Experimental methods for Lode angle characterization in ductile fracture

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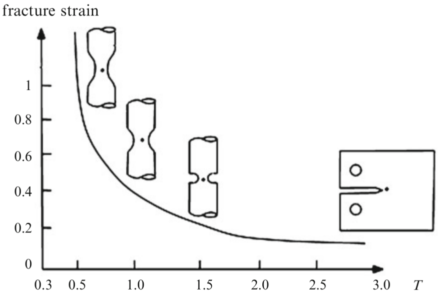
Introduction

- The stress state has a strong influence on damage development and fracture.
- Triaxiality has been used to evaluate the stress state effect on damage/fracture.



[Pineau and Pardoen, 2007]

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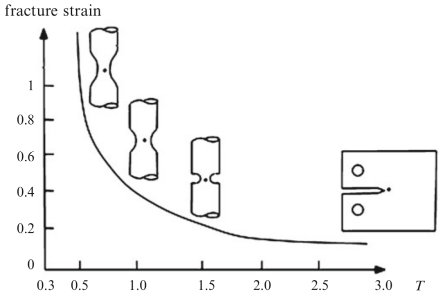


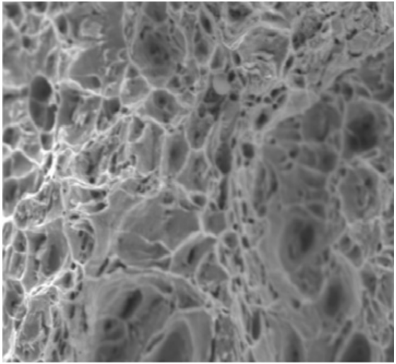
[Pineau and Pardoen, 2007]

$$T(I_1, J_2) = \frac{\sigma_m}{\sigma_{eq}} = \frac{1}{3\sqrt{3}} \frac{I_1}{\sqrt{J_2}}$$

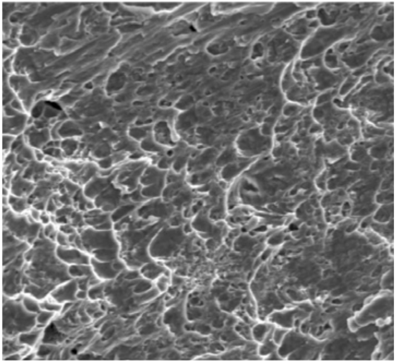
- T ratio between volumetric I_1 and distorsion J_2 effects.
- $T \to 0 \Longrightarrow \epsilon_f \to \infty$

Introduction

- Forming processes are characterized by low triaxialities.
- The failure mode (coalescence) is different at high/low triaxialities:



Cavity controlled (Dimples)
$T = 1.10$



Shear controlled
$T = 0.47$

[Barsoum and Faleskog, 2007a]

Introduction

- Given the Gurson [1977] model:

$$F = \frac{\sigma_{eq}^2}{\sigma_Y^2} - 1 + \underbrace{2f \cosh \frac{3}{2} \frac{\sigma_m}{\sigma_Y} - f^2}_{\text{Damage}} = 0$$

- No damage is predicted when $T = 0$. Further extensions are required.
- Gologanu et al. [1996] note that the void expansion can vary at same triaxialities.
- At low triaxiality, void shape evolution becomes more important than void growth.

Lode angle influence

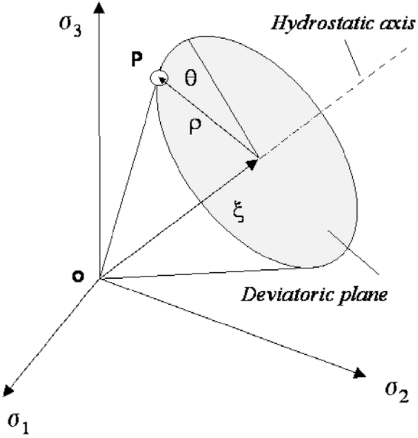
- Triaxiality is not able to account the shape effects on voids.
- Solution: fully account the stress state with the set (I_1, J_2, J_3).
- A *physical meaning* can be asigned to J_3 through the **Lode angle** θ.

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \frac{I_1}{3} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \frac{2}{\sqrt{3}} \sqrt{J_2} \begin{pmatrix} \cos\theta \\ \cos(120 - \theta) \\ \cos(120 + \theta) \end{pmatrix}$$

- Stress state:
  - $\theta = 0$: uniaxial tension plus hydrostatic pressure (triaxial tension).
  - $\theta = 30$: pure shear plus hydrostatic pressure.
  - $\theta = 60$: uniaxial compression plus hydrostatic pressure.
- The relation between θ and J_3 is given by:

$$X(J_2, J_3) = \cos 3\theta = \frac{27}{2} \frac{J_3}{\sigma_{eq}^3}$$

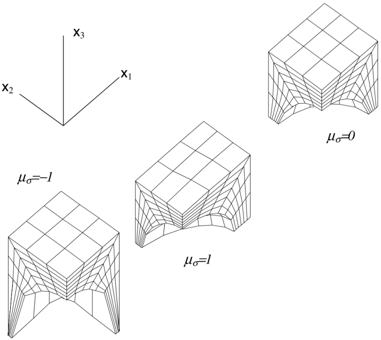
Lode angle

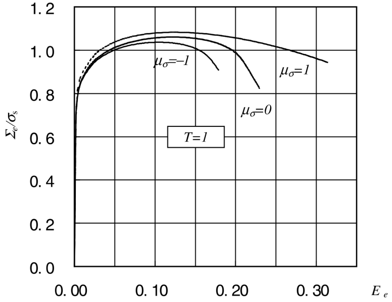


[Coppola et al., 2009]

- P : Stress state.
- ξ : Hydrostatic stress (I_1).
- ρ : Deviatoric stress (J_2).
- θ : Lode angle (J_3).

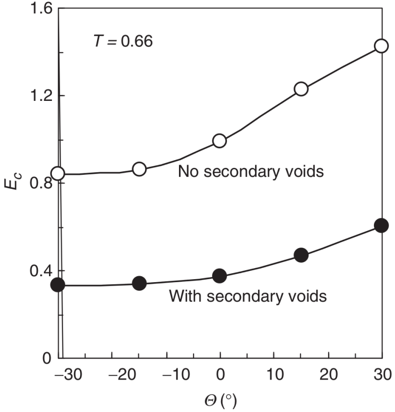
- Unit cell deformation at constant triaxiality $T = 1$.

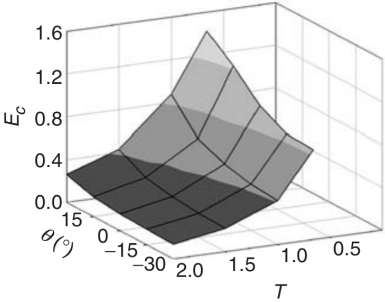




[Zhang et al., 2001]

Lode angle
Micromechanics

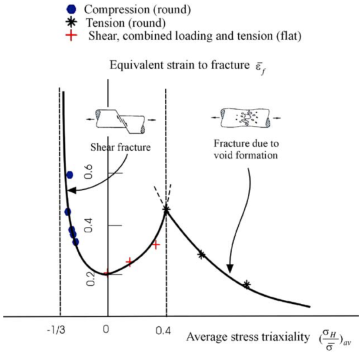




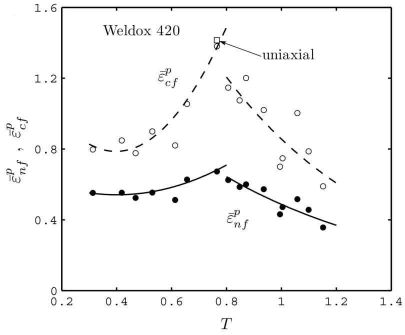
[Gao et al., 2009]

Lode angle
Influence on fracture strain

- The strain at fracture is not monotonically decreasing function of the triaxiality.
- Note that the peaks are at different triaxialities.



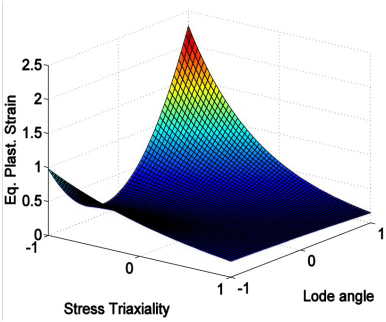
[Bao and Wierzbicki, 2004]



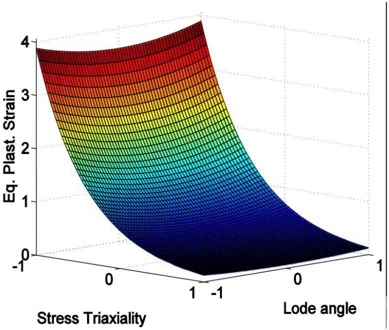
[Barsoum and Faleskog, 2007b]

Lode angle
Influence on fracture strain

- They are *lode angle independent* materials.



Aluminum 2024-T351



1045 steel

[Bai and Wierzbicki, 2008; Malcher et al., 2012]

Experimental characterization

Influence on fracture strain

- The Lode angle play an important role in fracture strain.
- To investigate of the Lode angle the effect, three-dimensionsal stress state is needed.
- At plain stress state [Bai and Wierzbicki, 2008]:

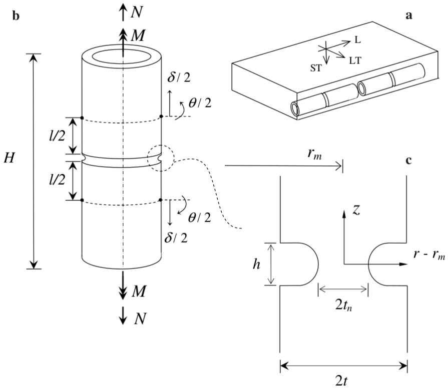
$$X(T) = \cos 3\theta = -\frac{27}{2} T \left(T^2 - \frac{1}{3} \right)$$

- Usually compressive and shear specimens are used to study the low-triaxiality regime.
- Some special specimens have been proposed.

Experimental characterization

Barsoum and Faleskog [2007a] specimen

- Double notched specimen, subjected to a combination of tensile and torsional loading.
- By changing the tensile-to-torsional force ratio, different values of triaxiality can be obtained.

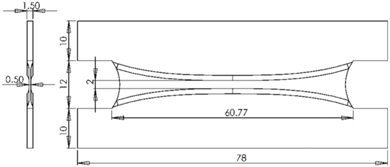


$$t_{max} = 3.2\,\text{mm}$$
$$t_{min} = 1.2\,\text{mm}$$

Experimental characterization
Butterfly specimen

- Specially designed to calibrate a fracture locus for lode angles between the limiting cases $X = \pm 1$.
- The specimen is charged in two directions.
- The fracture initiation is at the center.

Bai and Wierzbicki [2008]

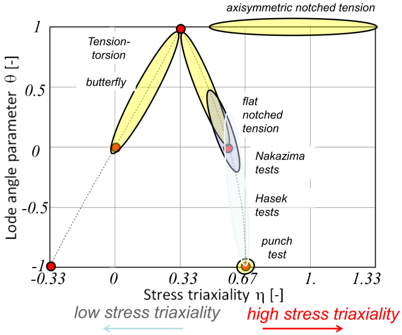


Dunand and Mohr [2011]

Experimental characterization

Butterfly specimen

- For the same triaxiality, but for different loading histories, the strain to fracture is not the same.
- The inaccuracies in the geometry could not be over 10 μm



Experimental characterization
Driemeier et al. [2010] specimen

- Shear specimens with out-of-plane notches (0.2 mm and 0.5 mm in a 1.56 mm Aluminium sheet).
- Proposed to study at triaxialities near zero.

Experimental characterization
Driemeier et al. [2010] specimen

- Shear specimens with out-of-plane notches (0.2 mm and 0.5 mm in a 1.56 mm Aluminium sheet).
- Proposed to study at triaxialities near zero.

- No numerical results were presented.
- The Lode angle cannot be studied in these thin sheet because no geometric effects (diffuse necking, shear band localization) were observed.
- This behaviour is observed in thicker sheets, leading to necking through-the-thickness.

Discussion

Experimental limitations

- Specimens have very low fabrication tolerances.
- Experimental test to evaluate low triaxialities should be carried on in bulk material (compression, bars,. . .).
- Physical mechanisms of the Lode angle are not clear (shape change? growth direction?).

Discussion

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So, what we can do?

- Shear test allow to study low values of triaxiality, but not the Lode dependence.
- Is the DC01 steel really *Lode angle dependent*?.
- Most of these experimental campaigns are done for calibration and/or evaluation, not for particular applications.
- *Is the Lode angle important during SPIF?*

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