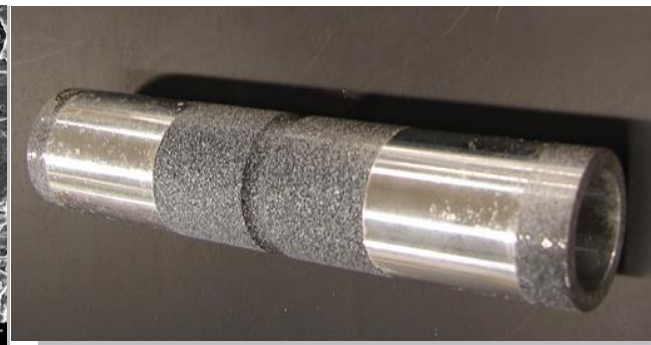
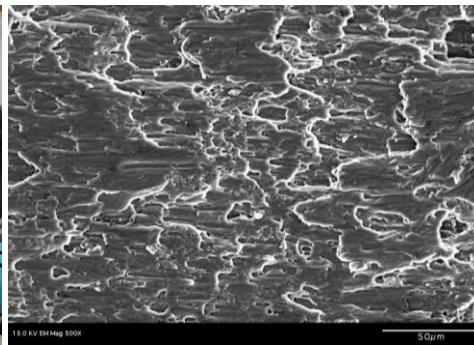
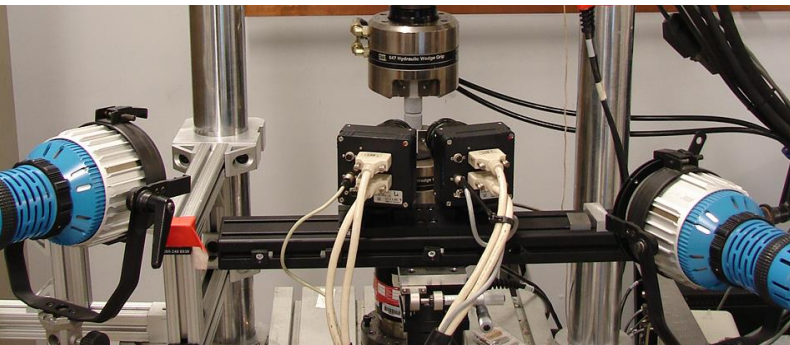


Exceptional service in the national interest



Multiaxial Ductile Failure of Aluminum Alloys

Wei-Yang Lu and Helena Jin

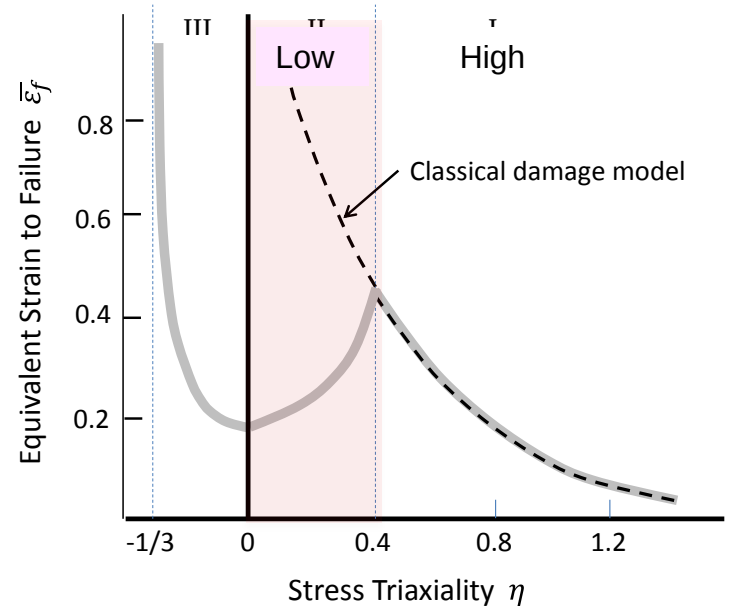
November 17, 2014

- Johnson-Cook (1985) Failure criterion

- $\bar{\epsilon}_f = C_1 + C_2 \exp(C_3 \eta)$
 $\eta = \sigma_m / \bar{\sigma}$
- ϵ and σ are values at the initial failure location

- Bao and Wierzbicki (2004) Failure locus of Al2024-T351

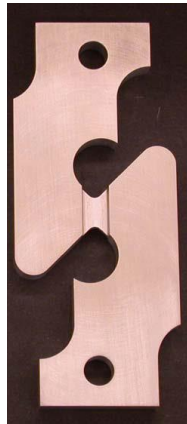
- A series of tests covers a wide range of triaxiality
- Hybrid method
 - FE simulations of tests and using model to determine the equivalent plastic strain at the failure location by matching the displacement to failure



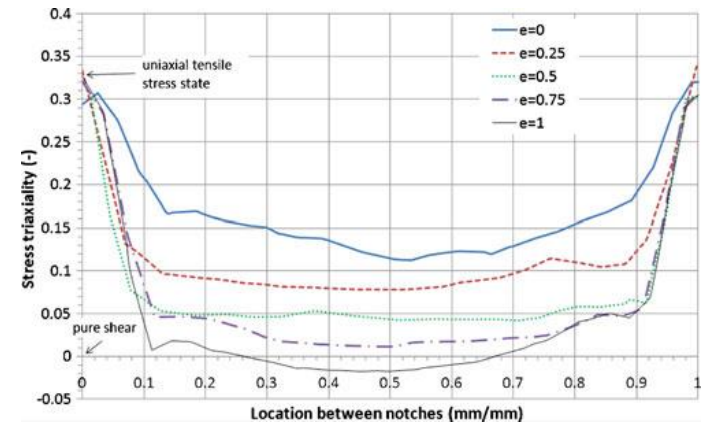
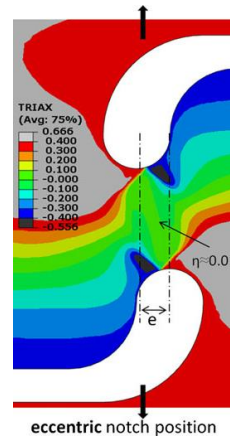
Low Triaxiality Experiments

Butterfly Type Specimens

I

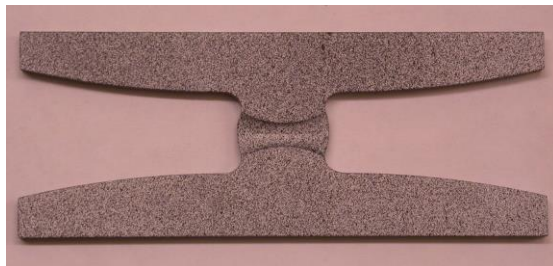


Bao and Wierzbicki, 2004
Gruben et al, 2011



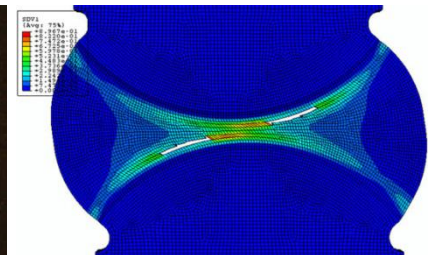
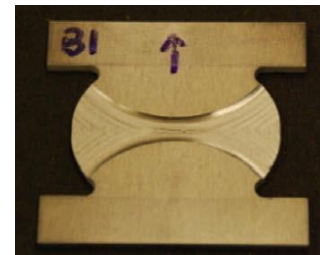
Peirs, Verleysen and Degrieck, 2012

II



Wierzbicki, Bao and and Bai, 2005

III



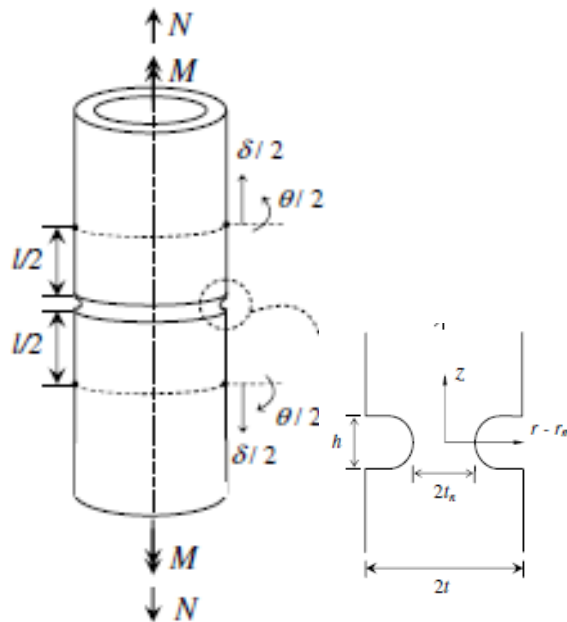
Beese, Luo, Li, Bai and Wierzbicki, 2010
Kofiani, Nonn and Wierzbicki, 2014

Low Triaxiality Experiments

Double notched tube

Barsoum and Faleskog, 2007

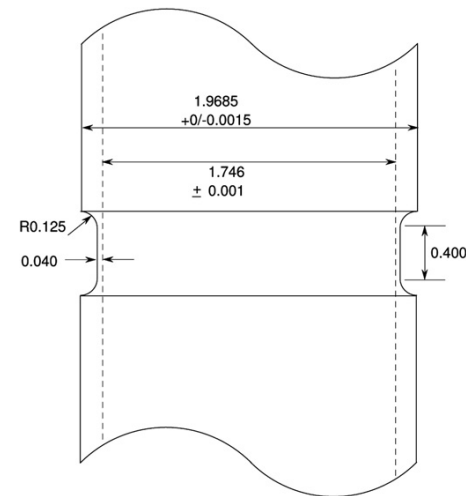
Faleskog and Barsoum, 2013



Smooth tube

Haltom, Kyriakides and Ravi-Chandar, 2013

Papasidero, Doquet and Mohr, 2014

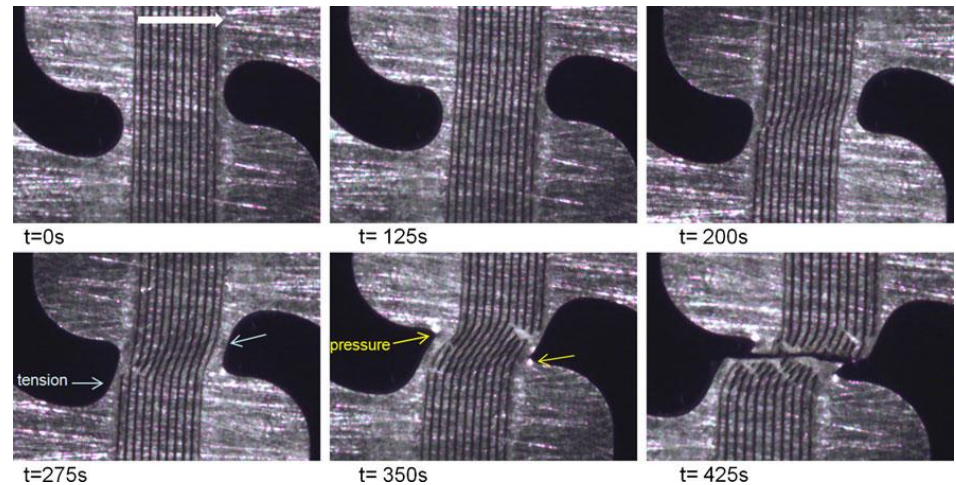


Strain Measurement Methods

- Numerical Simulation
- Digital Image Correlation (DIC)
- Grid Method
- Grain Analysis

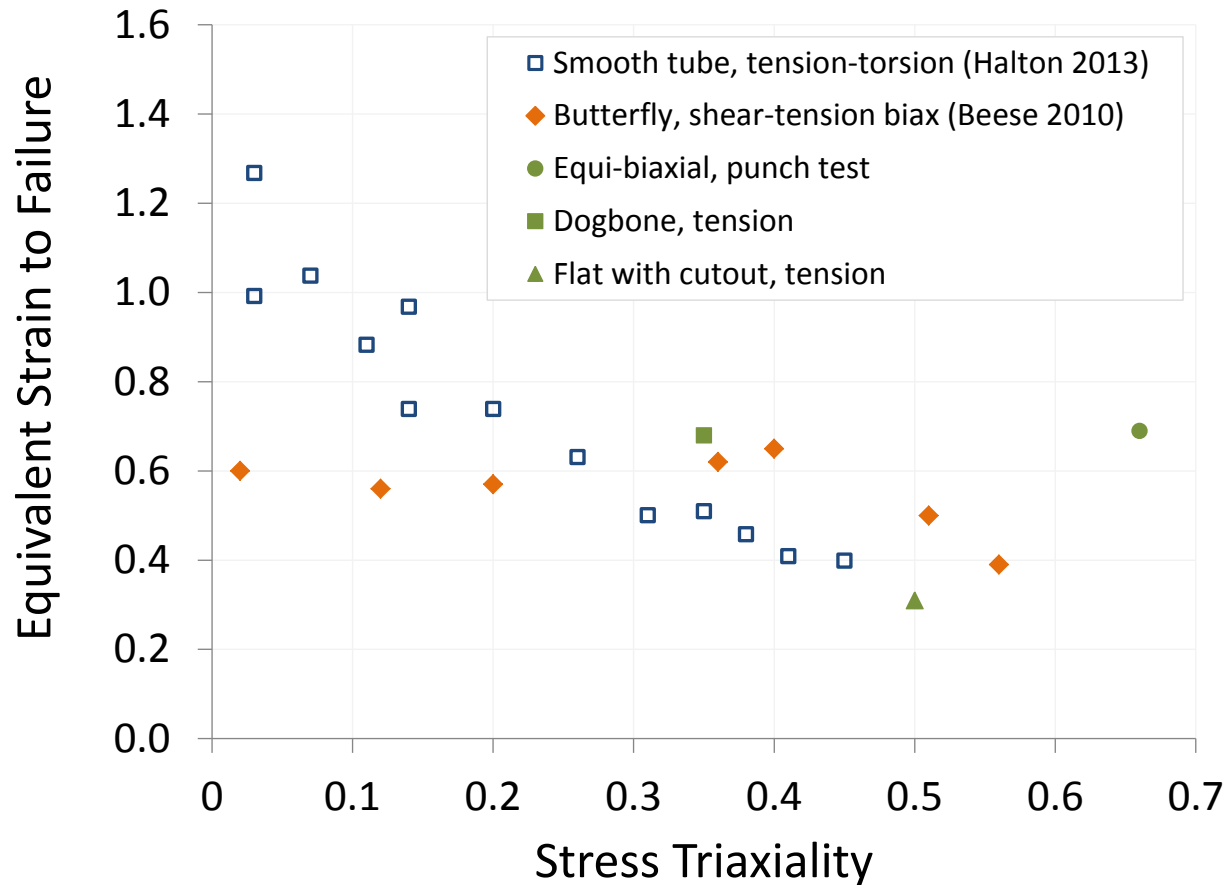


Haltom, Kyriakides and Ravi-Chandar, 2013



Peirs, Verleysen and Degrieck, 2012

Inconsistent Results of Al6061-T6



Beese, A. M., Luo, M., Li, Y., Bai, Y., and Wierzbicki, T., 2010, "Partially coupled anisotropic fracture model for aluminum sheets," Eng. Fracture Mechanics 77, pp. 1128–1152.

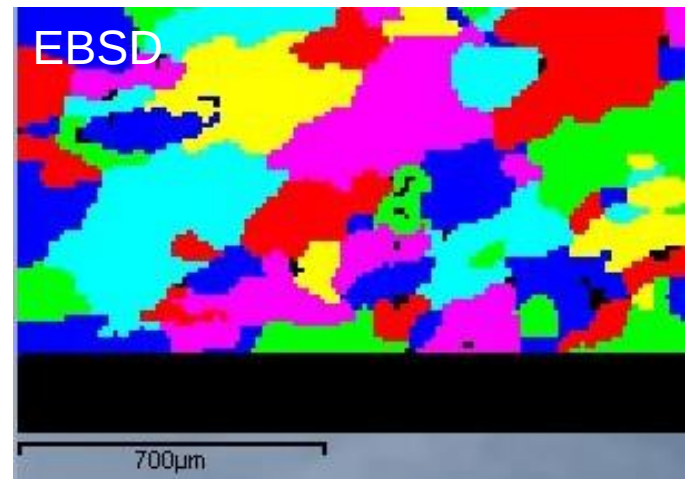
Halton, S.S., Kyriakides, S., and Ravi-Chandar, K., 2013, "Ductile failure under combined shear and tension," Int. J. of Solids and Structures, 50, pp. 1507–1522.

Failure of Al6061-T651

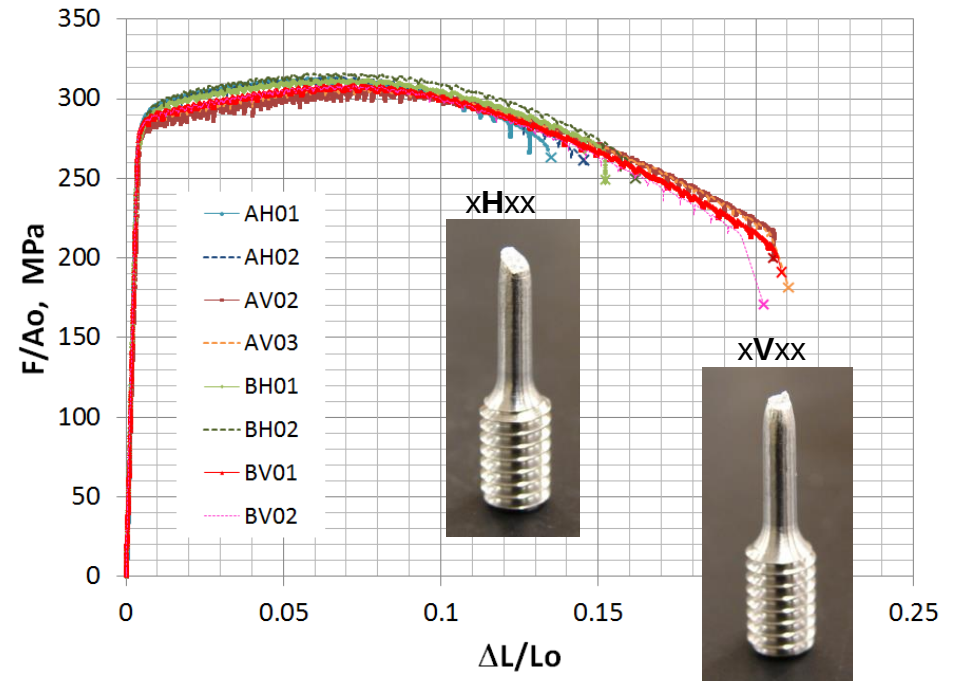
- Material
- Tensile test
 - Smooth bar
 - Notched bar
- Compression test
- Biaxial experiment
 - Thin smooth tube
 - Double notched tube



- All specimens were machined from a certified Al6061-T651 solid bar with a diameter of 1.5 inch
- The average grain size is about 200 μm

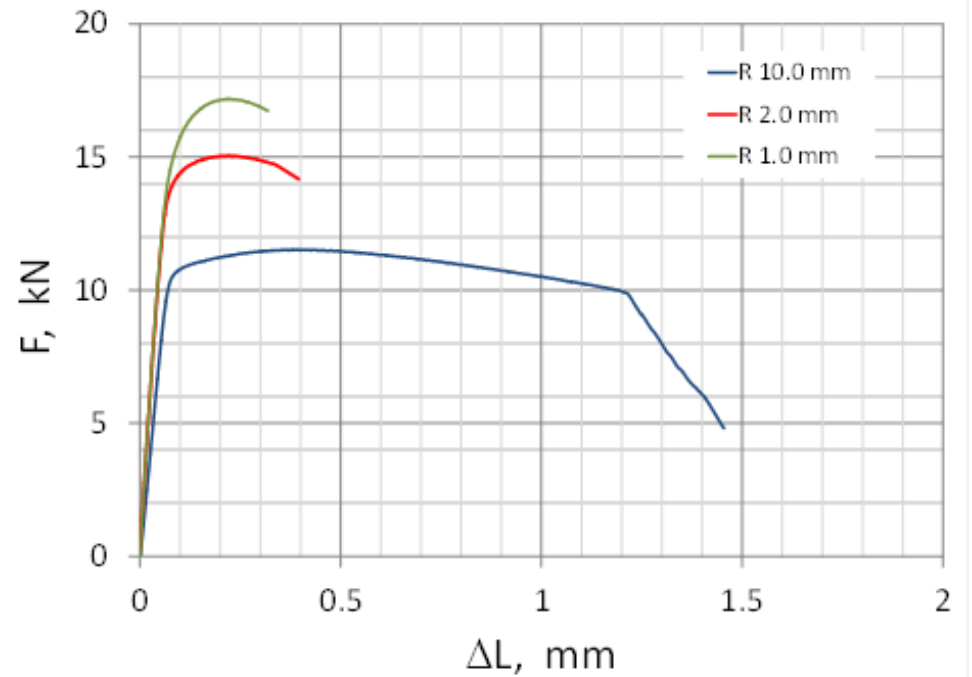


Smooth Bar Tensile Test

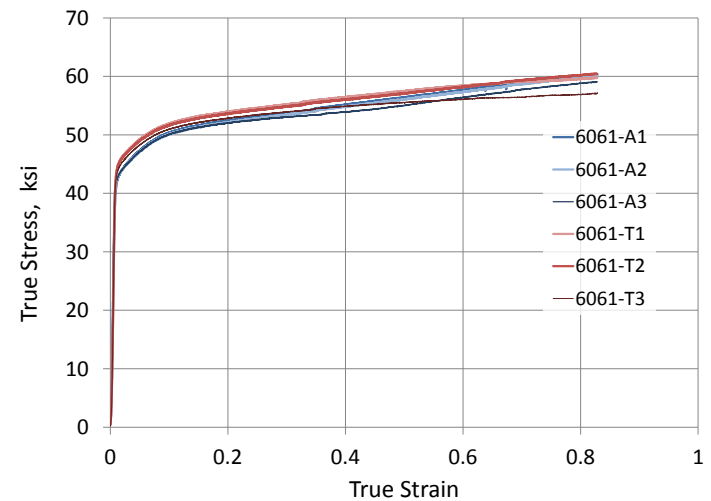
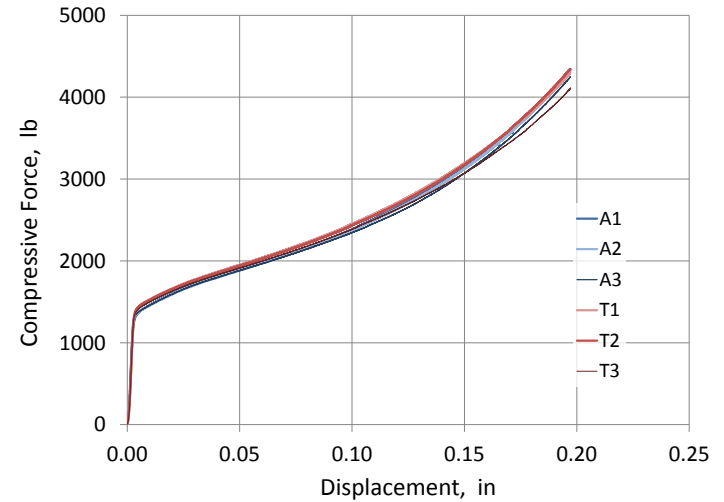
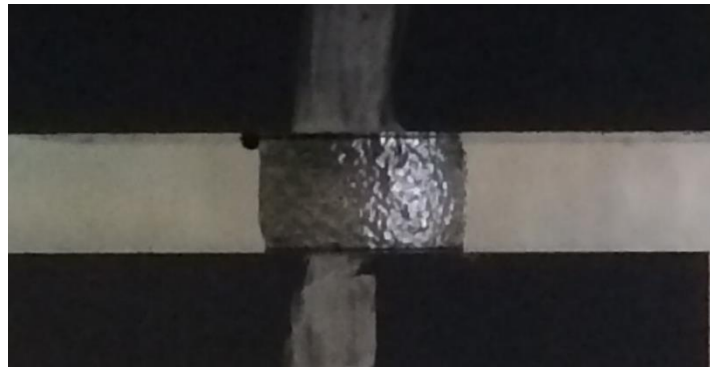
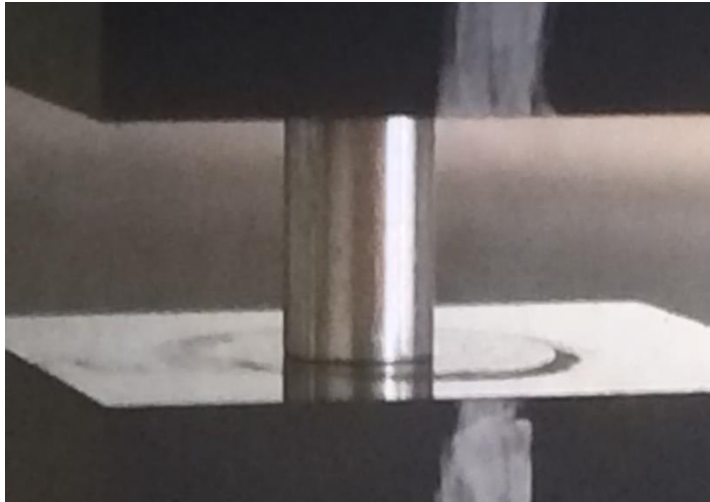


- Tensile specimen
 - Obtained from various orientations: AH, AV, BH, BV
 - The gage section diameter: 0.1".
- Nearly isotropic plastic behavior
- Anisotropic failure behavior.

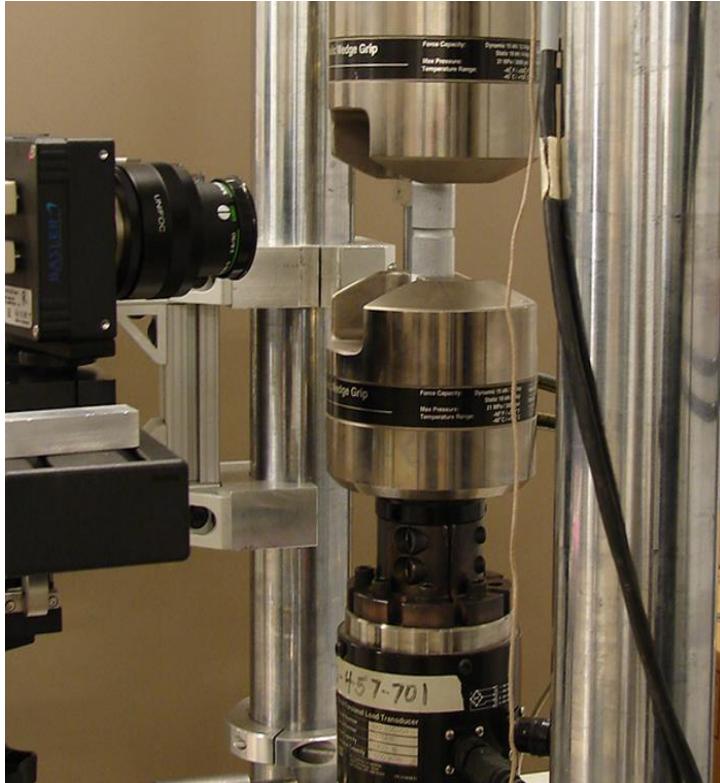
Notched Bar Tensile Test



Compression Test



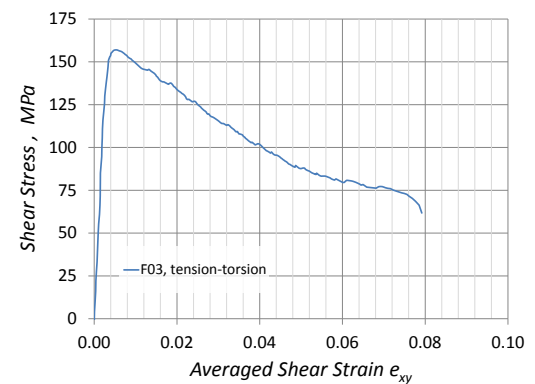
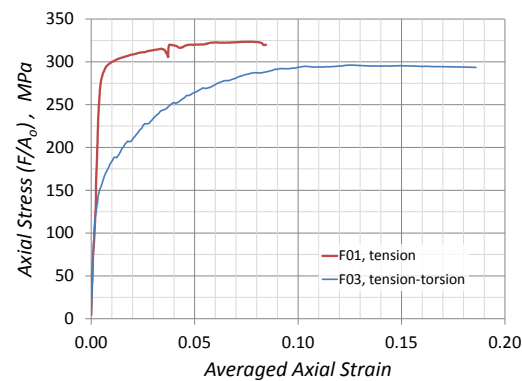
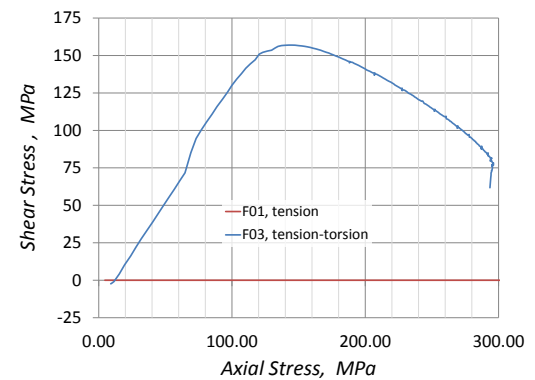
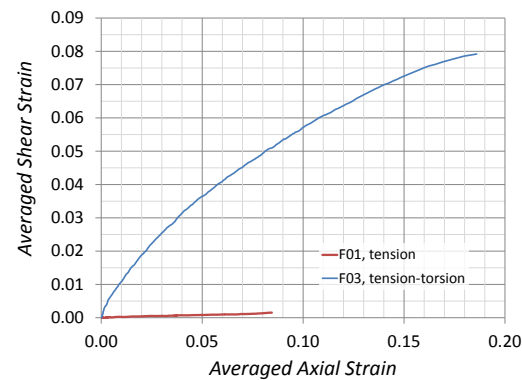
Multi-axial Experiments



- Tension-torsion of tubular specimens
 - Smooth tubes
 - Notched tubes
- 3D DIC for displacement and strain measurement
- MTS Bionic system

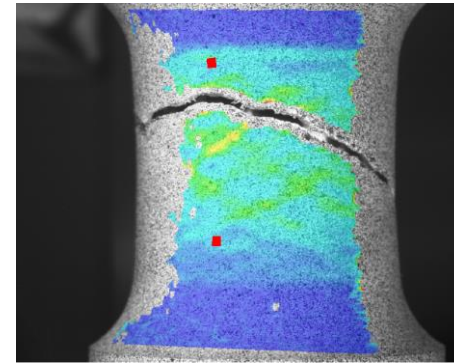
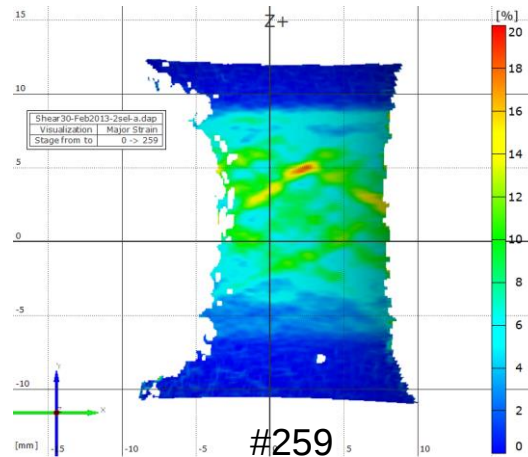
Thin Smooth Tube Tests

- Tube F01 - tension
- Tube F03 – tension-torsion



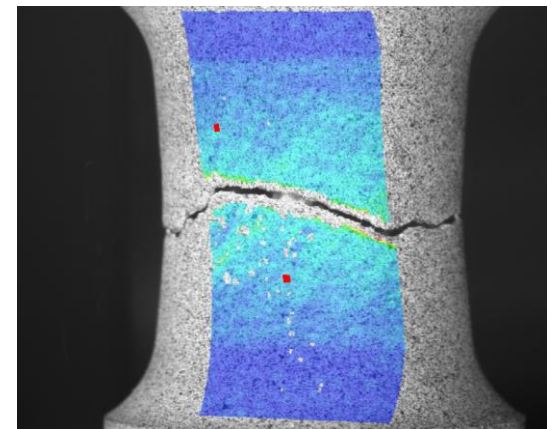
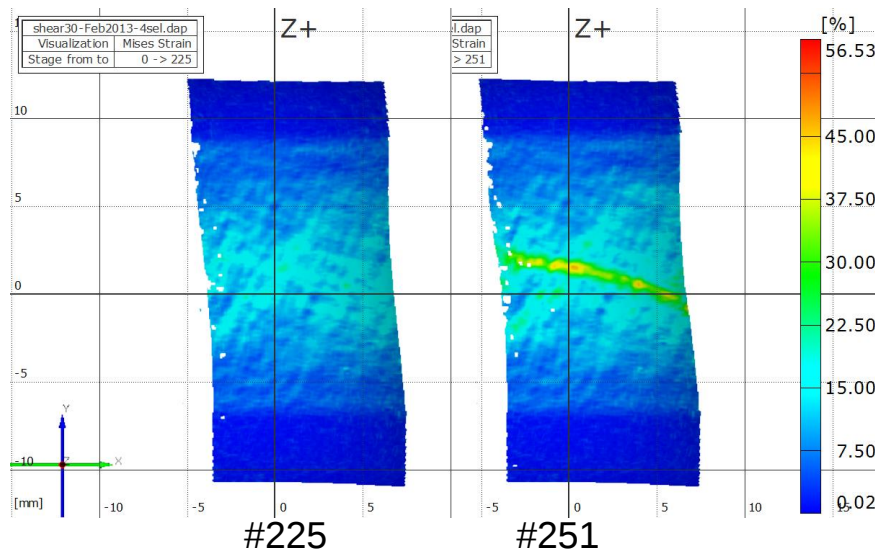
Equivalent Plastic Strain Field

F01
Tension



#260

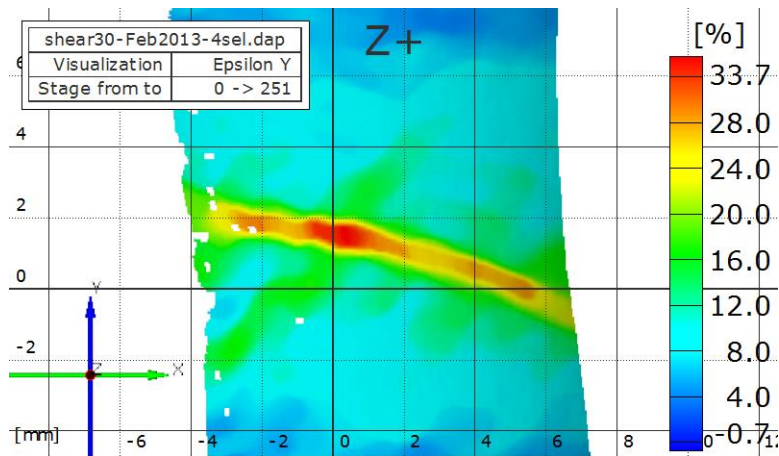
F03
Tension-
Torsion



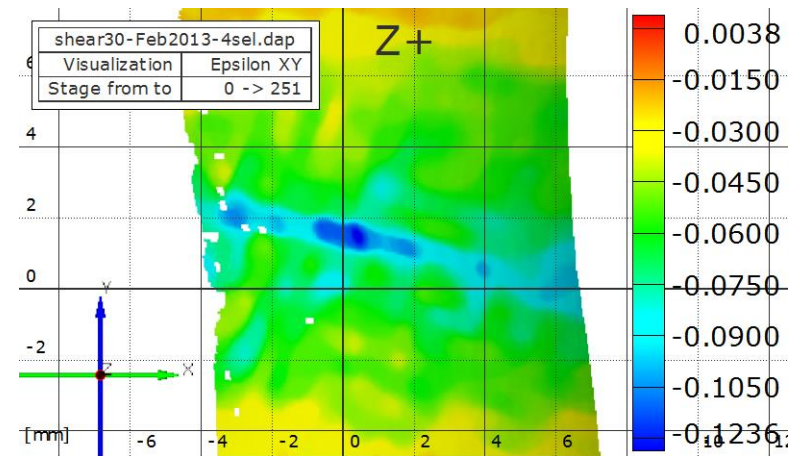
#252

Specimen F03 ϵ_y and ϵ_{xy} Fields

ϵ_y



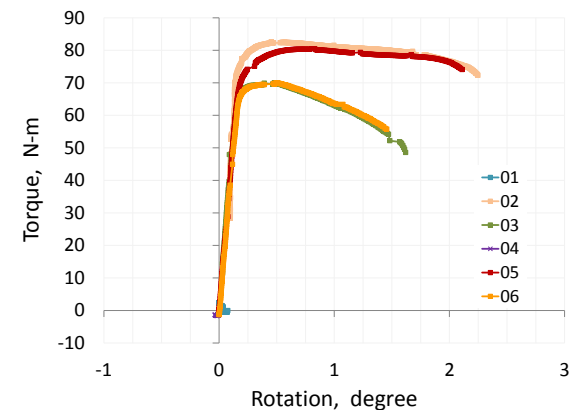
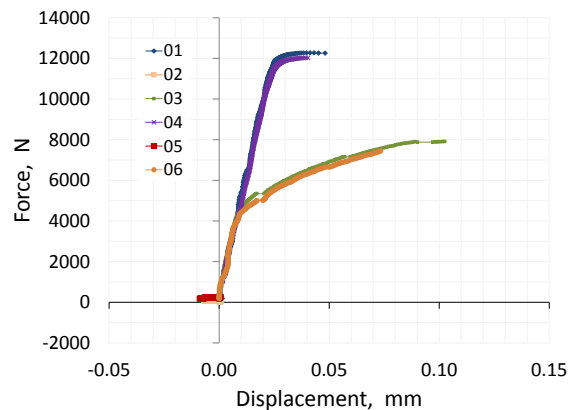
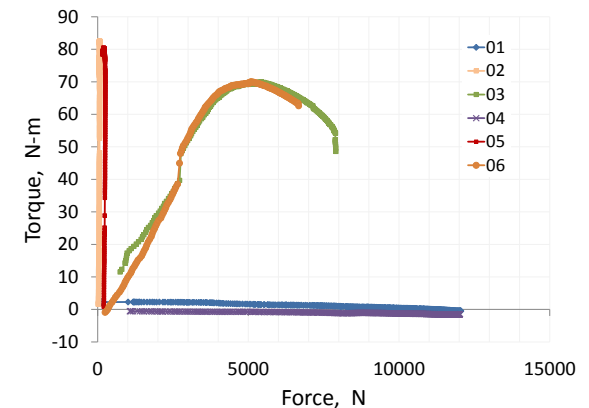
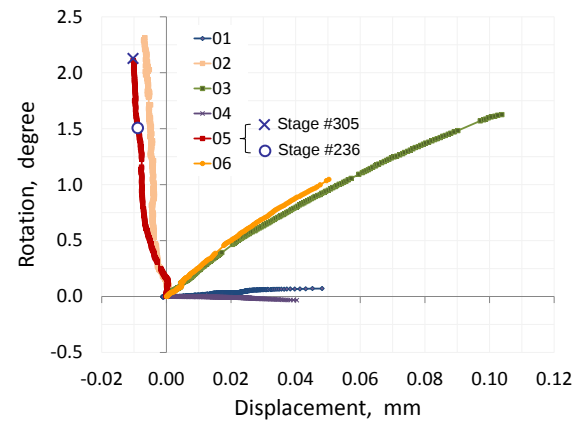
ϵ_{xy}



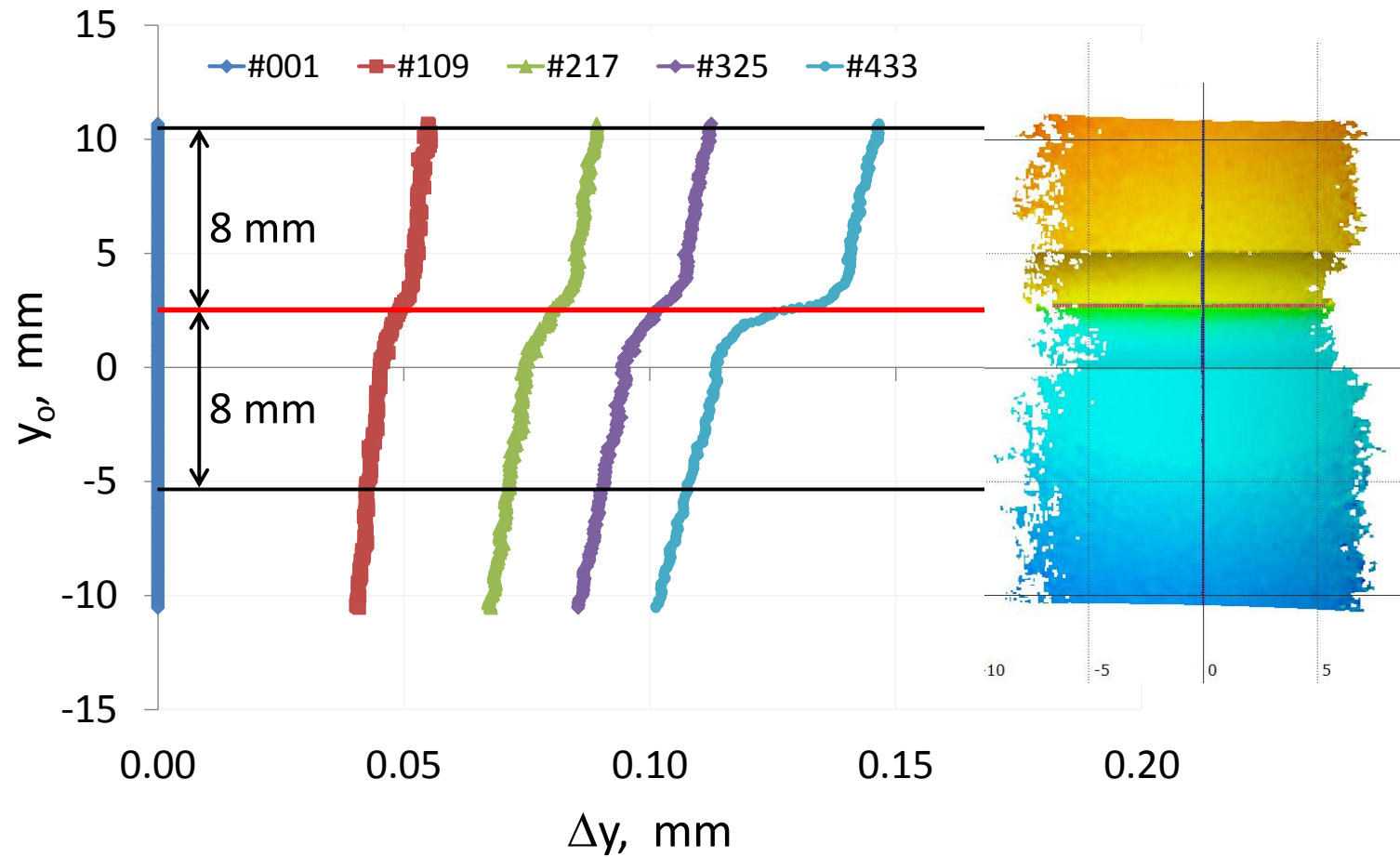
Double Notched Tube Tests



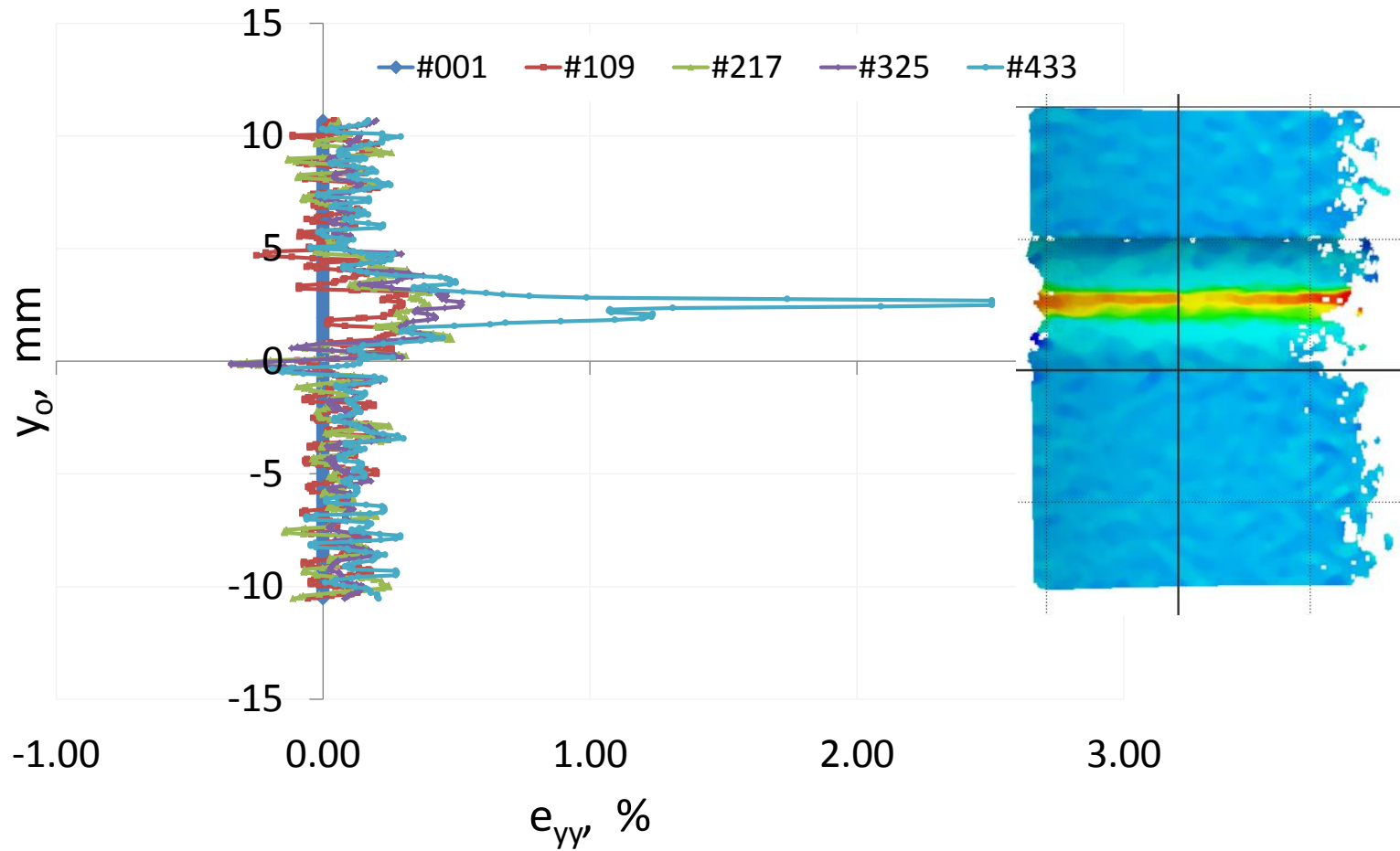
Specimen	Path
01, 04	Tension
02, 05	Torsion
03, 06	Ten / Tor



Tube04 Δy Field

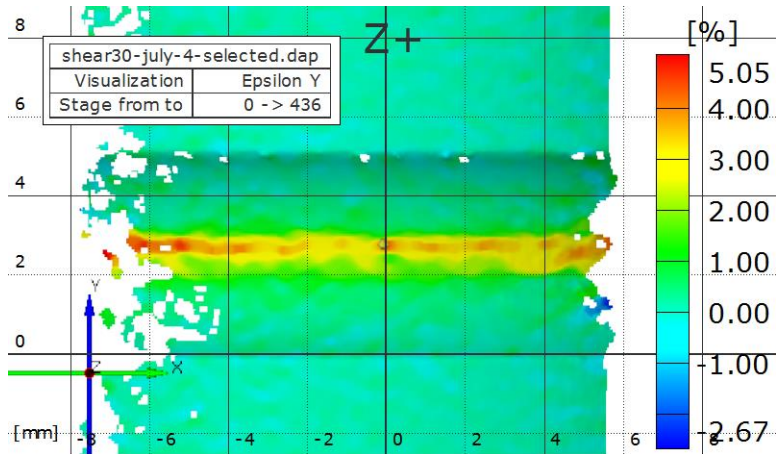


Tube04 ε_y Field

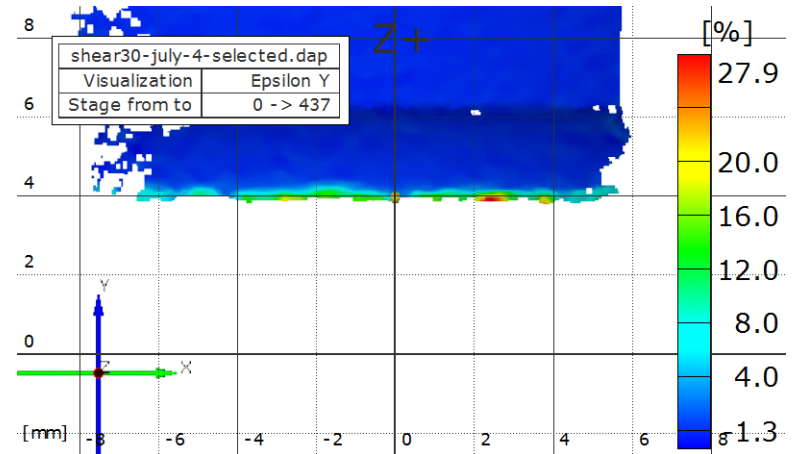


Tube04 ε_y Field

Tension



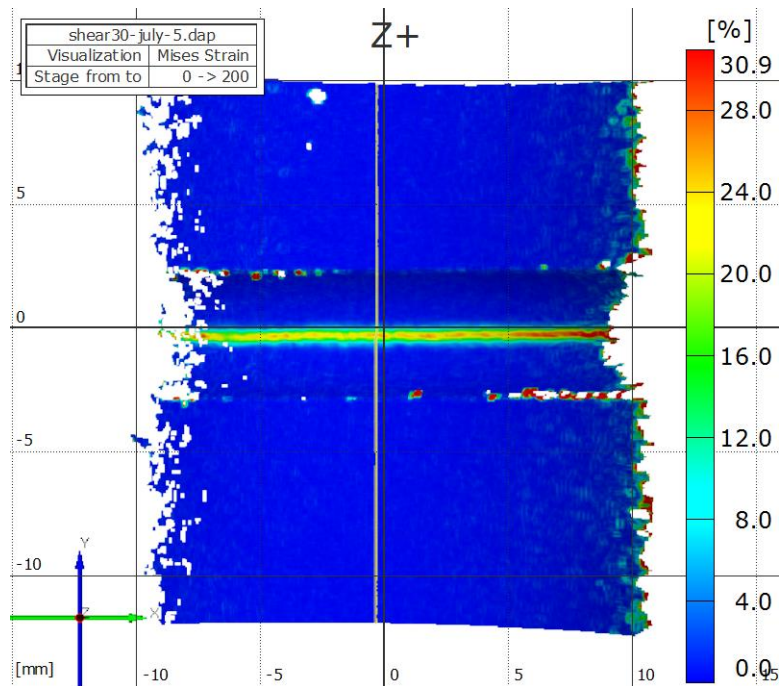
#436



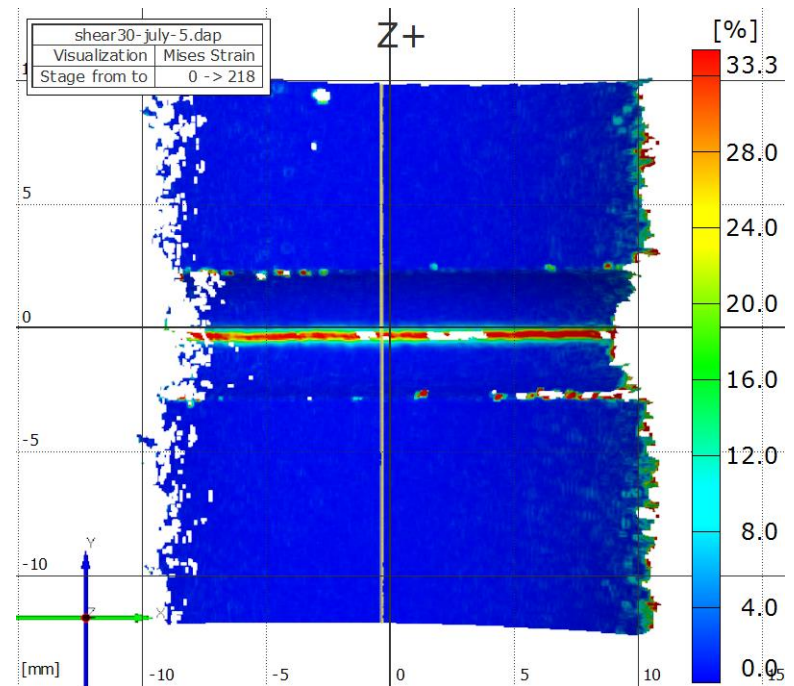
#437

Tube05 Equivalent Strain Field

Torsion



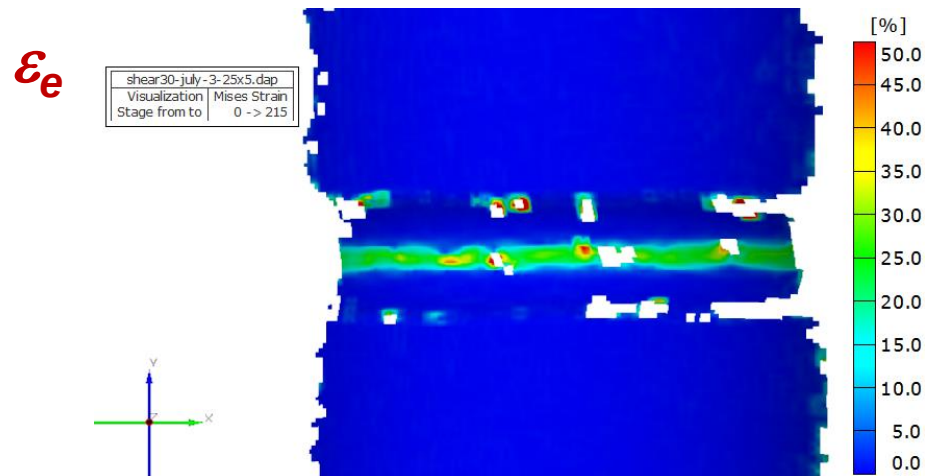
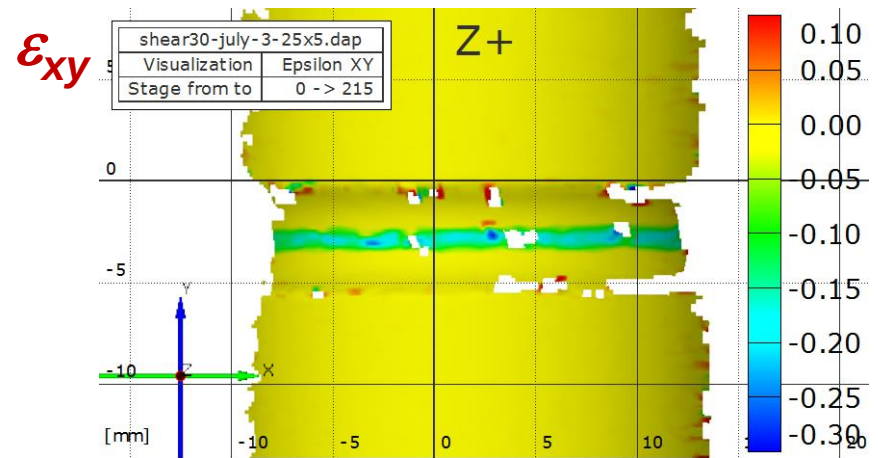
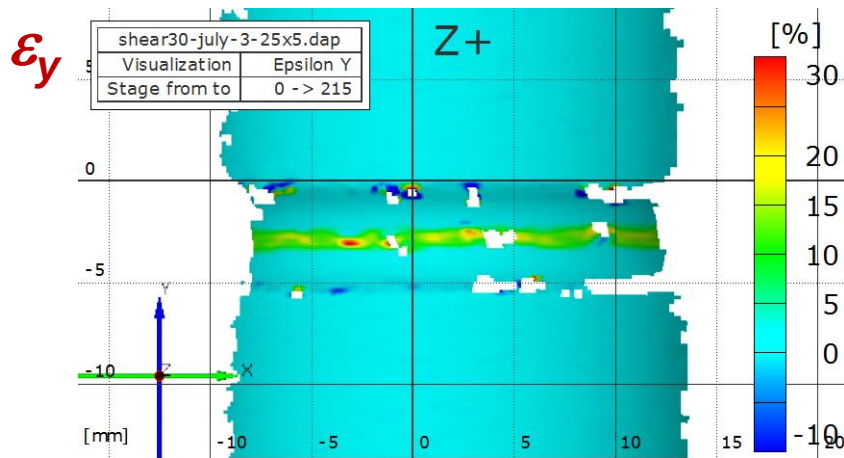
#200



#218

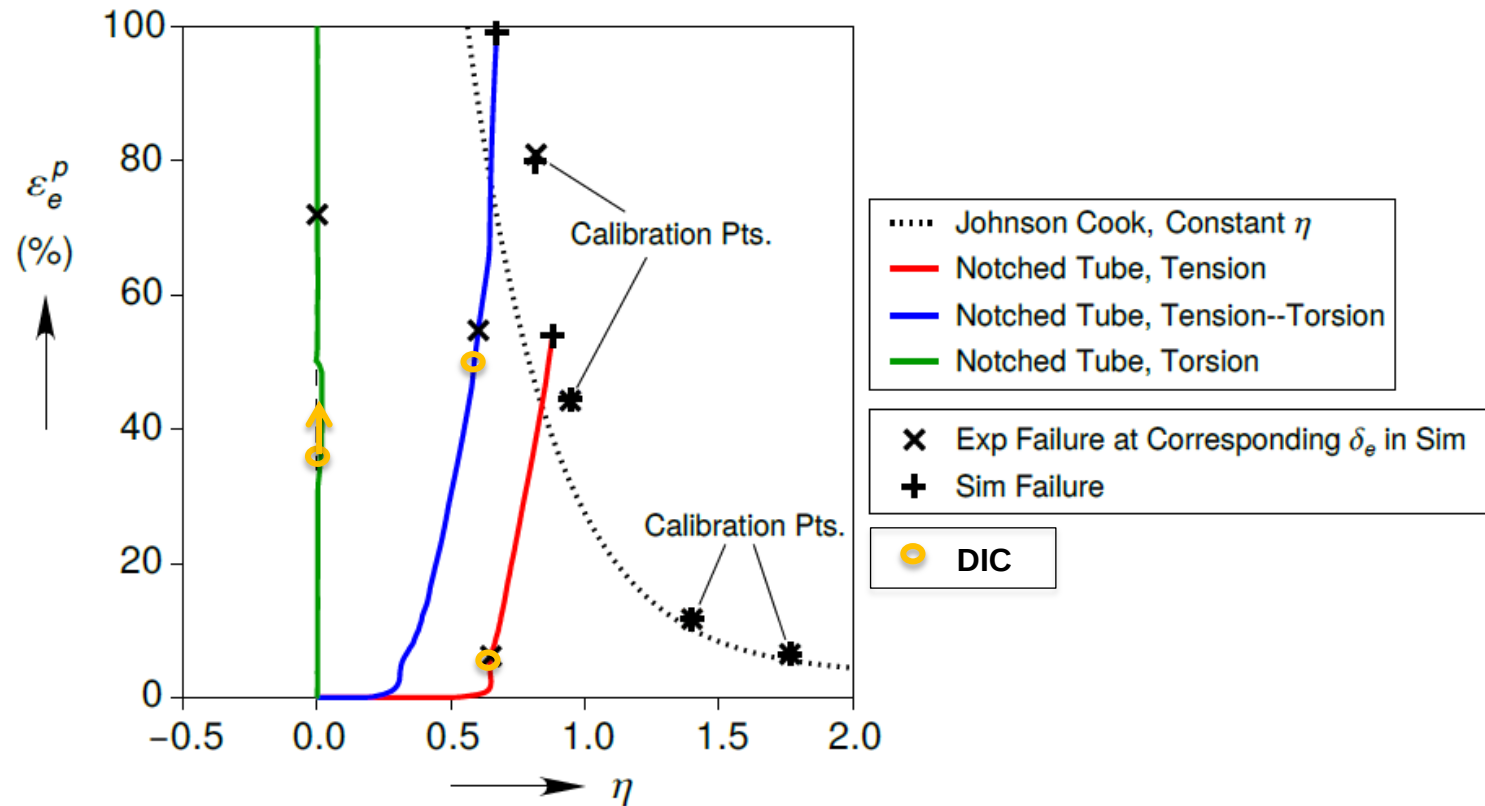
Tube03 Strain Fields

Tension / Torsion #215



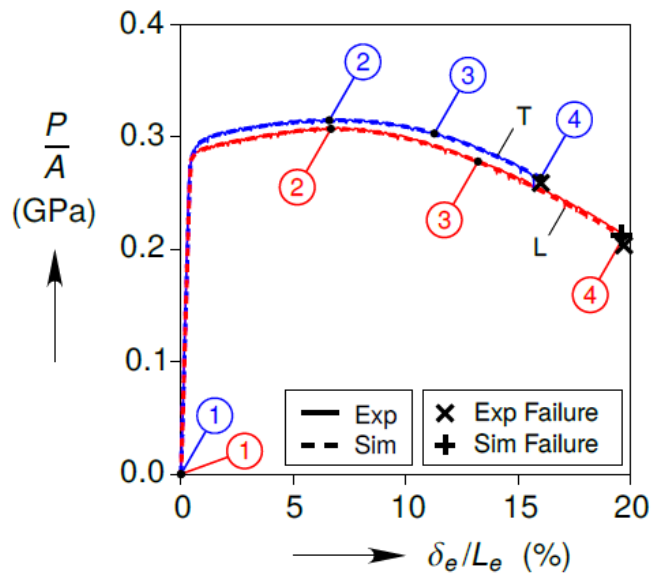
Failure Prediction

Reedlunn, B. and Lu, W. USNCTAM 2014 “Calibration and Validation of a Ductile Failure Model Against Aluminum Axial Torsion Experiments”

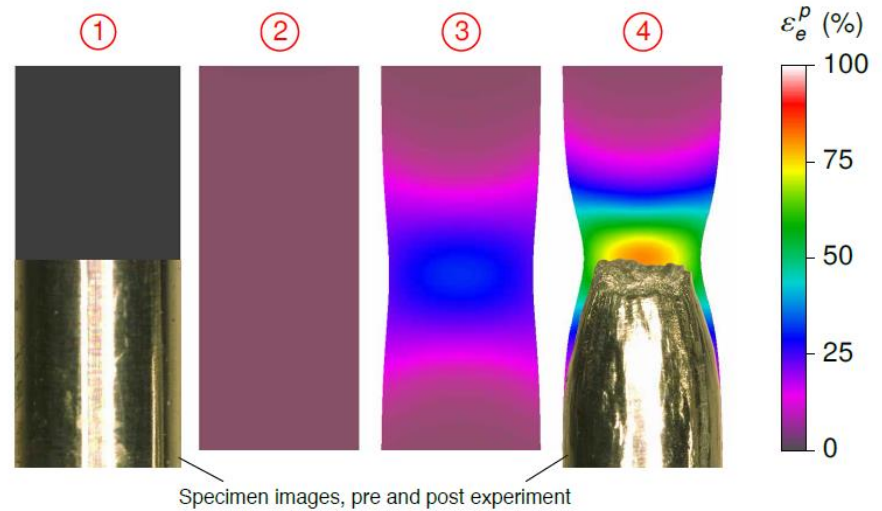


Area Reduction

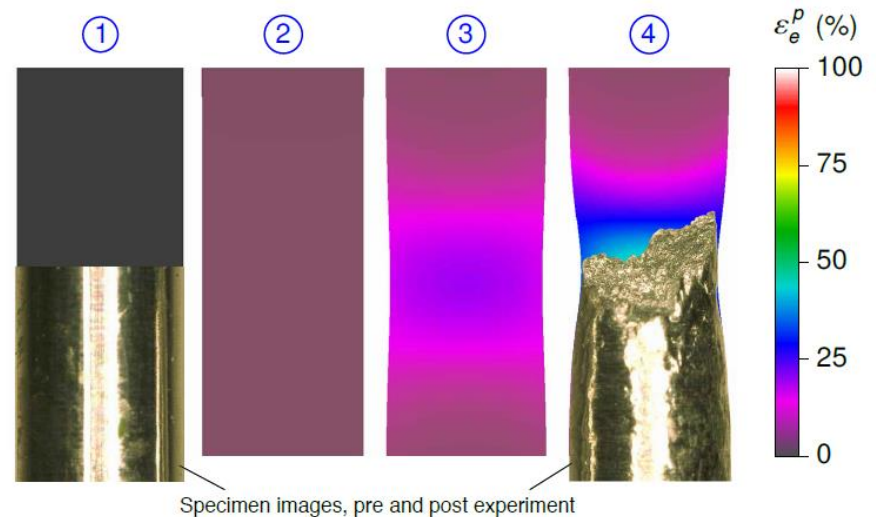
Tensile Tests



Transverse
deformed
shapes

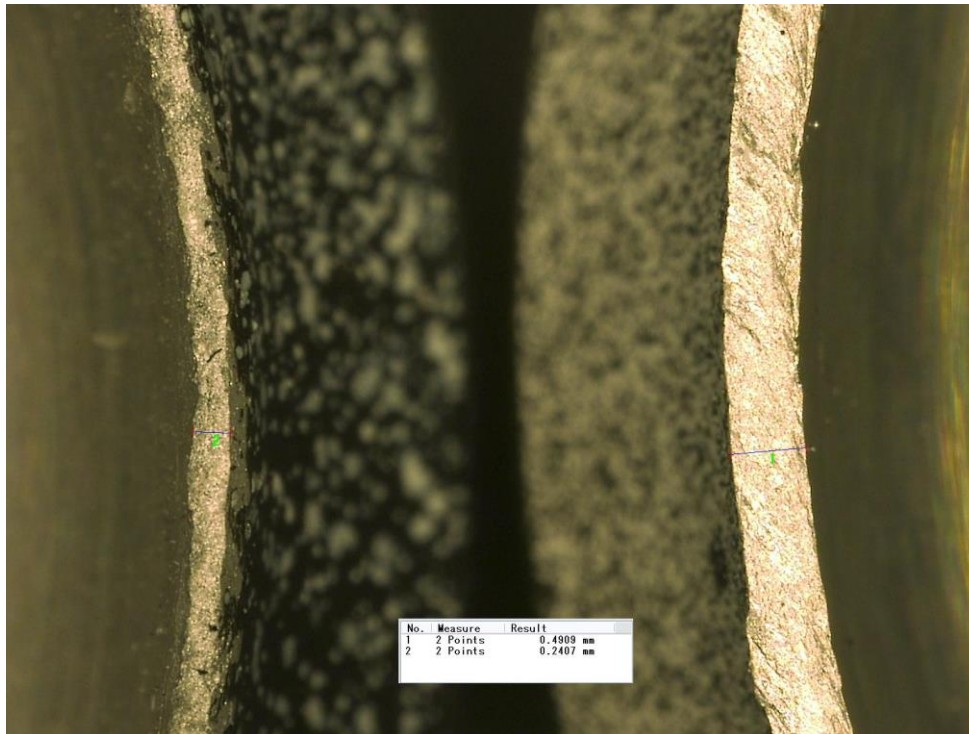


Longitudinal
deformed
shapes



Thickness Reduction

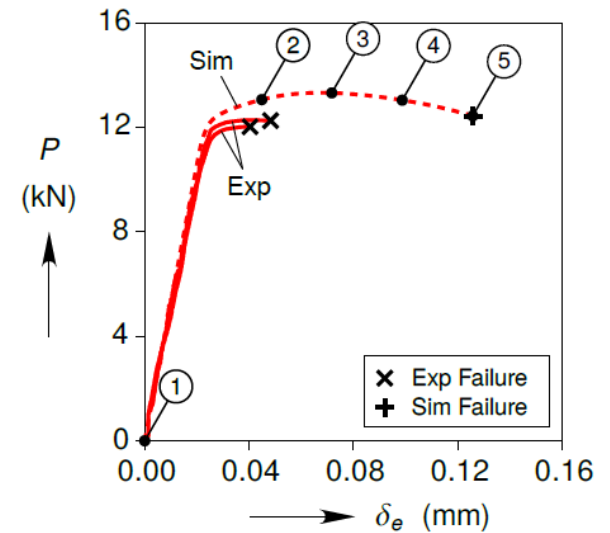
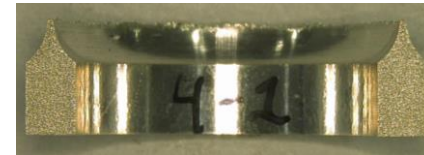
Double notched tubular specimen



tensile failure

torsion failure

Tension at ②



- A set of accurate displacement fields, load-displacement and rotation-torque data is provided for calibrating and validating ductile failure models of Al6061-T651
- Determining the failure strain at the localized narrow band using DIC method is very challenging
 - Time and Location of measurement
 - Speckle size
 - Statistical significance (multiple experiments)
 - Alignment
- Model predictions of failure strains and area reductions are compared with experimental measurements
 - Anisotropic failure behavior
 - Yield surface
 - etc.