains at Failure

Sharper strain localization and higher peak strains using the grain-level strain measurement as compared to DIC measurements.

[Graphs and images showing strain localization and peak strains at different strain rates.]
Implications for crash CAE

- Given the coarse meshes necessitated in vehicle CAE, failure strains should be measured using a length scale on the order of the element size.
- DIC virtual strain gauge length: 0.3 mm versus 3-5 mm element size.
- For these materials, shear strain to failure \textit{input to FEA decreases} with strain rate.
- Less impact on positive triaxiality regime, however, confounding results exist in the literature.
High Speed Thermography

Ductibor® 500-AS: Shear
\(T_{\text{peak}} \sim 234 \, ^\circ\text{C}\)

Ductibor® 500-AS: Notched Tension
\(T_{\text{peak}} \sim 230 \, ^\circ\text{C}\)
Thermal Softening in Shear (Ductibor® 500-AS)

\[ \Delta T = \frac{\beta W^p}{\rho C_p} \]

Temperature (Calculated)

Temperature (100s\(^{-1}\))
Shear Response: Martensitic Condition

Fully-quenched Usibor® 1500-AS condition – primarily martensitic

Microstructure
- Lower strains to failure
- Higher heat generation rates
Shear Response: Martensitic Condition

Thermal localization at lower strains due to higher internal work rate and low work hardening rate.
Effect of strength on onset of localization

- Earlier localization, narrower thermal field for the higher strength conditions
- Thermal localization enhanced for higher strength alloys
- The strong work hardening of the DP600 is clearly beneficial
Characterization of failure in spot weld groups

- Interaction between nugget, HAZ and parent metal strength (single weld)
- Test method for weld group testing (Mode I Caiman)
MODE I DYNAMIC (1.6MM)

Wall Assembly  Specimen  Fork Assembly

Honeycomb supports

Thermal Camera  High Speed Cameras

LED Light  Mercury Light
Fully Martensitic

DYNAMIC SIDE VIEW

1.6mm 25°C

1.6mm 700°C

400 or 700 °C die temperature in flange regions
Mode 1 Quasi-Static

1.2 mm
Full quench
400C Tailored Flange
700C Tailored Flange
Weld Failure Surface (1.6 mm)

Mode 1 Dynamic

25°C

700°C

Dynamic

Quasi-static
DYNAMIC THERMOGRAPHY

1.6 mm, 25°C

![Thermography Image 1.6 mm, 25°C](image1)

1.6 mm, 700°C

![Thermography Image 1.6 mm, 700°C](image2)

Softer flanges (high flange die temperature) contribute more towards energy dissipation.

370 K

290 K

370 K

290 K
Mode 1 Quasi-Static

- Key data for CAE validation
- Weld assessment tool for AHSS and UHSS
- Shear version of the "Caiman"

Displacement [mm] vs. Crack Length [mm]

- 1.6 mm Crack Length
- Full quench
- 700°C Tailored Flange
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