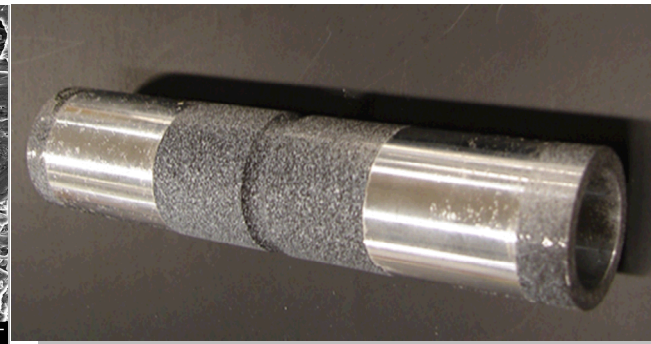
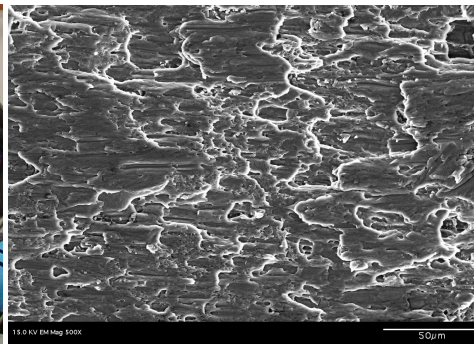
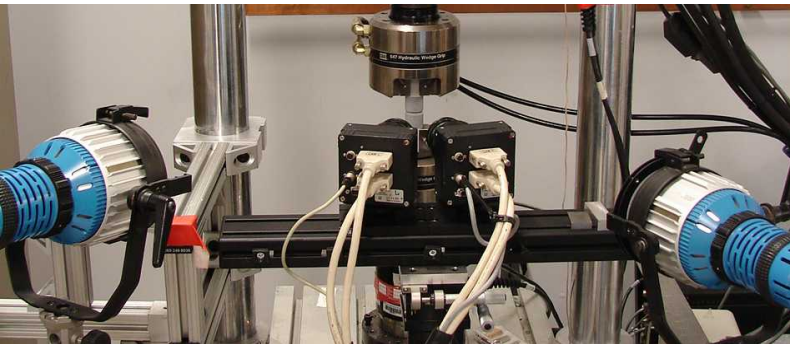


Exceptional service in the national interest



An Experimental Study of Ductile Failure Under Multi-axial Loading

Wei-Yang Lu and Helena Jin

Bao, Y., and Wierzbicki, T., 2004,
“On Fracture Locus in the Equivalent Strain and Stress
Triaxiality Space,” Int. J. Mech. Sci., 46(1), pp. 81–98

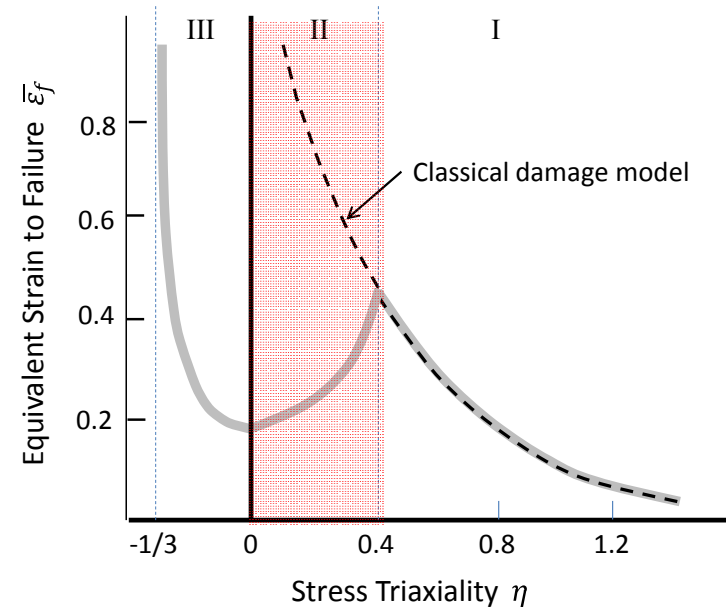
Experiment	Triaxiality
Smooth round bars, tension	H
Plate dogbone	H
Plate plane strain, tension	H
Flat specimen with cut out	H
Notched round bars, tension	H
Flat grooved plates, tension	H
Butterfly I (in-plan shear), tension	L
Notched round bars, compression	N
Cylinders, compression	N
Material	Al2024-T351
Measurement Method	Numerical Simulation

■ Failure criterion

$$\bar{\epsilon}_f = C_1 + C_2 \exp(C_3 \eta)$$

$$\eta = \sigma_m / \bar{\sigma}$$

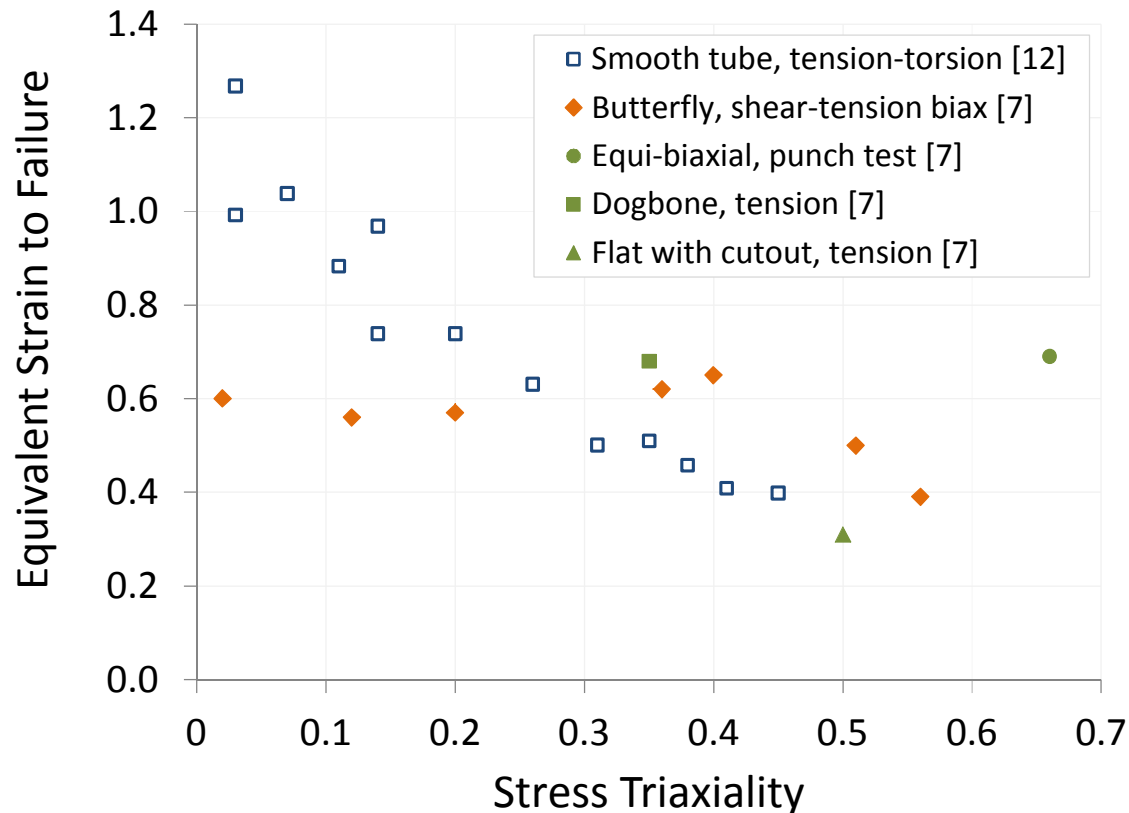
- ϵ and σ are values at the initial failure location



Recent Experiments

Experiment	Author Year Ref	Bao 2004 [3]	Wierzbicki 2005b [4]	Barsoum 2007 [5]	Bai 2009 [6]	Beese 2010 [7]	Gruben 2011 [8]	Dorogoy 2011 [9]	Lu 2012 [10]	A.G. 2013 [11]	Haltom 2013 [12]	Faleskog 2013 [13]
Material		Al2024 -T351	A710 steel	Weldox 420 & 960 Steel	1045 DH36 steel	Al6061 -T6	Docol 600DL steel	4340 steel Al7075- T651	Al6061 -T651	Al6061 -T6	Al6061 -T6	Weldox 420 & 960 Steel
Measurement Method		NS	NS	NS	NS	DIC, NS, Area Reduct.	DIC, NS	NS	DIC	DIC, Grain Analy.	Grid, Grain Analy.	NS
Specimen Type	η											
Butterfly I (in-plan shear), tension	L	x					x			x		
Notched Arcan	H, L						x					
Butterfly II, tension or compression	H, L, N		x									
Butterfly III, tension & shear	H, L					x						
Smooth tube, torsion	L				x				x		x	
Smooth tube, tension/torsion	H, L								x		x	
Double notched tube, tension and torsion	H, L			x					x			x
Shear Compression Disk	L, N							x				

Inconsistent Results of Al6061-T6



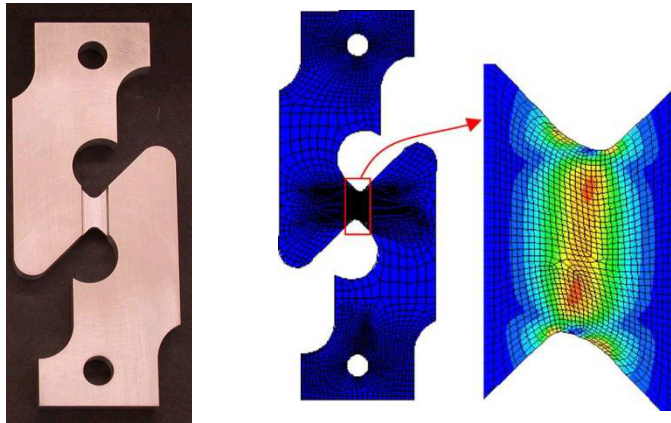
[7] Beese, A. M., Luo, M., Li, Y., Bai, Y., and Wierzbicki, T., 2010, "Partially coupled anisotropic fracture model for aluminum sheets," Eng. Fracture Mechanics 77, pp. 1128–1152.

[12] Haltom, 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.

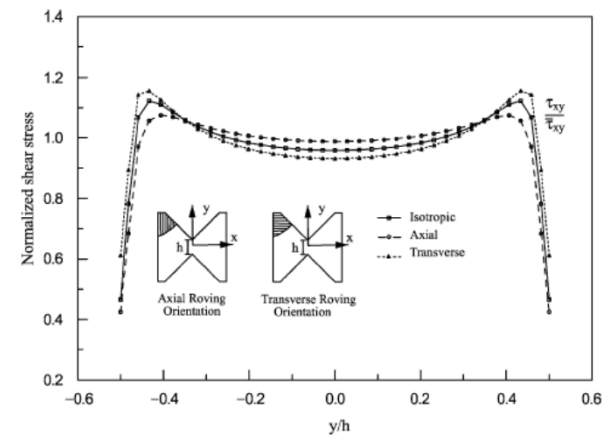
Low Triaxiality Experiments

Butterfly Type Specimens

I

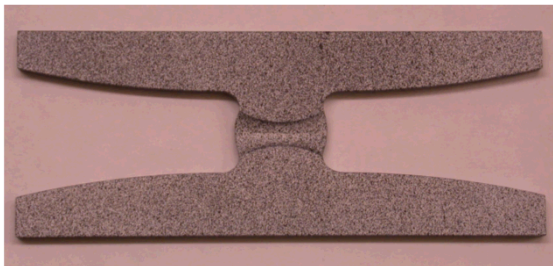


Bao, Y., and Wierzbicki, T., 2004



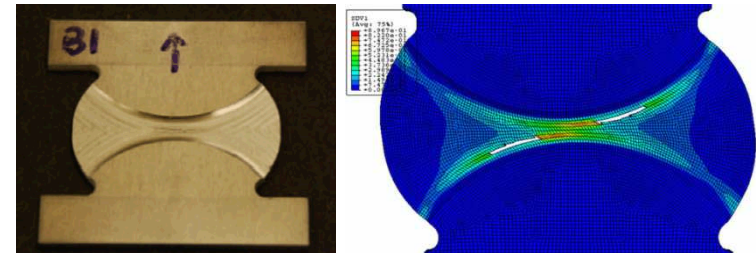
El-Hajjar, R. and Haj-Ali, R., 2004

II



Wierzbicki, T., Bao, Y., and and Bai, Y., 2005

III

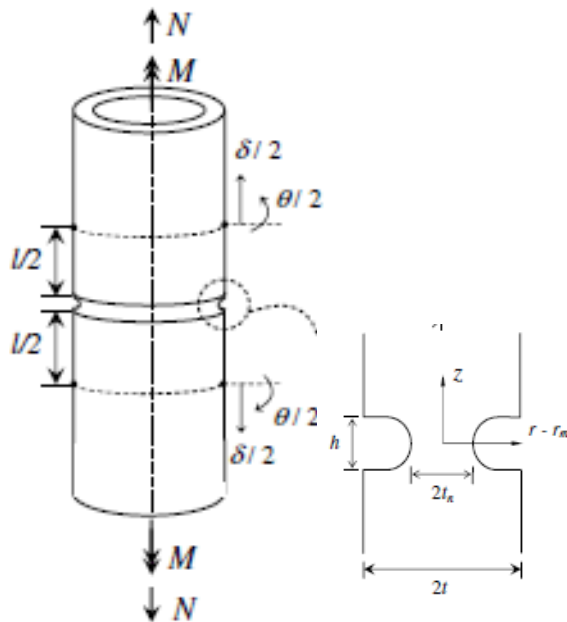


Beese, A. M., Luo, M., Li, Y., Bai, Y., and Wierzbicki, T., 2010

Tubular Type Specimens

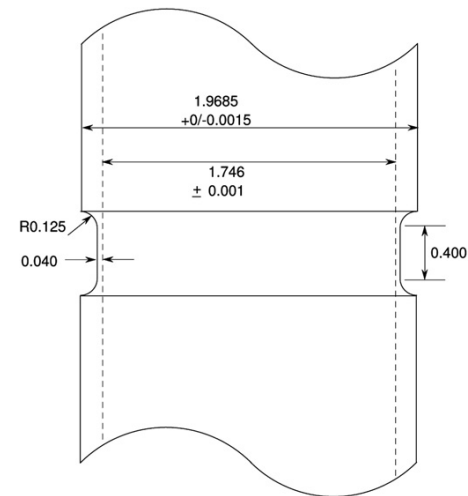
Double notched tube

Barsoum, I., and Faleskog, J., 2007



Smooth tube

Haltom, S.S., Kyriakides, S.,
and Ravi-Chandar, K., 2013



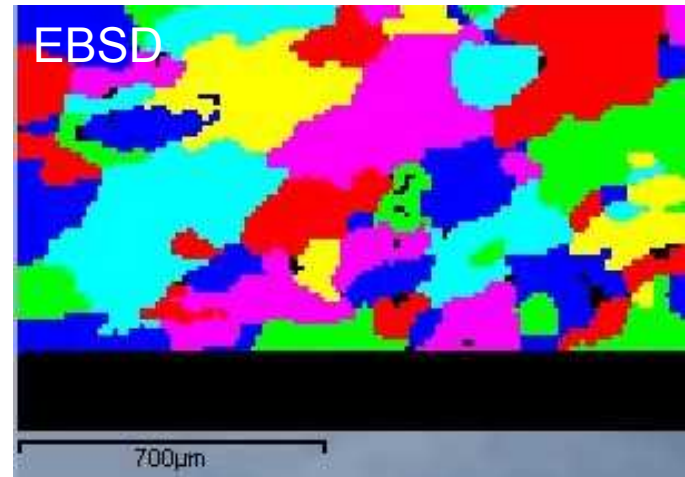
Failure of Al6061-T651

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

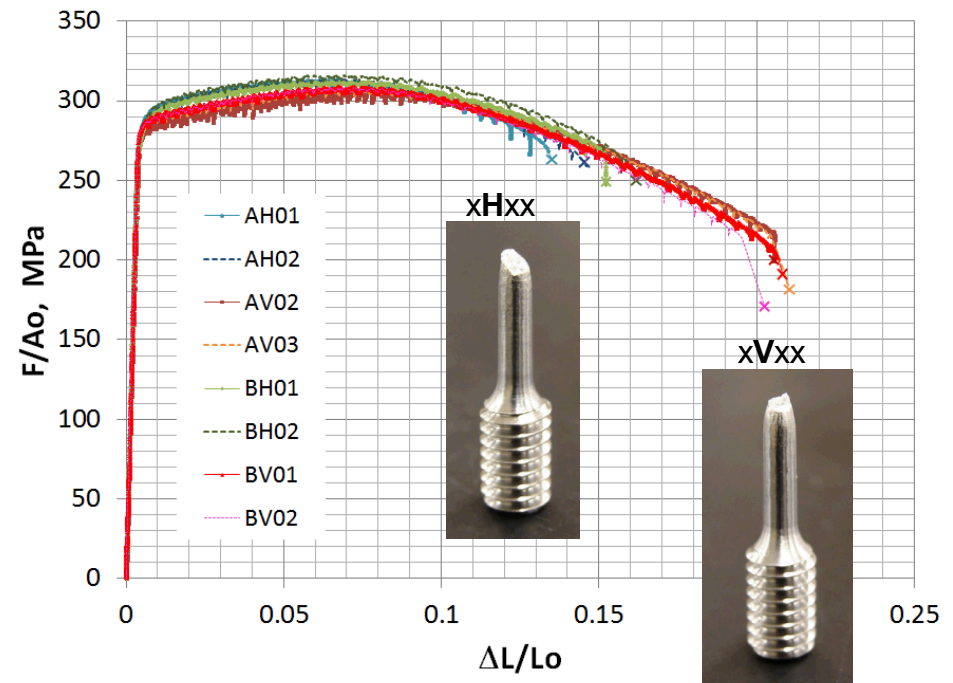
Material



- 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



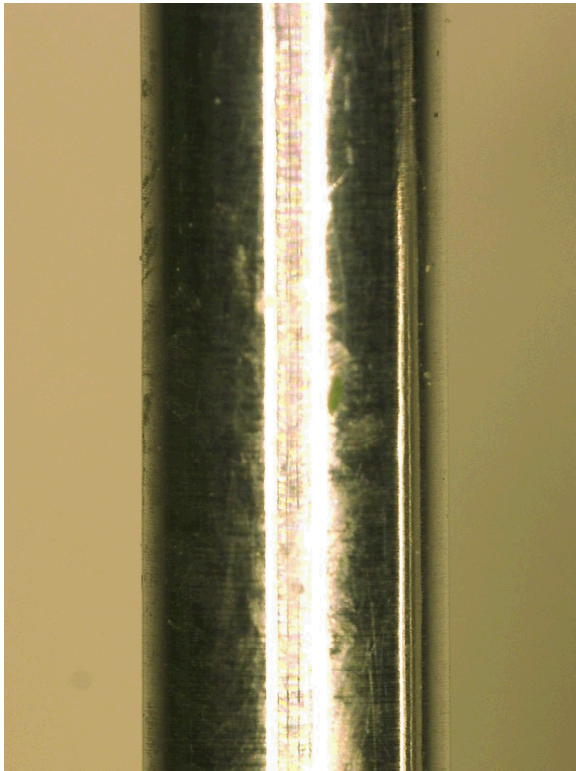
Smooth Tensile Test



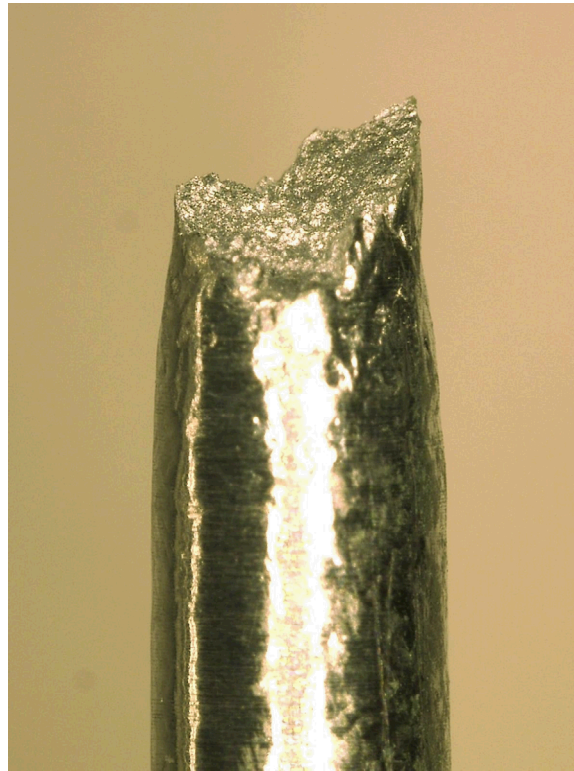
- Tensile specimen
 - Obtained from various orientations: AH, AV, BH, BV
 - The gage section diameter: 0.1".
- Nearly isotropic plastic behavior
- Anisotropic failure behavior.

Area Reduction

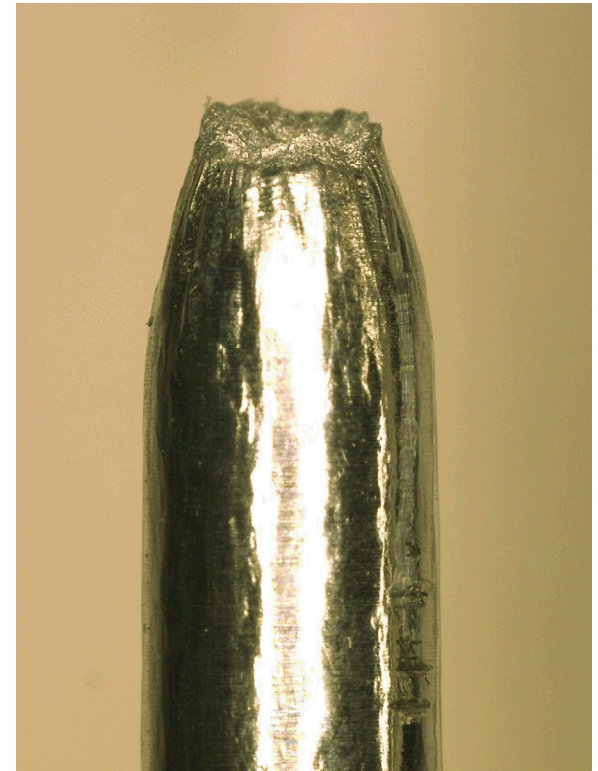
Smooth Tensile Specimens (x50)



Undeformed

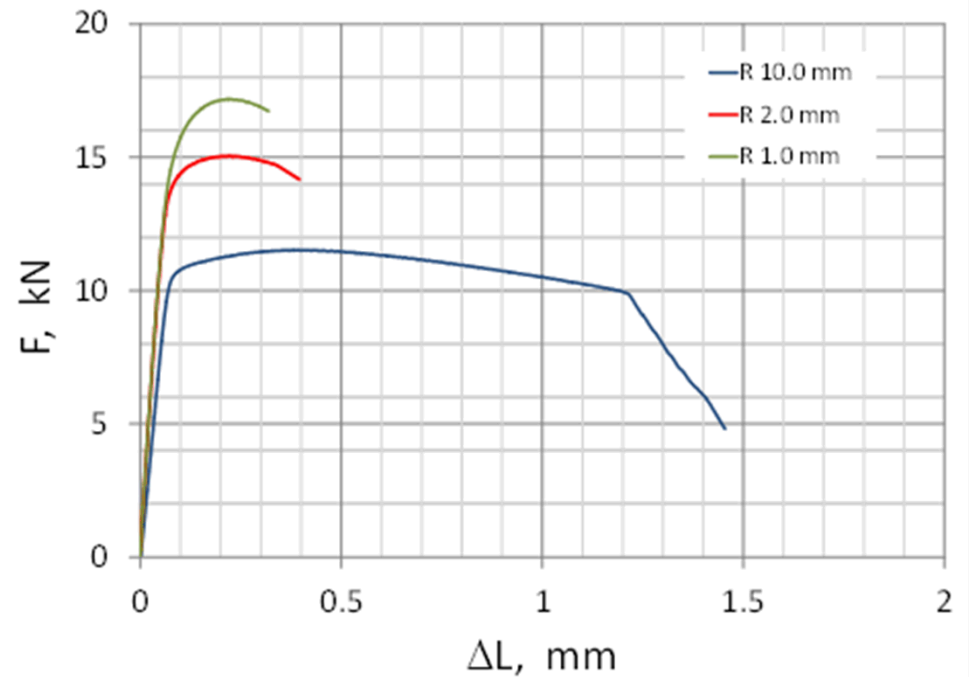
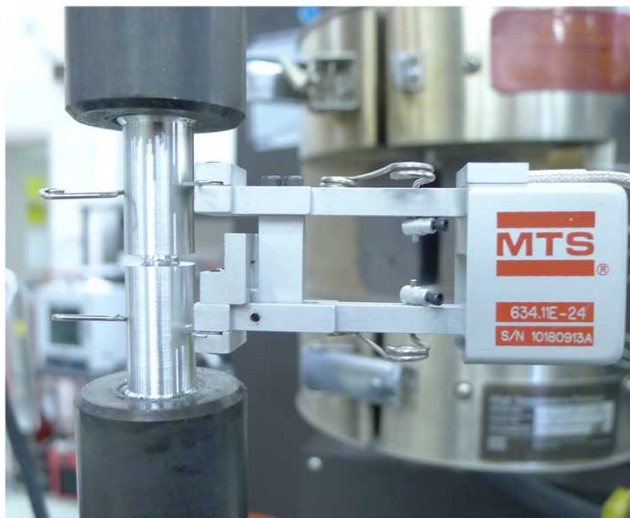


BH02

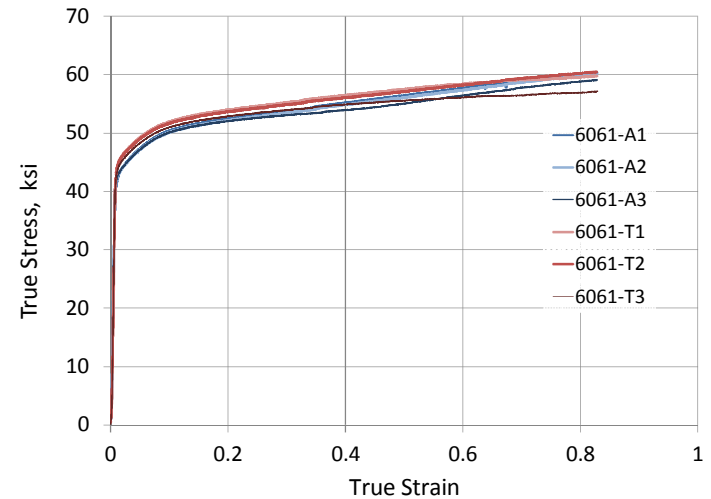
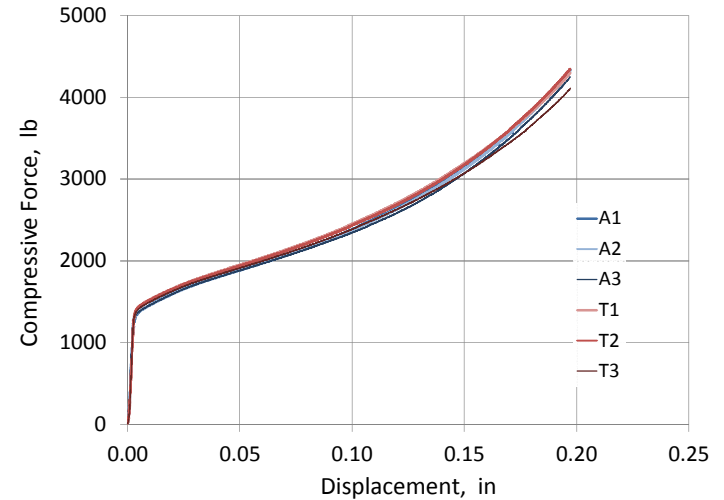
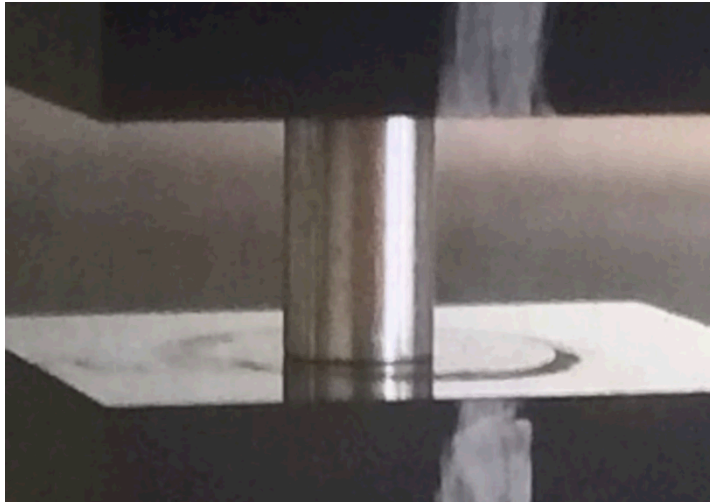


BV02

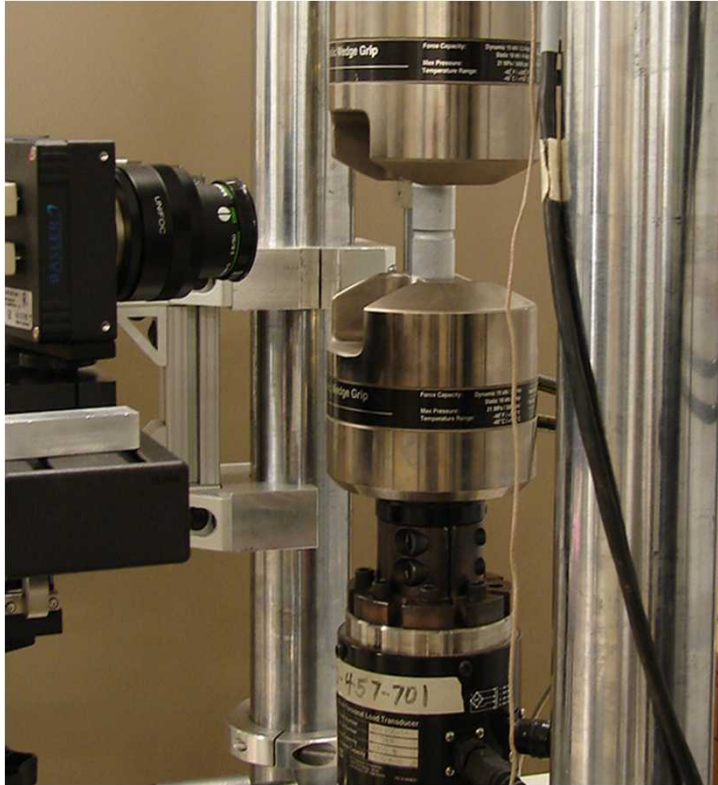
Notched tensile Specimens



Compression Test



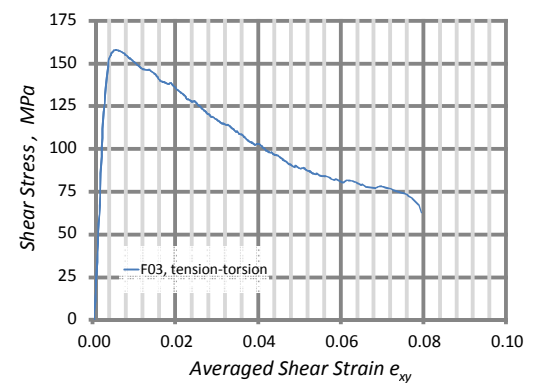
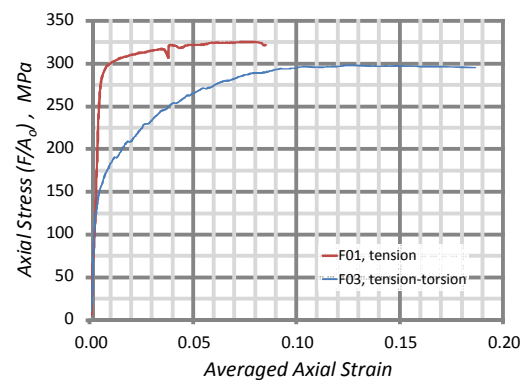
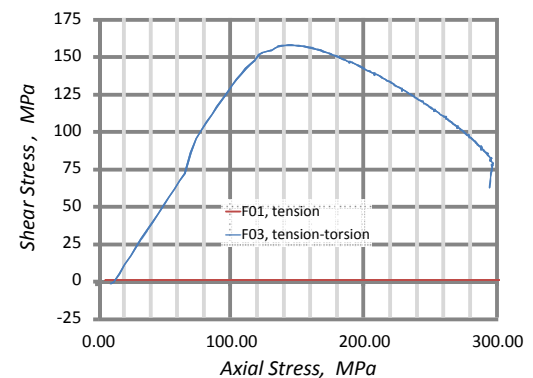
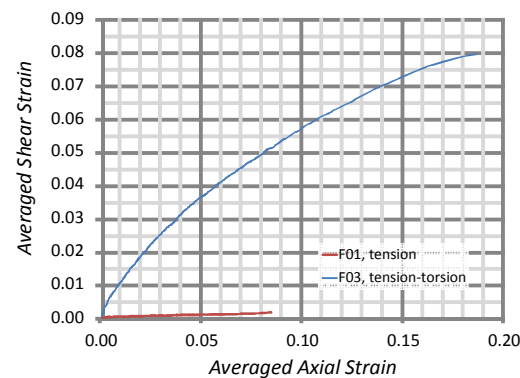
Multi-axial Experiments



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

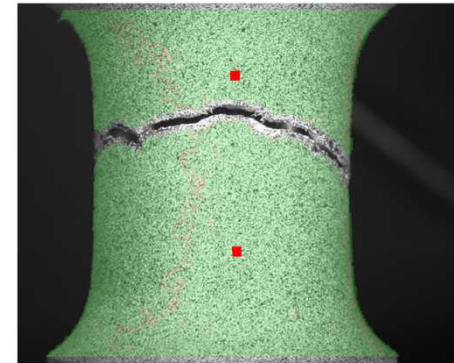
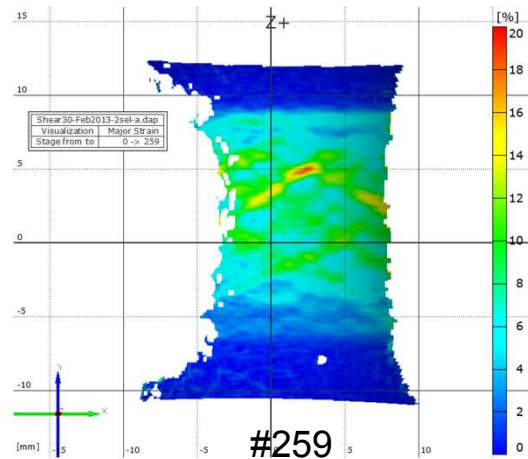
Thin Smooth Tube Tests

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



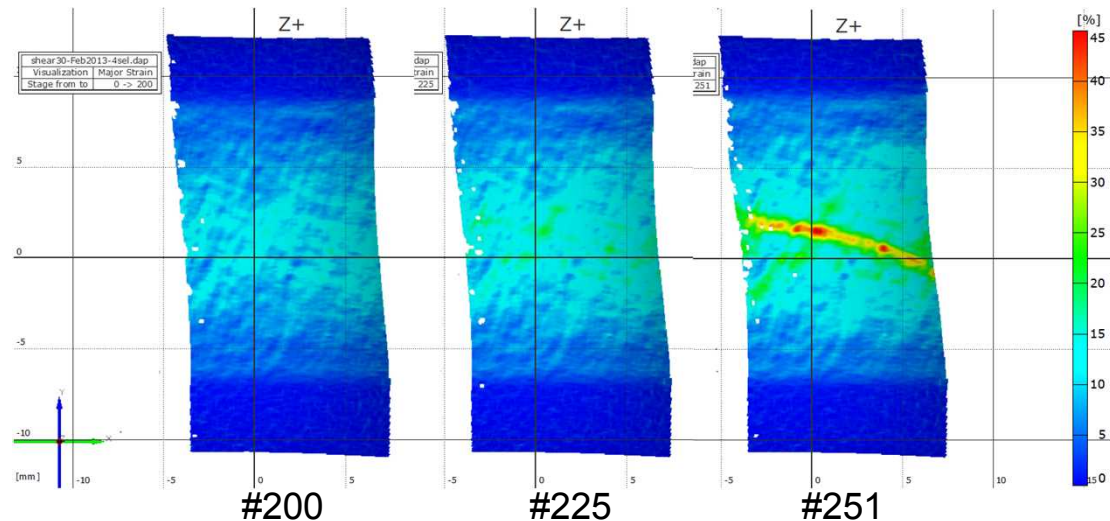
Strain Distribution

F01
Tension

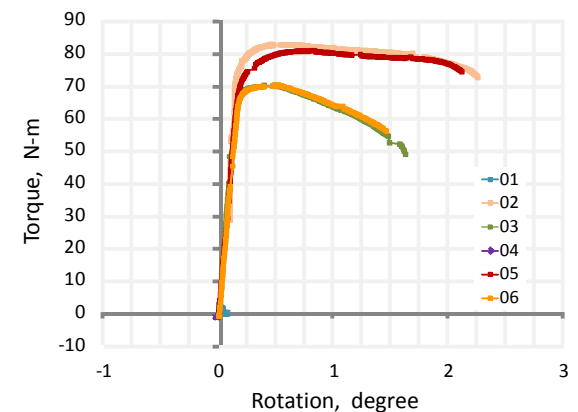
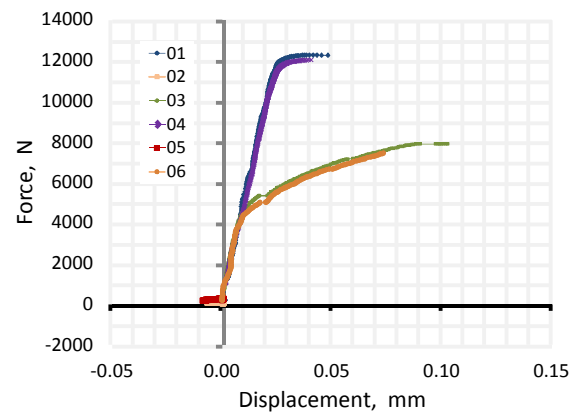
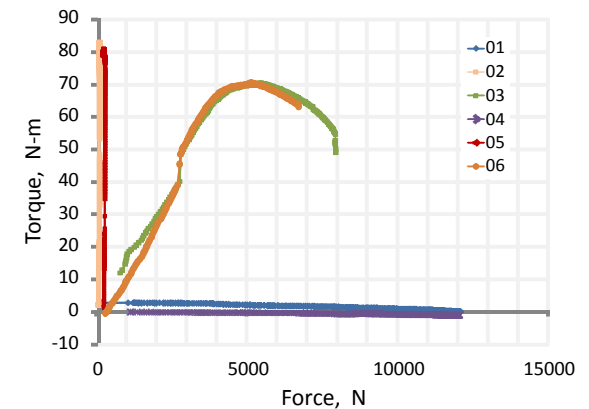
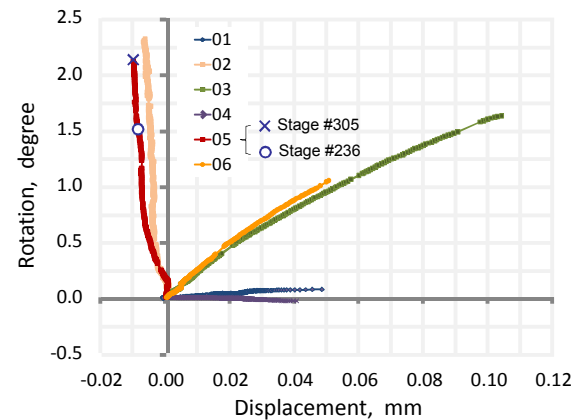


#260

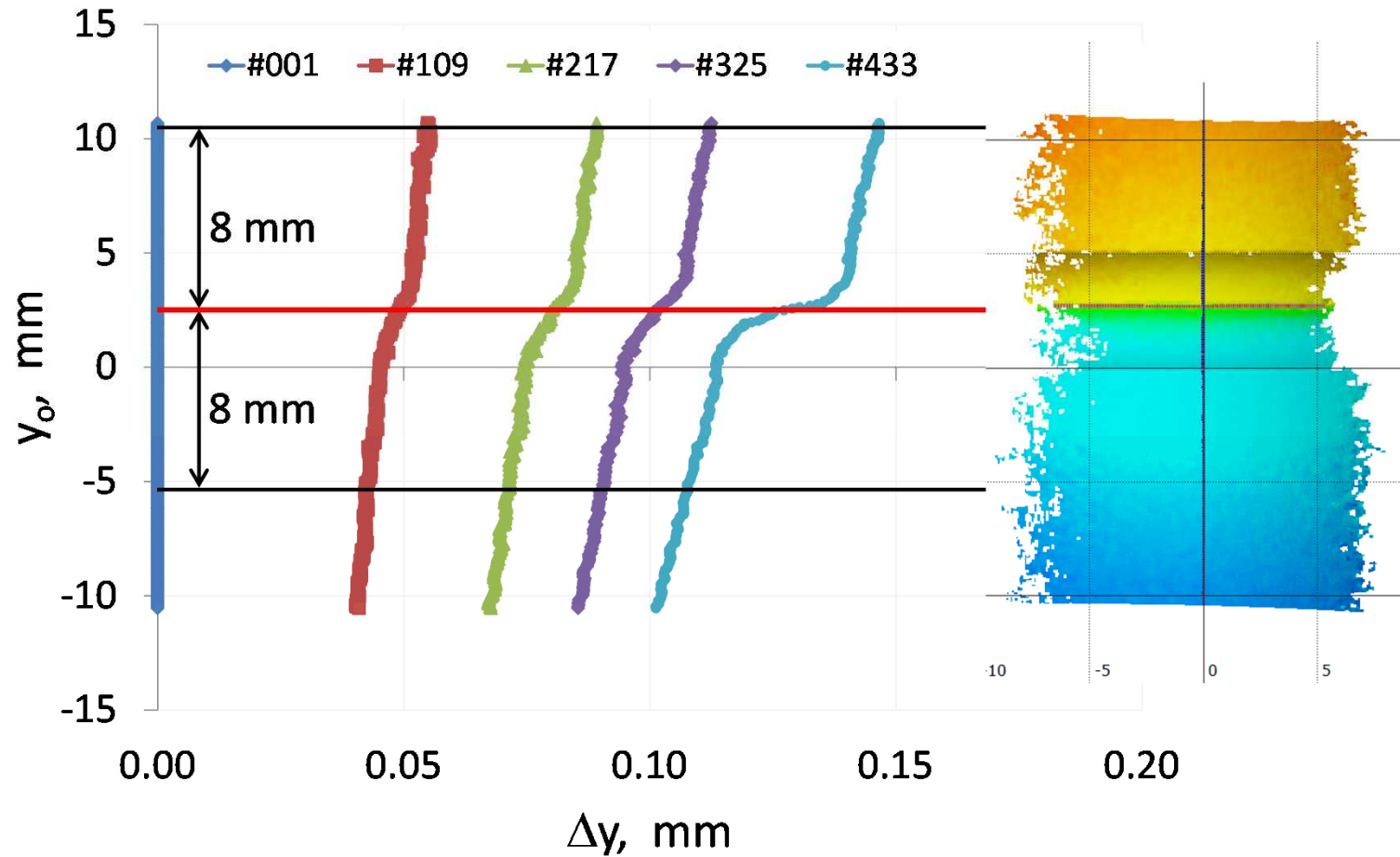
F03
Tension-
Torsion



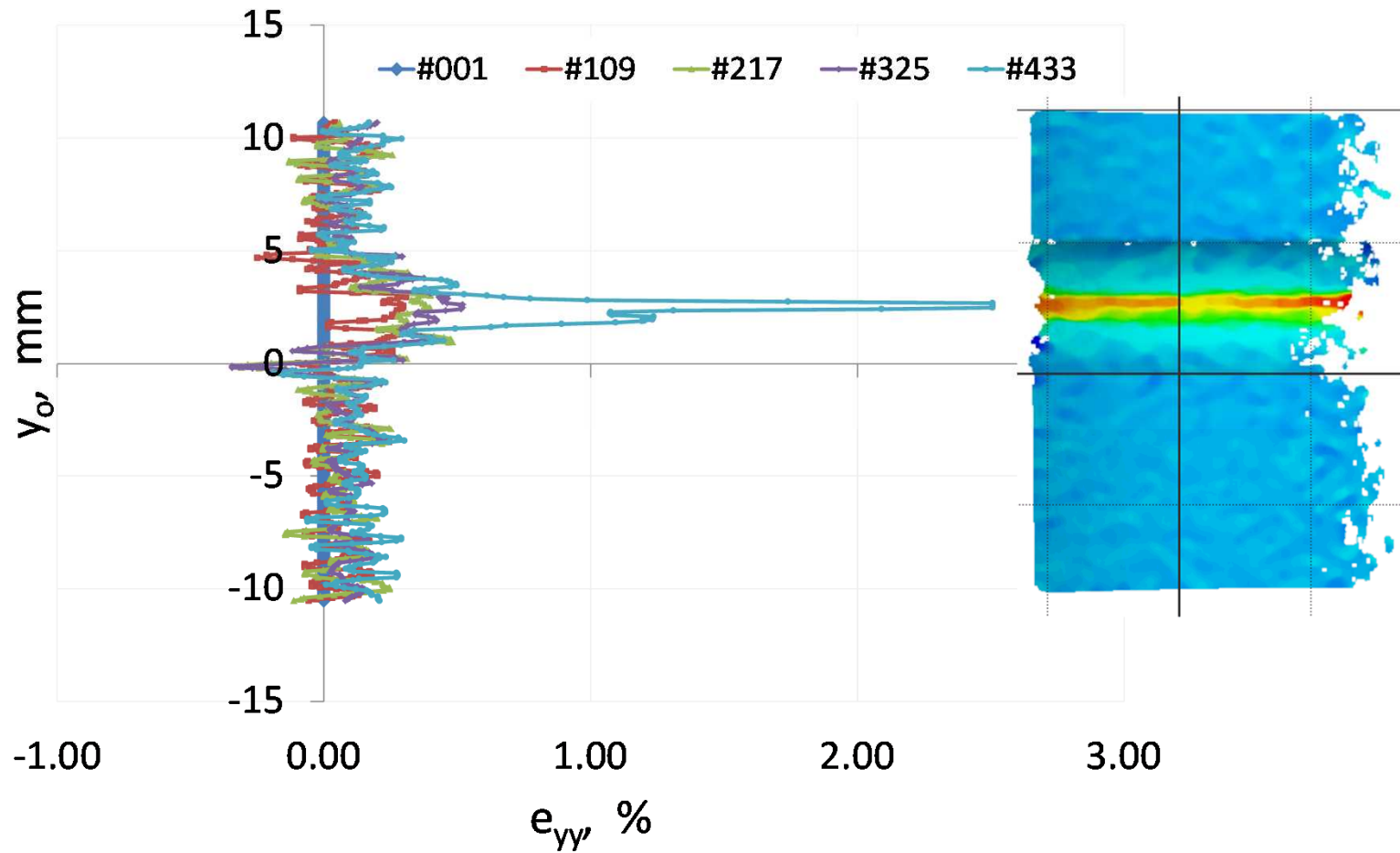
Double Notched Tube Tests



Tube04 Δy Field

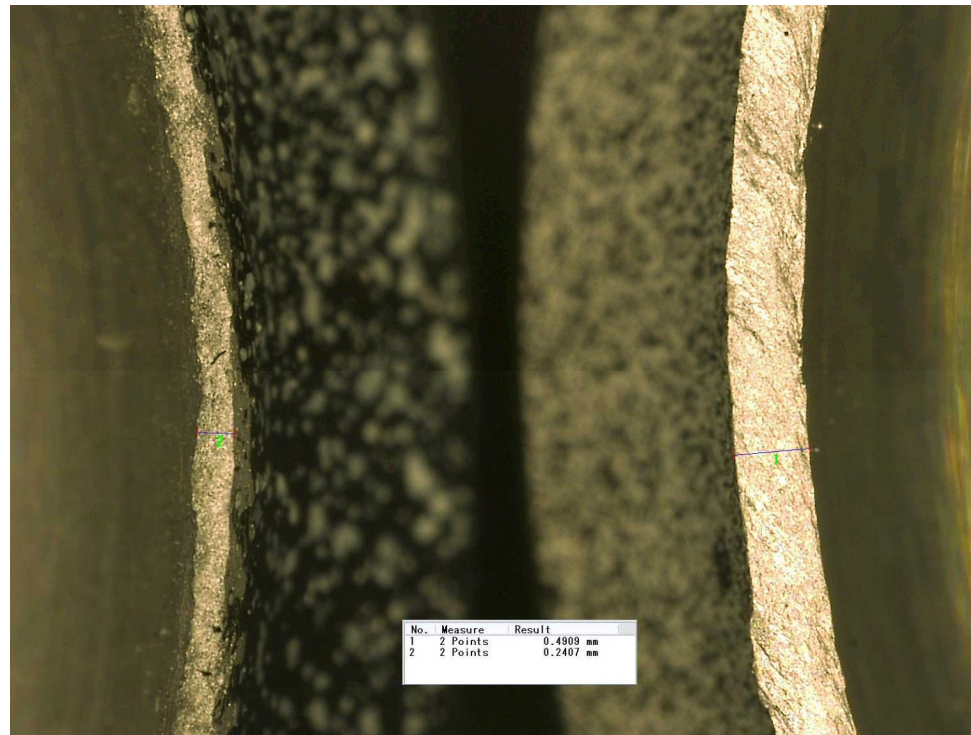


Tube04 ε_y Field



Thickness Reduction

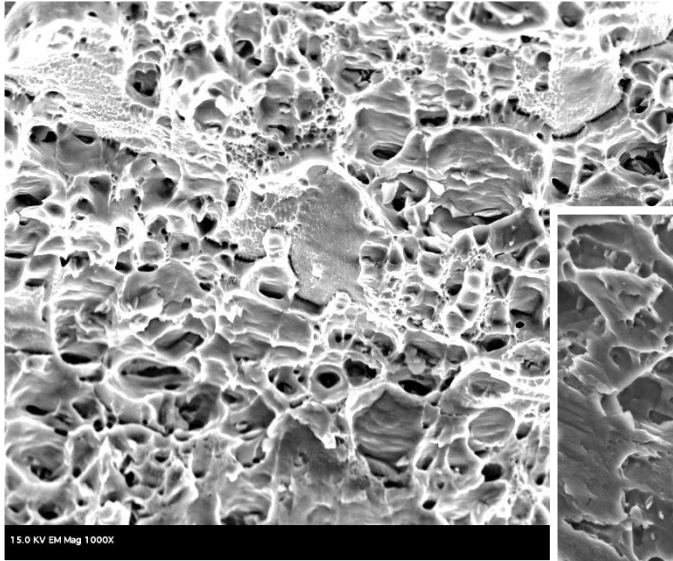
Double notched tubular specimen



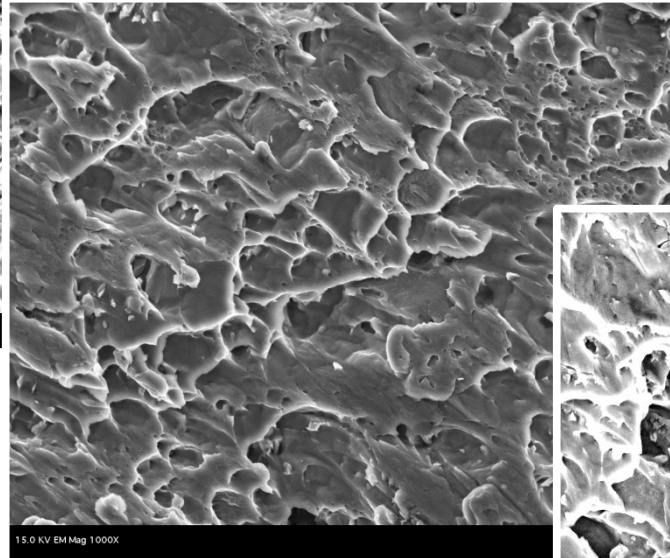
tensile failure

torsion failure

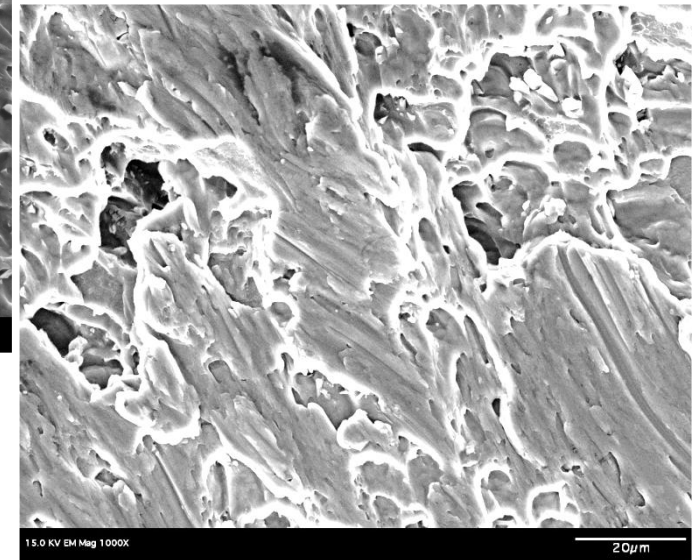
Fractography of Double notched tubular specimens



Tension



Tension-Torsion



Torsion

Summary

- Experimental Issues
 - Time and Location of measurement
 - Physical vs hybrid method
 - Anisotropic behavior
 - Statistical significance (multiple experiments)
- Determining the failure strain at the localized narrow band using DIC method is very challenging
- A set of accurate displacement fields, load-displacement and rotation-torque data is provided for calibrating and validating ductile failure models of Al6061-T651