SAND2019-6260C

Solid Cylindrical Bar Torsion for Characterizing Shear Plastic Deformation and Failure

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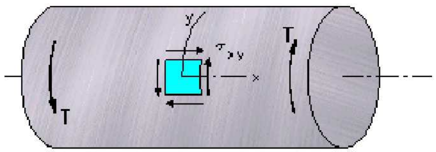
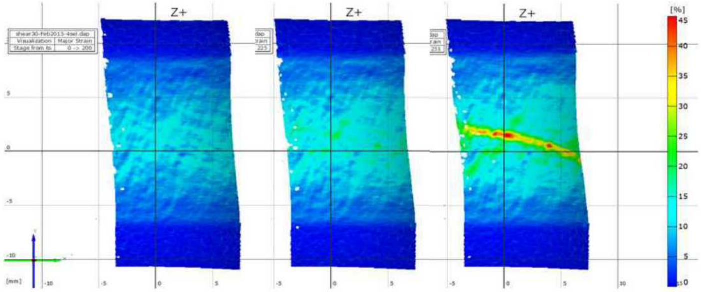
Ductile Shear Deformation and Failure Experiments

Torsion

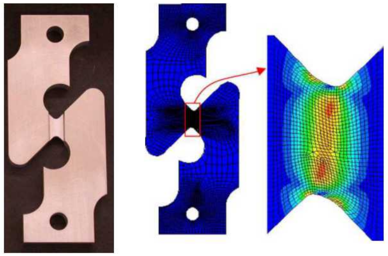
- Thin wall tube
- Solid or thick wall cylinder

Others (Shear Dominated)

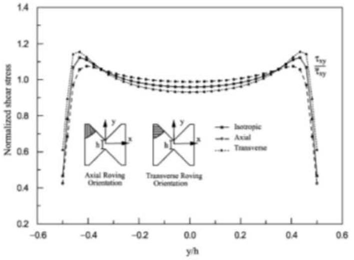




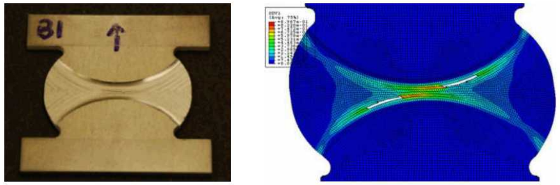
Lu, W. and Jin, H., 2014



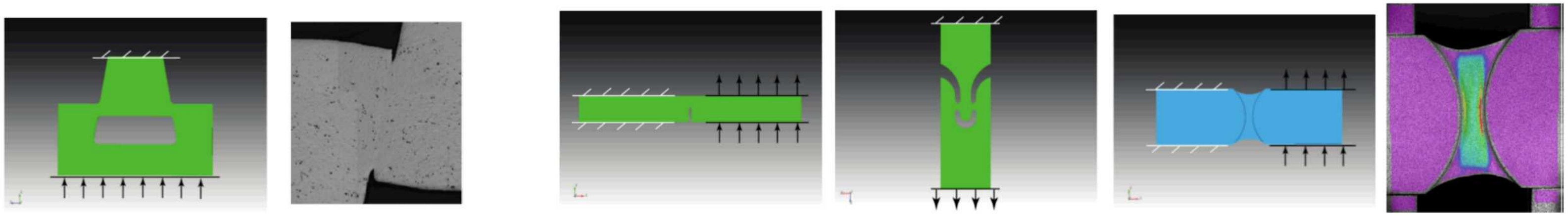
Bao, Y., and Wierzbicki, T., 2004



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



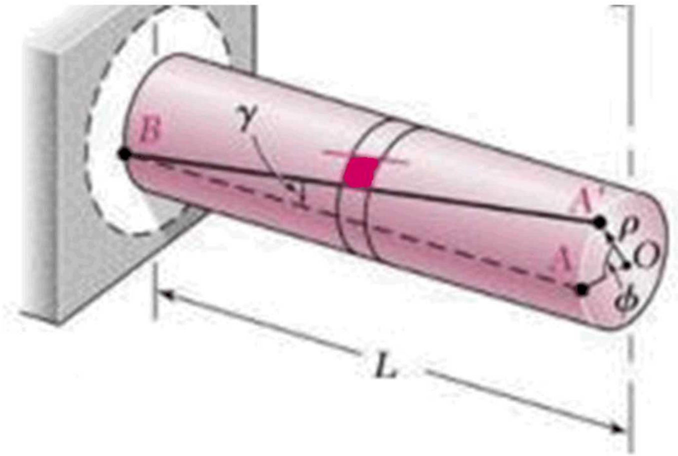
Beese, A. M., Luo, M., Li, Y., Bai, Y., and Wierzbicki, T., 2010



Edmundo Corona et al., SAND2016-9285R, SAND2016-7972C

Nadai's Solution

1. Plane sections remain plane
2. All radii remain straight
3. No change in axial length
4. No change in radius
5. Material is isotropic



- Strain $\gamma_o = r_o\omega, \;\; \omega = \frac{d\phi}{dz}$
- Stress
  - Thin wall tube

$$\tau_o = \frac{Tr_o}{I_z}, \;\; I_z = \frac{\pi {r_o}^4}{2}\left(1 - \frac{{r_i}^4}{{r_o}^4}\right)$$

  - Solid Cylinder

$$\tau_o = \frac{1}{2\pi {r_o}^3}\left(\omega\frac{dT}{d\omega} + 3T\right)$$

Wu’s Method

1. Plane sections remain plane
2. All radii remain straight
3. Change in axial length, second-order strain effect
4. Change in radius, second-order strain effect
5. Material is transversely isotropic

Wu’s solution for large torsion adding axial elongation and radius change of cylinder:

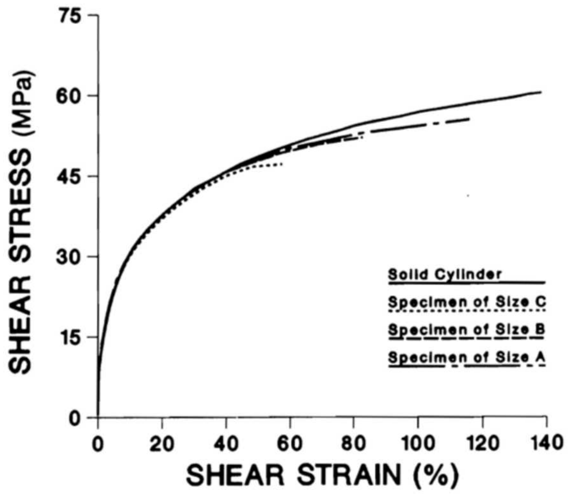
- Strain $\gamma_t = r\omega = r_o(1 + e_x)\omega$

  $$e_x = e_z = -\frac{1}{2}e_y$$

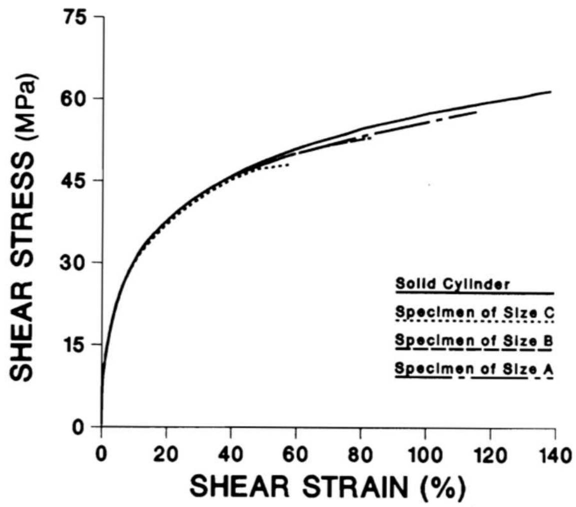
- Stress
  - Solid Cylinder

$$\tau_t = \frac{1}{2\pi {r_o}^3}\left(\omega\frac{dT}{d\omega} + 3T\right)\left(\frac{1}{1 - \frac{1}{2}\left(3e_y + \omega\frac{de_y}{d\omega}\right)}\right)$$

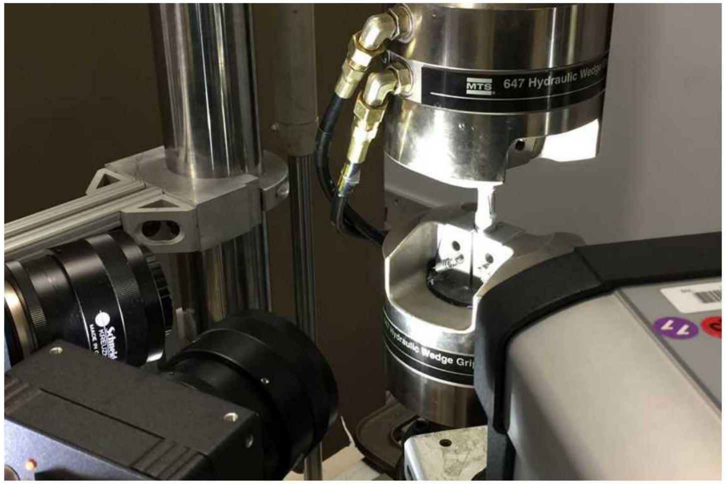
Nadai’s method

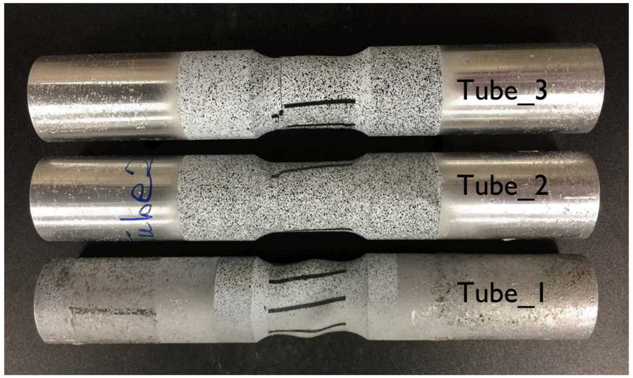


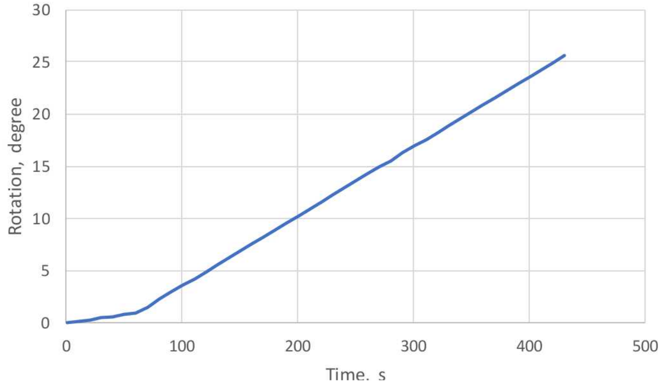
Wu’s method

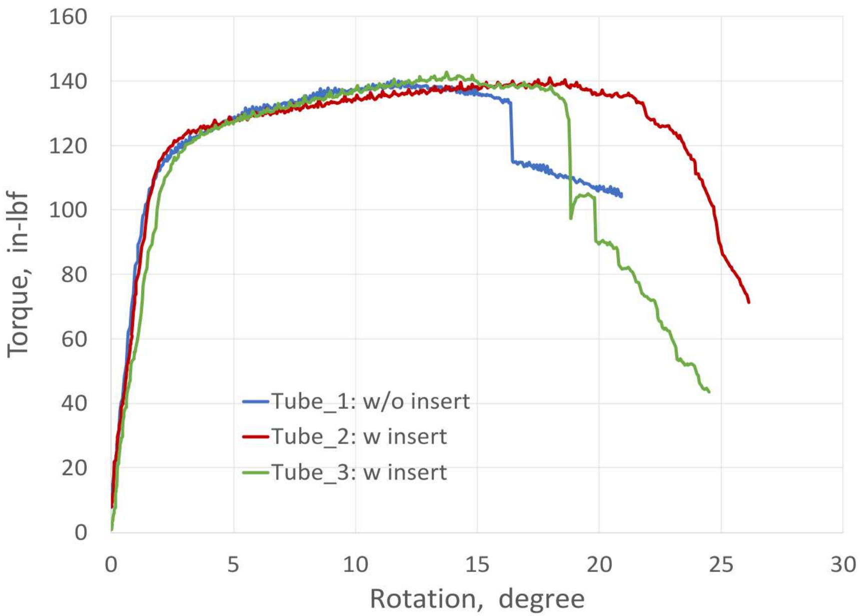


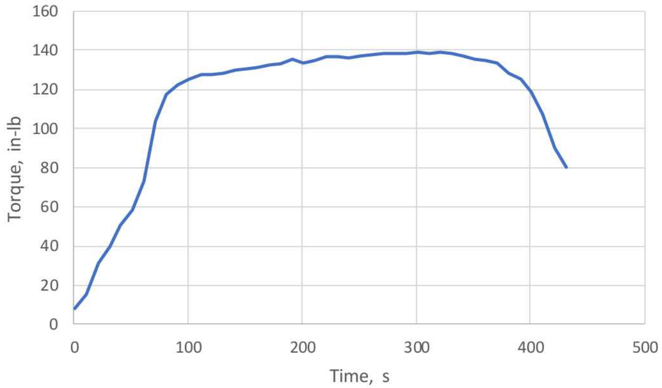
Torsion of Thin Wall Tubes



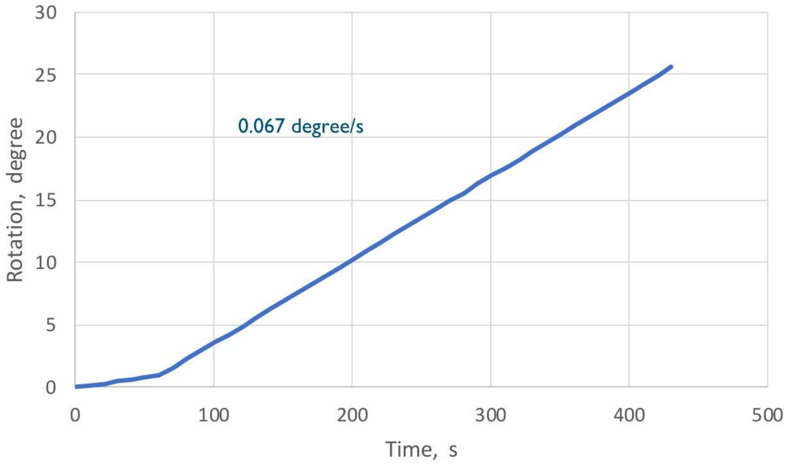


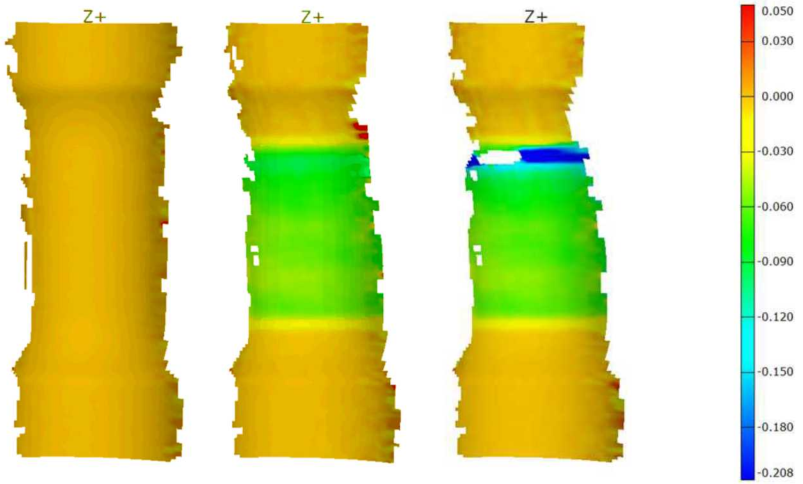




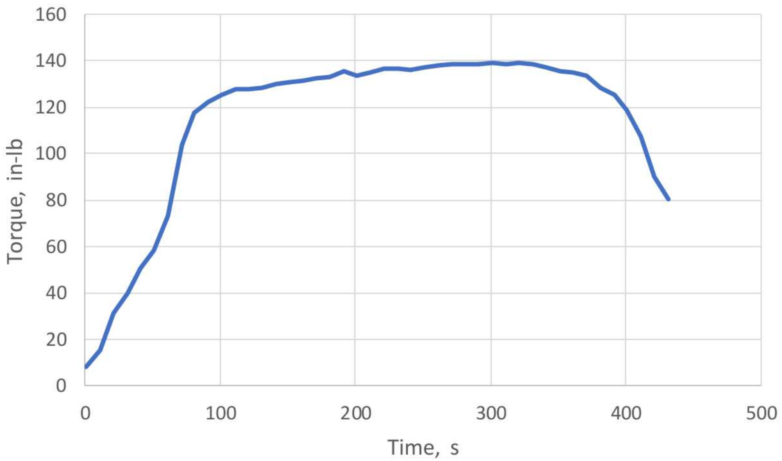


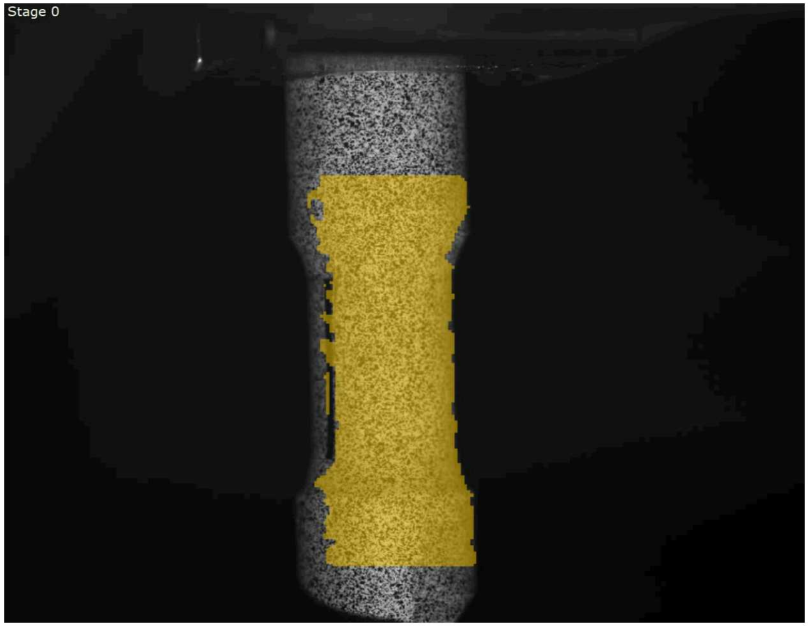
Tube_2 Experiment





t = 10 s   300 s   330 s





Literature on Solid or Thick Wall Cylinder

(1950) A Nadai, Theory of Flow and Fracture of Solids, McGraw-Hill Book Company

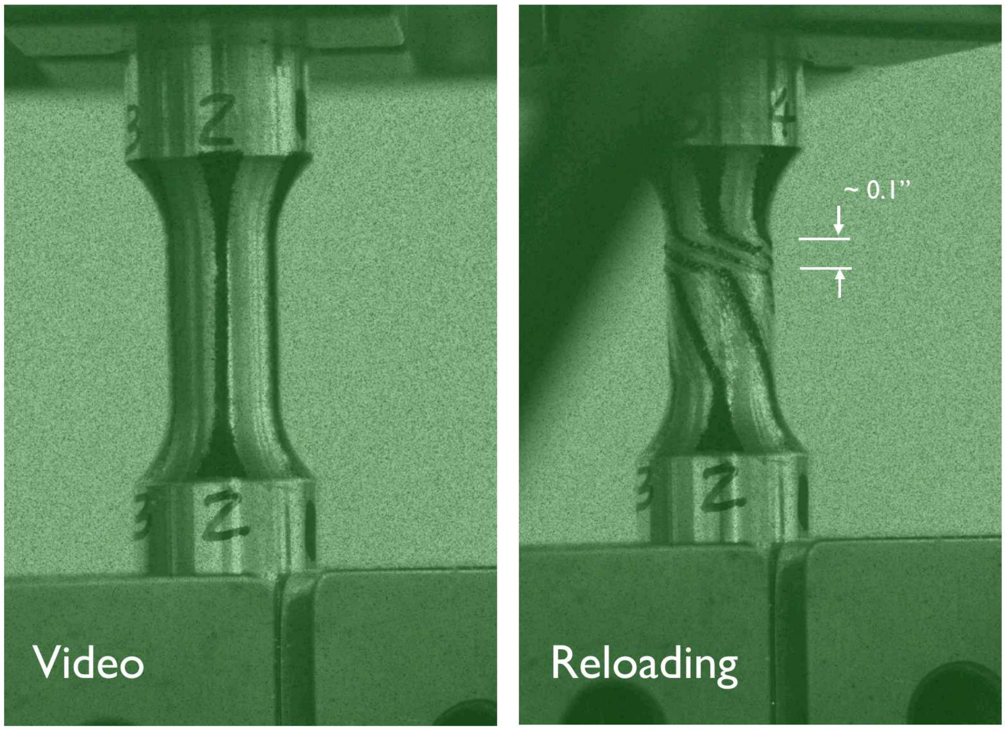
(1991) Richard E Lyon, "Shear Strength of a Ductile Material from Torsion of Solid Cylinders," *Journal of Testing and Evaluation*, JTEVA, Vol. 19, No. 3, pp. 240-243

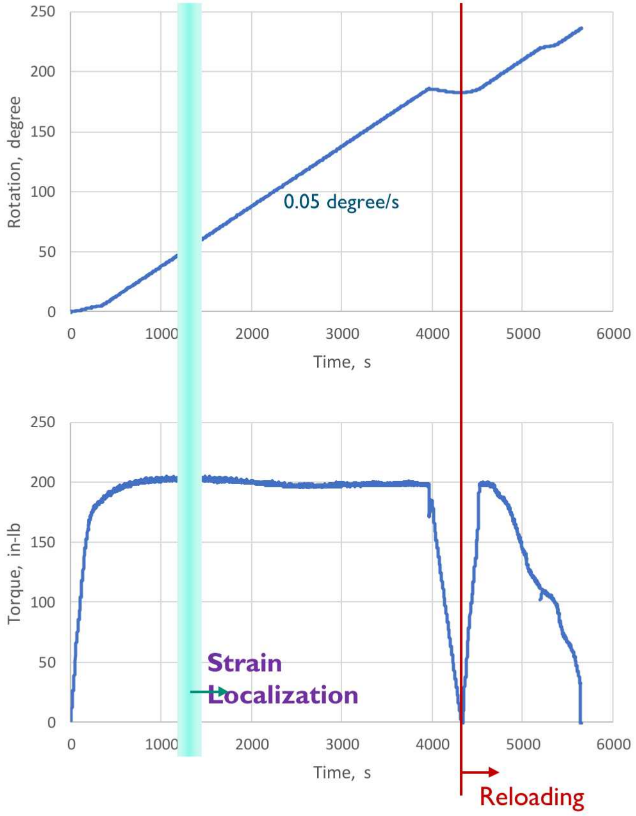
(1992) Han C. Wu, Zhiyou Xu and Paul Wang, "The Shear Stress-Strain Curve Determination from Torsion Test in the Large Strain Range," *Journal of Testing and Evaluation*, JTEVA, Vol. 20, No. 6, pp. 396-402

(2011) Cassandra M. Kingsbury, Preston A. May, Douglas A. Davis, Scott R. White, Jeffrey S. Moore and Nancy R. Sottos, "Shear activation of mechanophore-crosslinked polymers," *Journal Materials Chemistry*, 21, 8381-8388

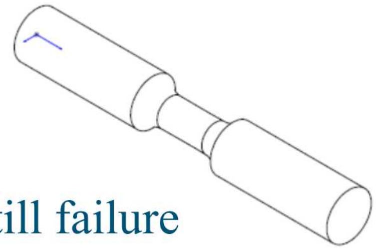
(2014) Jessica Papasidero, Véronique Doquet, Sebastien Lepeer, "Multiscale investigation of ductile fracture mechanisms and strain localization under shear loading in 2024-T351 aluminum alloy and 36NiCrMo16 steel," *Materials Science & Engineering* A, 610, 203–219

Torsion of Specimen Solid_1

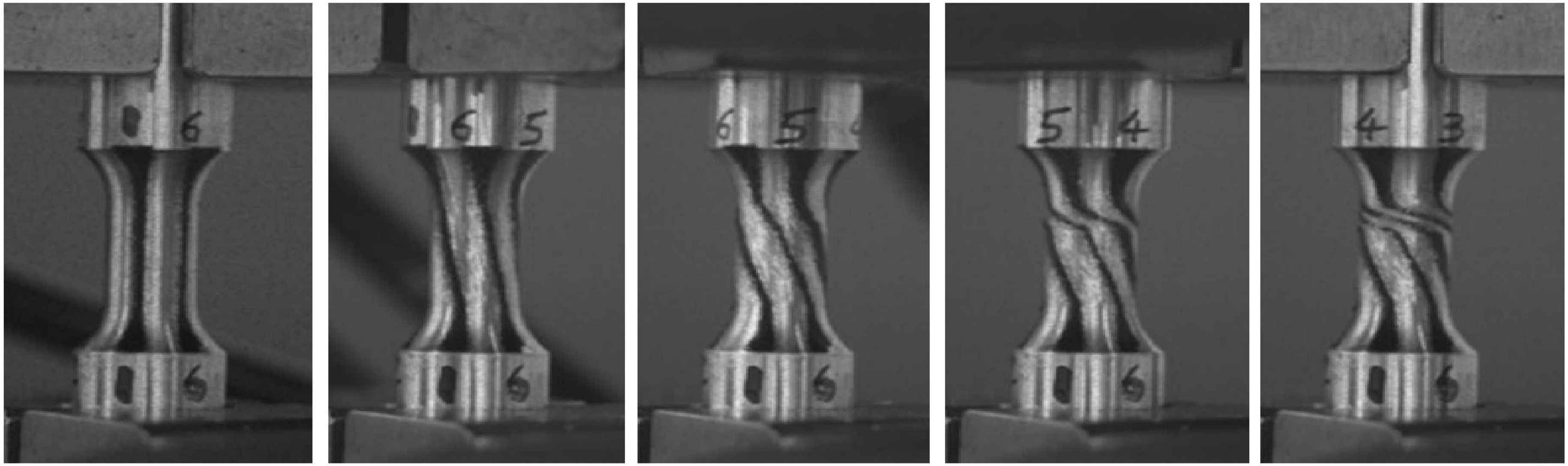




Deformation Images



Deformation images of specimen Solid_Torsion – Stable large shear till failure

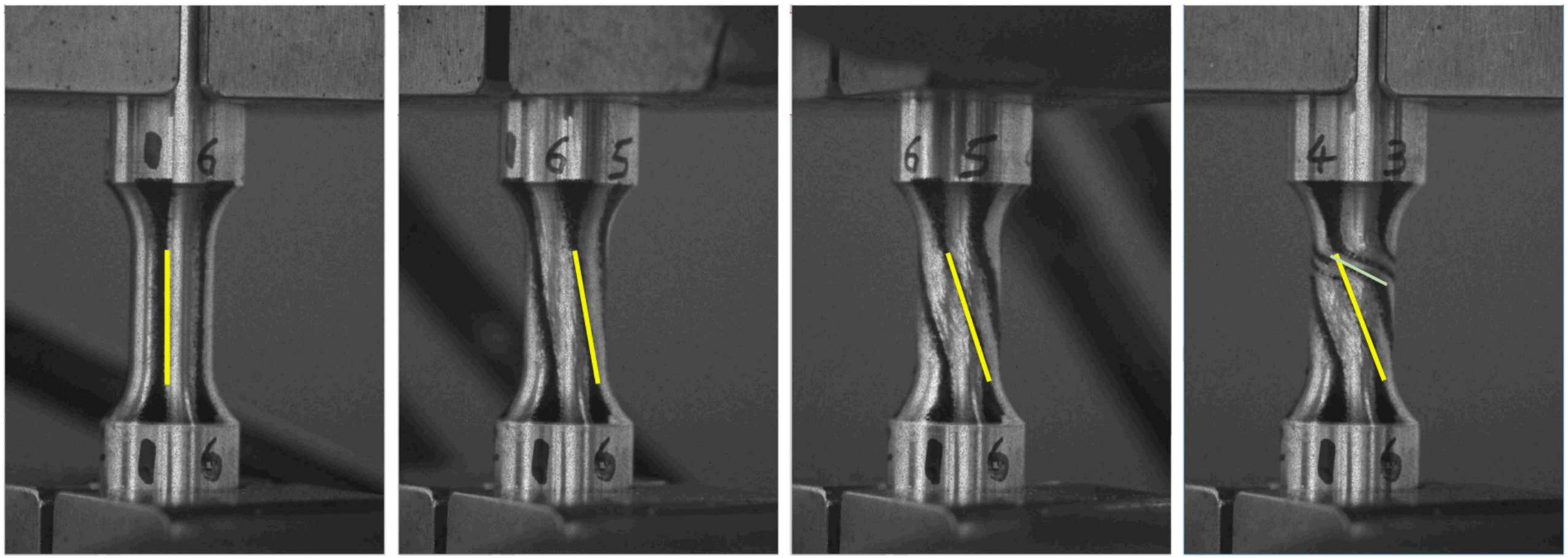


Stage 0, 0 degree   Stage 211, 40 degree   Stage 371, 80 degree   Stage 532, 120 degree   Stage 850, 180 degree

(1) At $\Omega=40^o$, inclined straight lines within the gage section indicated uniform deformation.
(2) Lines were kinked at upper part of the gage section at $\Omega=80^o$, which denoted surface deformation was not uniform and localization had occurred. The transition from uniform to localization was gradual; it started approximately at $\Omega=60^o$.
(3) For further rotation, the deformation was evidently concentrated at the localized zone as shown in $\Omega=120^o$ and 180^o images.
(4) Finally, the specimen cracked within the localized zone and separated the cracked cross-section. The system stroke showed a maximum 0.013 mm axial displacement. It corresponds to about 0.1% axial strain if all elongation is from the gage section.

Shear Angle Estimation

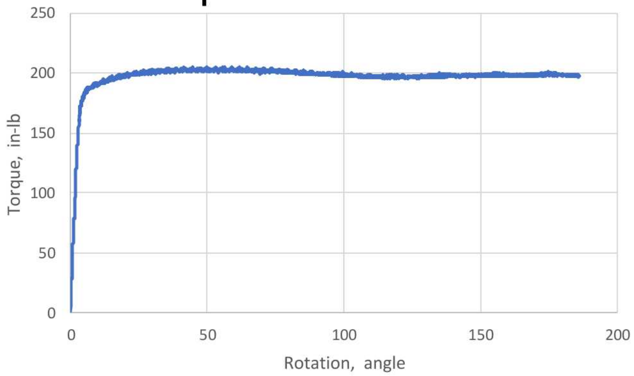
Right Camera



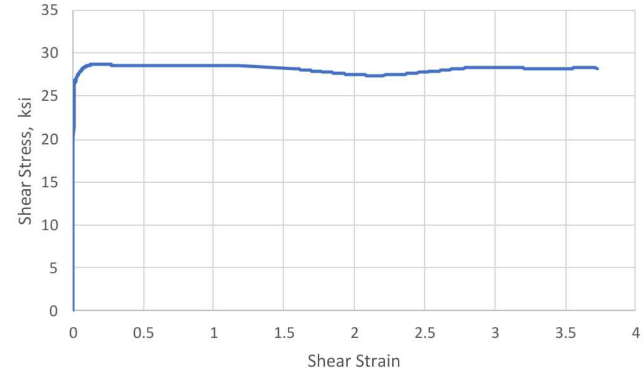
	$\alpha = -10^o$	$\alpha = -18^o$	$\alpha = -22^o$
			$\alpha = -64^o$
$\gamma = \tan \alpha$	$\gamma = 0.176$	$\gamma = 0.325$	$\gamma = 0.404$
			$\gamma = 2.05$

Estimated Shear Stress-Strain Curve

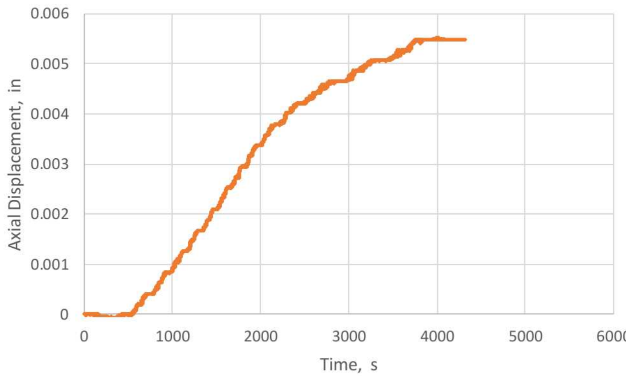
Experimental Data

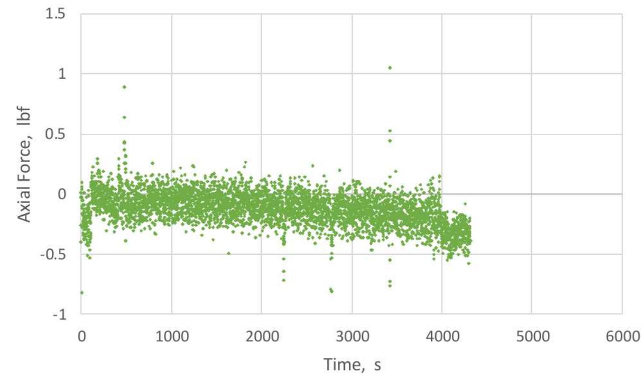


Estimated $\tau - \gamma$ Curve, Nadai's Method

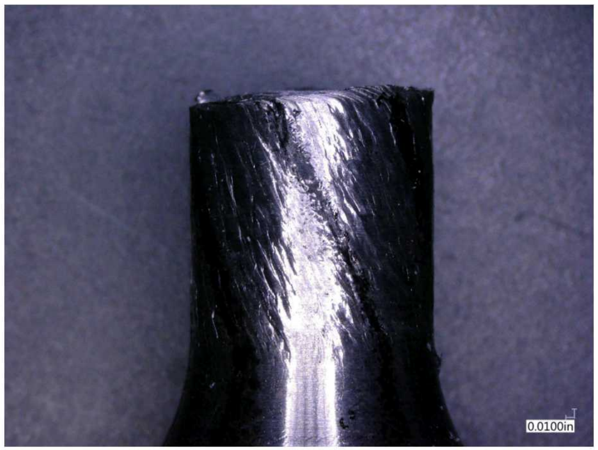


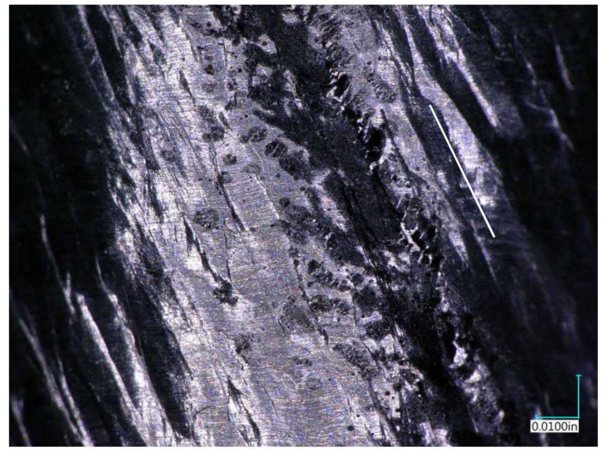
- Swift effect - Axial elongation under torsion



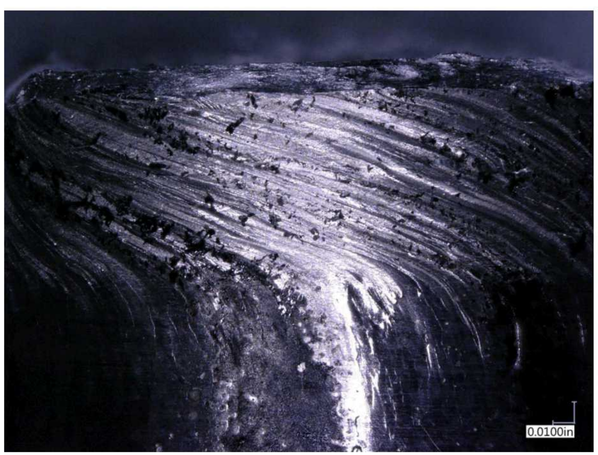


Shear Strain Measurement





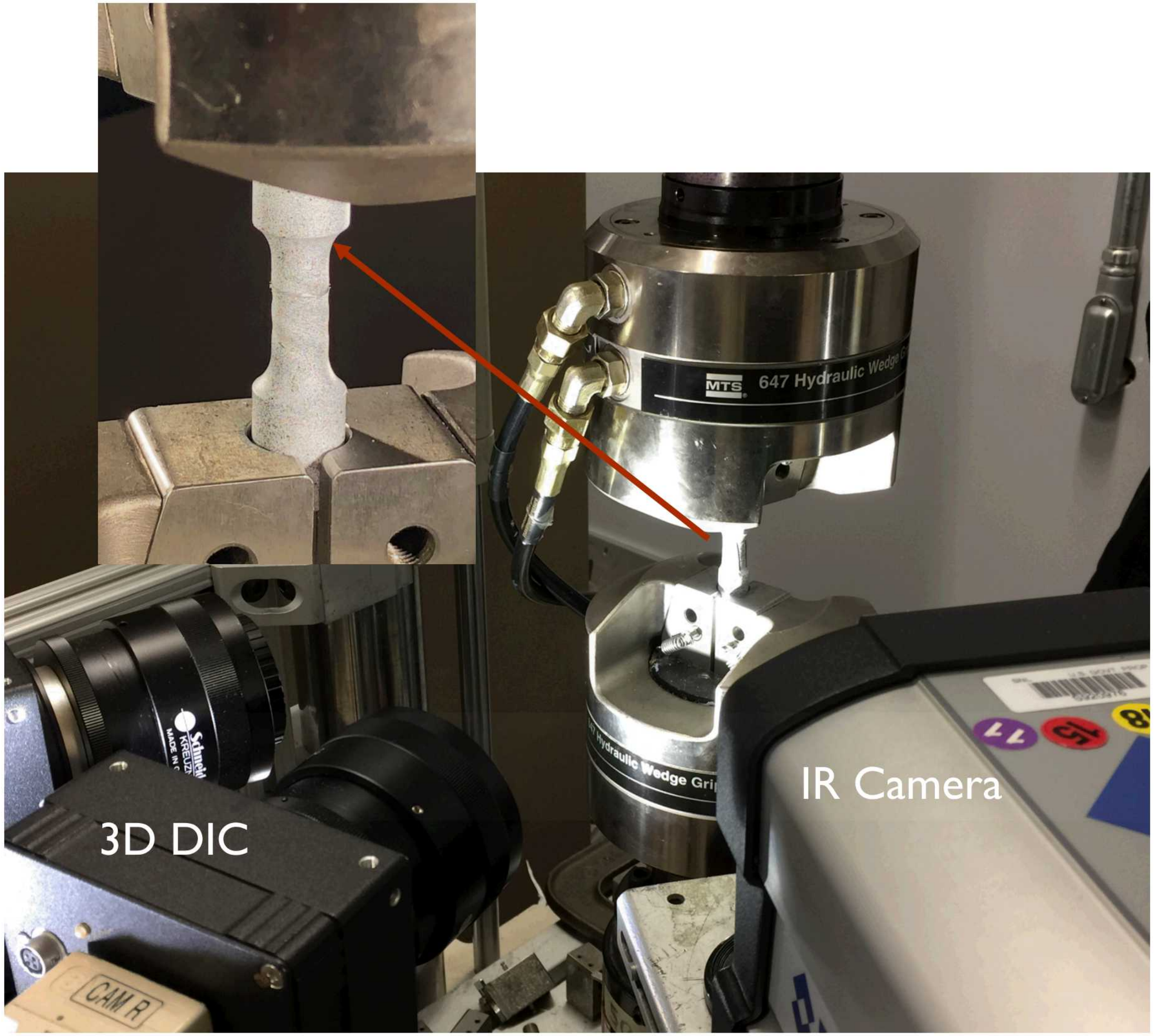
$\alpha = -26°$ $\gamma = 0.488$



$\alpha = -80°$ $\gamma = 5.67$

$\alpha = -73°$ $\gamma = 3.27$

Experimental Setup with 3D-DIC



1. MTS Mini Bionix AT Testing System
2. GOM ARAMIS System (3D DIC)
3. FLIR SC6000 Infrared Camera

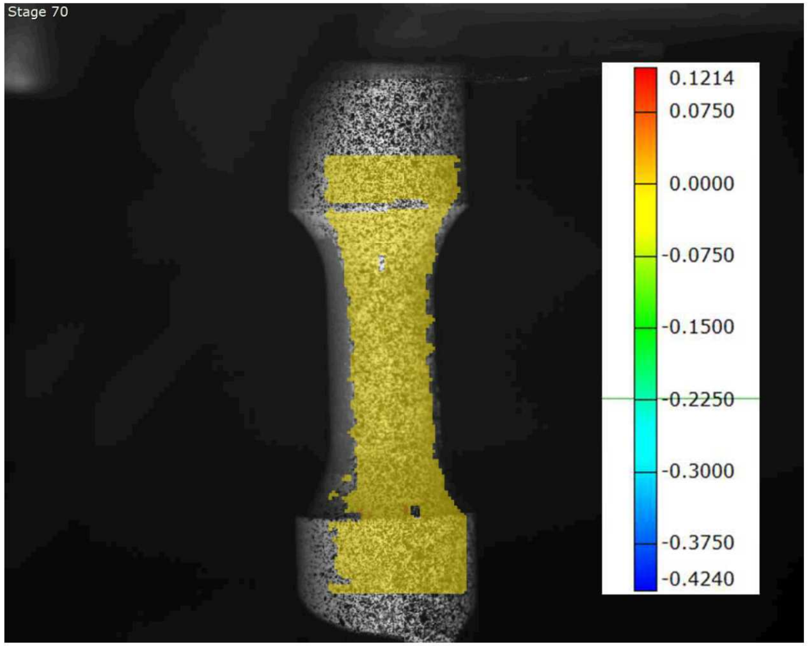
- Control parameter
  - Axial: Force
  - Torsion: Rotation

- Specimen with DIC pattern

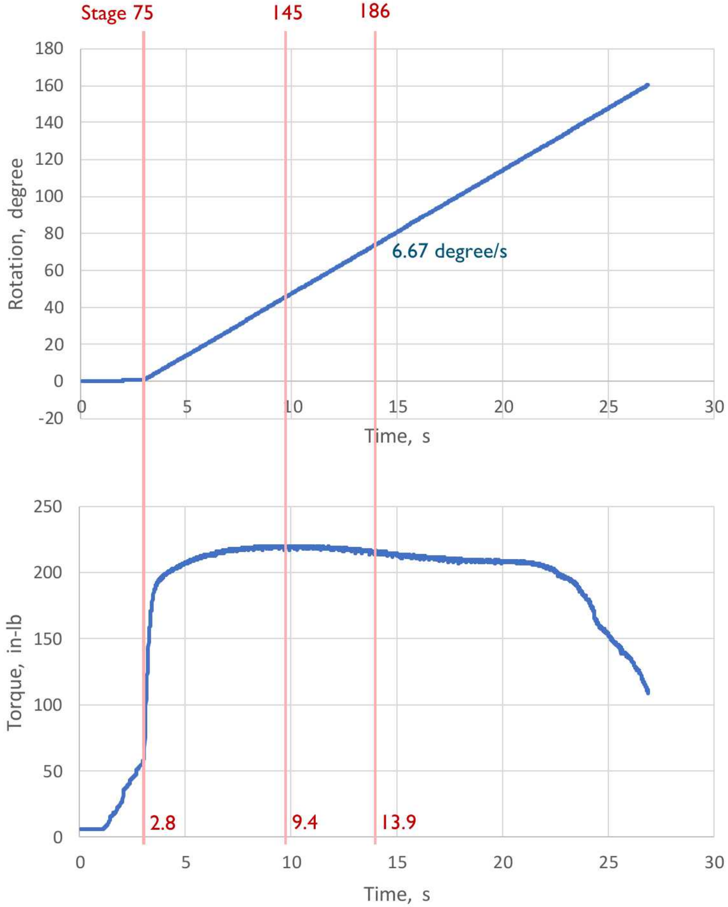
Shear Strain of Solid_3 Torsion Experiment

Video: Solid_3 ε_{xy}

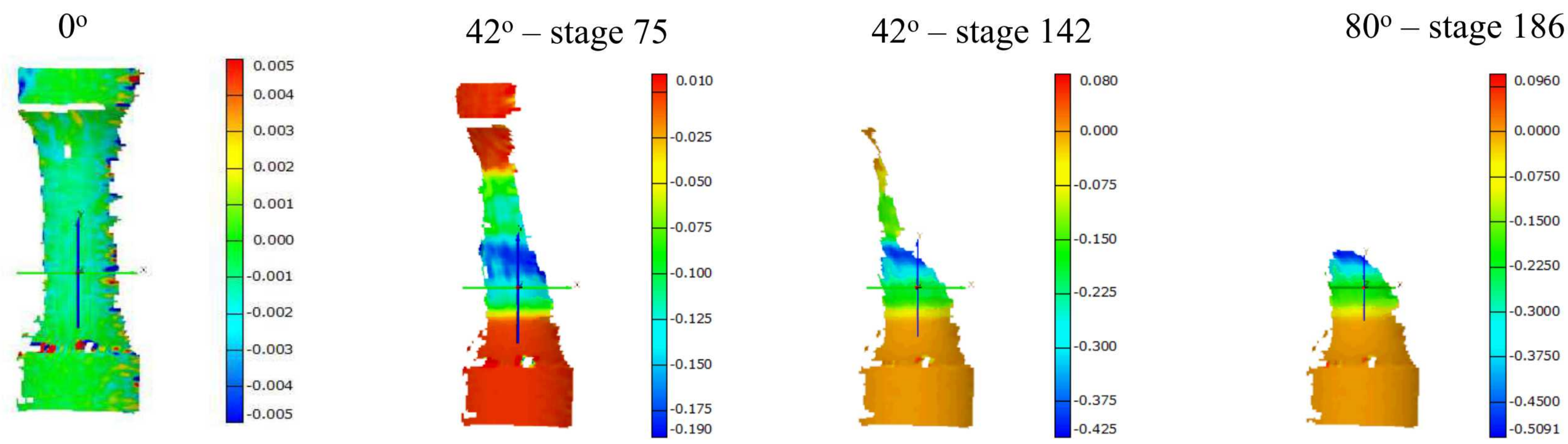
Actual testing time: ~ 25 s



6.67 degree/s, DIC, IR



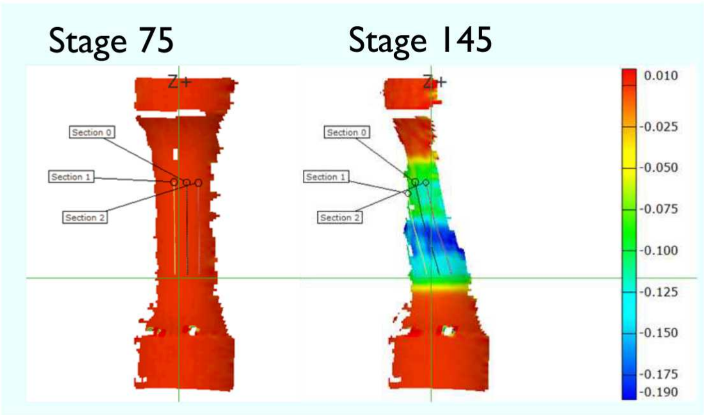
Solid_3 Shear Strain e_{xy} Distribution at Different Stages

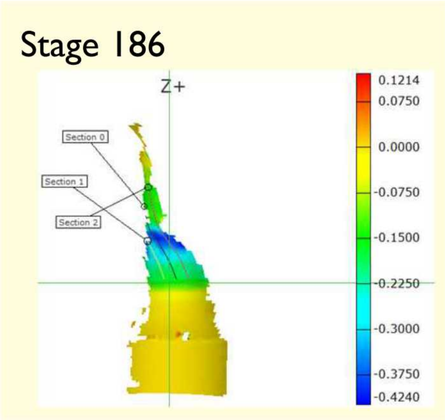


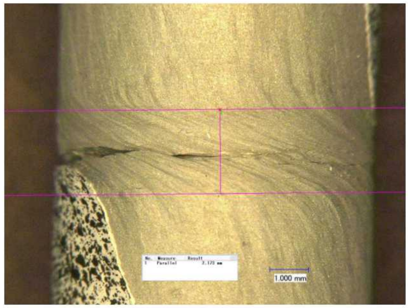
(1) Full-field shear strain $\mathbf{e}_{xy}$ measurement with 3D-DIC system;

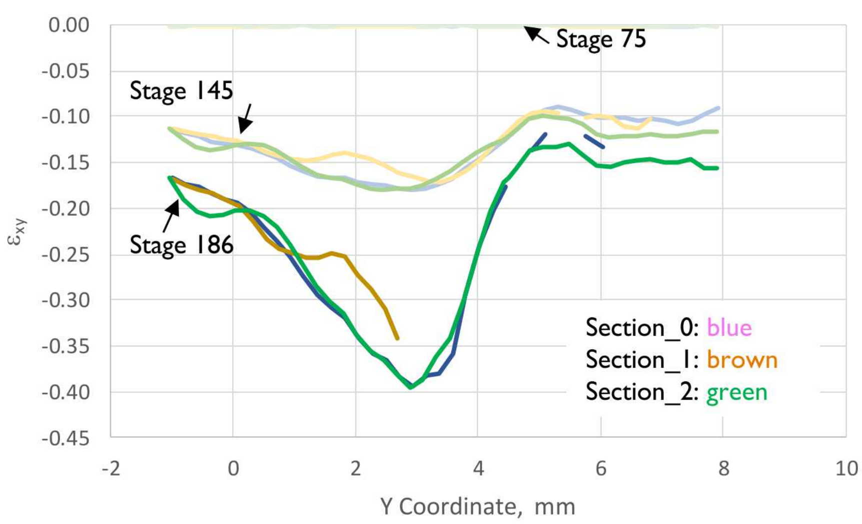
(2) Due to large rotation the area utilized for DIC measurements, or the measurable area, became smaller and smaller. Since a pair of cameras only covered a portion of the cylinder surface, part of the DIC pattern gradually rotated out of the camera view; and those speckles newly rotated into the view did not have a reference state.

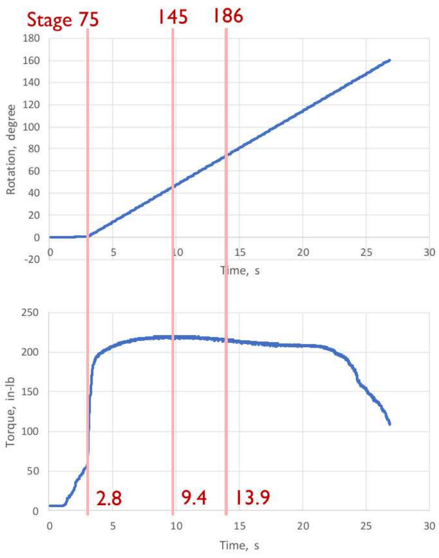
Solid_3 Shear Strain e_{xy} Distribution



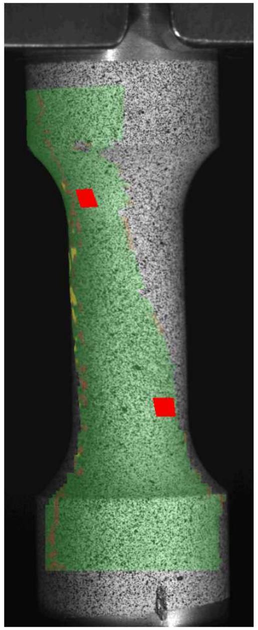


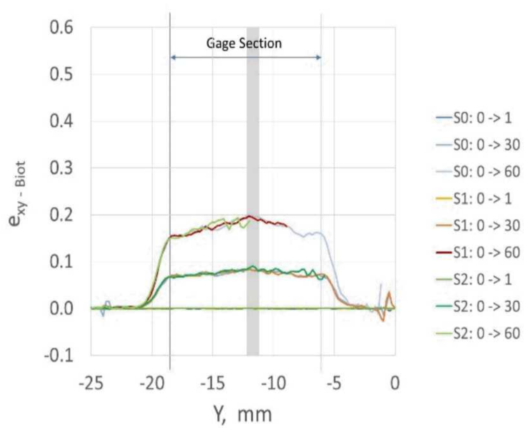




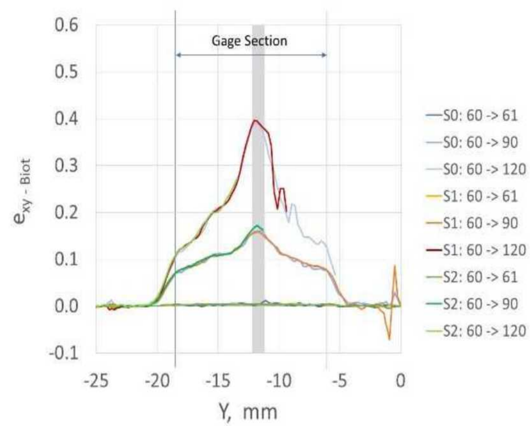


Shear Strain e_{xy} from Incremental DIC Analysis

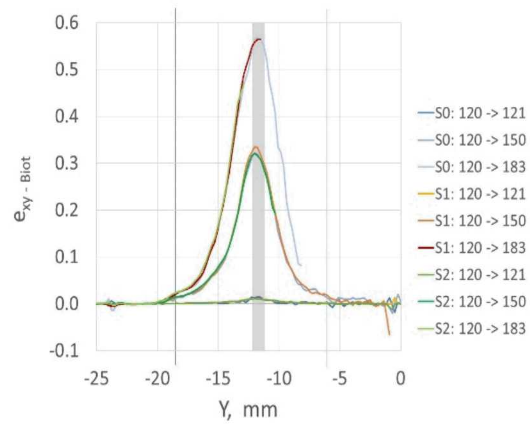




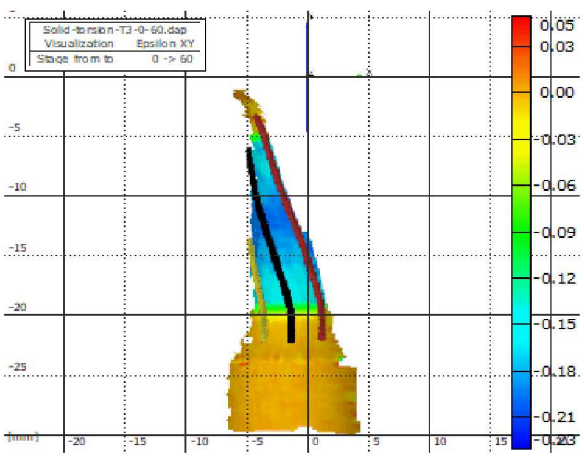
(a) 0 -> 60



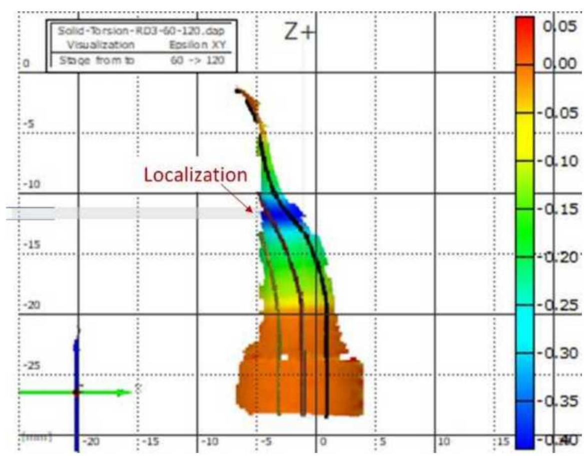
(b) 60 -> 120



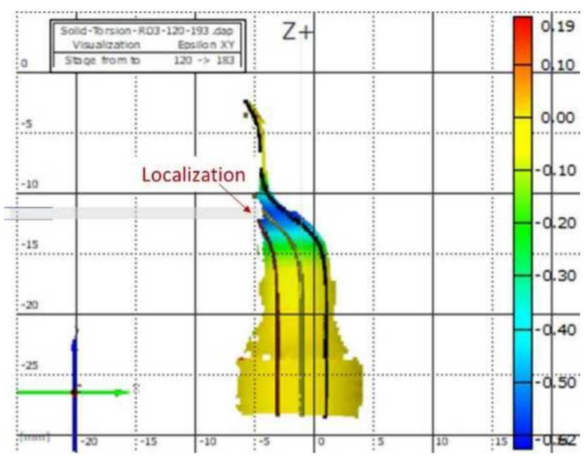
(c) 120 -> 183



(d) Stage 0 -> 60



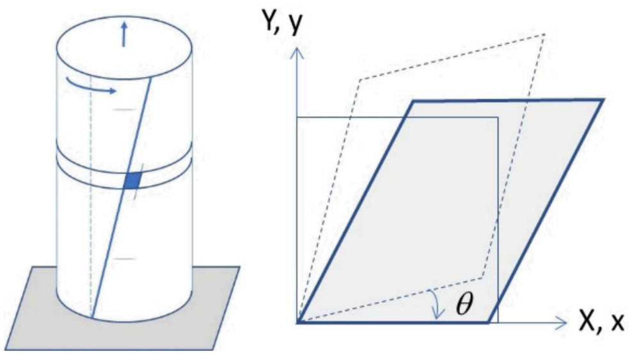
(e) Stage 60 -> 120



(f) stage120 -> 183

Deformation Gradient and Engineering Shear Strain e_{xy}

Deformation gradient tensor:



$$F = \begin{bmatrix} p & k & 0 \\ 0 & q & 0 \\ 0 & 0 & s \end{bmatrix} = \begin{bmatrix} 1+e_x & \gamma & 0 \\ 0 & 1+e_y & 0 \\ 0 & 0 & 1+e_z \end{bmatrix}$$

$$F = RU$$

Where R is the rotation tensor

U is the right stretch tensor

$$R = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad U = \begin{bmatrix} pcos\theta & psin\theta & 0 \\ psin\theta & ksin\theta + qcos\theta & 0 \\ 0 & 0 & s \end{bmatrix}$$

Biot strain $\overline{U}$ is defined from the right stretch tensor as follows:

$$\overline{U} = \begin{bmatrix} e_{x-B} & e_{xy-B} & 0 \\ e_{xy-B} & e_{y-B} & 0 \\ 0 & 0 & e_{z-B} \end{bmatrix} = U - I$$

- Biot strain is direct output from DIC.
- Deformation gradient can be calculated from Biot strain.

$$p = e_{xy-B}/sin\theta = (e_{x-B} + 1)/cos\theta,$$

$$q = \left(1 + e_{y-B} - e_{xy-B} tan\theta\right)cos\theta, \quad tan\theta = \frac{e_{xy-B}}{e_{x-B}+1}$$

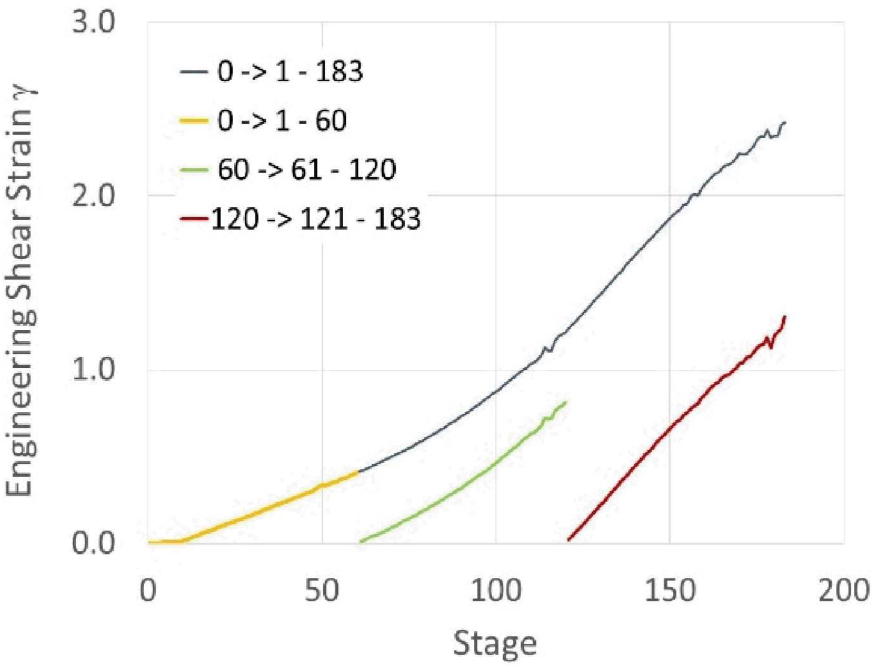
Mapping Engineering Shear Strain e_{xy} back to the Original Reference

Calculating shear strain from deformation tensor

$$\boldsymbol{F_i} = \boldsymbol{F_i}'\boldsymbol{F_I} = \begin{bmatrix} p_i' & k_i' & 0 \\ 0 & q_i' & 0 \\ 0 & 0 & s_i' \end{bmatrix} \begin{bmatrix} p_I & k_I & 0 \\ 0 & q_I & 0 \\ 0 & 0 & s_I \end{bmatrix}$$

$$\boldsymbol{F_i} = \boldsymbol{F_i}'\boldsymbol{F_{60}}, \text{ for } 60 < \mathrm{i} \leq 120$$

$$\boldsymbol{F_i} = \boldsymbol{F_i}'\boldsymbol{F_{120}}, \text{ for i} > 120.$$



Three "incremental" shear strain curves 0 -> 1 – 60, 60 -> 61 – 120 and 120 -> 121 – 183 are based on three distinct references. After transformation and composing, curve 0 -> 1-183 is the shear strain history of the specimen.

Shear Stress~ Shear Strain

Calculating Shear Stress

$$\tau = \frac{1}{2\pi {r_o}^2}\left(\omega \frac{dT}{d\omega} + 3T\right)$$

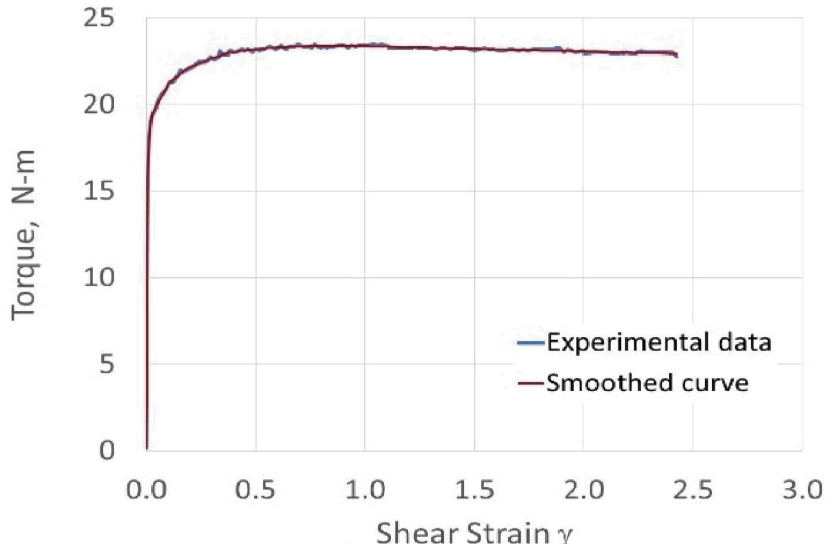
The radius r is constant for circular cylinder during torsion, so $\gamma = r_o\omega$

$\omega \frac{dT}{d\omega}$ is replaced by $\gamma \frac{dT}{d\gamma}$

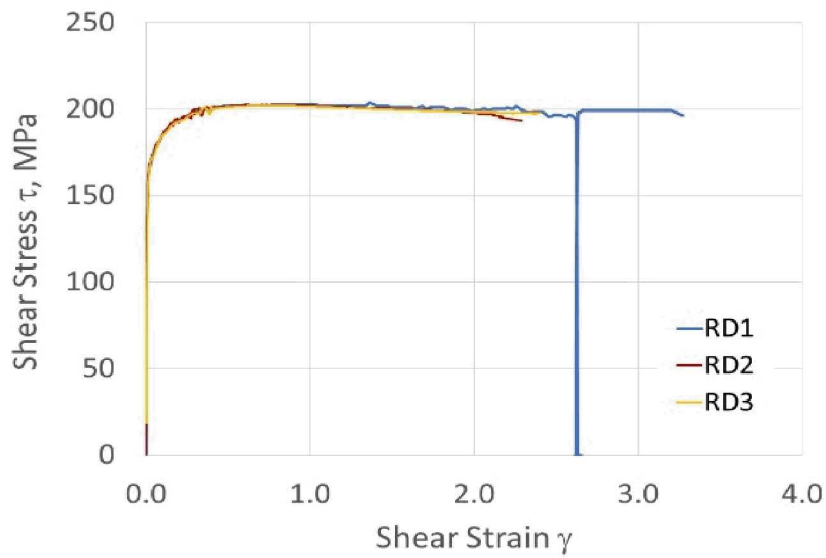
$$\tau = \frac{1}{2\pi {r_o}^2}\left(\gamma \frac{dT}{d\gamma} + 3T\right)$$

$\frac{dT}{d\gamma}$ This derivative can be calculated by differentiating the polynomial fitting function of T-γ curve.

The engineering shear stress-strain curve of the specimen is determined, shown on the right. Three specimens exhibit consistent stress-strain behavior.



Torque – engineering shear strain T-γ curve of TOR_RD_3



Shear stress vs shear strain for Al

Summary

- A new solid bar torsion test with 3D-DIC is developed.
- Several reference configurations need to be employed due to large twist of the cylindrical specimen. Total strain is calculated from incremental deformation data via repeated exploitation of the multiplicative decomposition of the deformation gradient.
- Shear strain of Al 6061-T6 is experimentally measured on the order of 2–3. Localized zone starts to develop at 60% shear strain, and most plastic deformation is developed in the localized zone. Substantial and repeatable strains are achieved up to failure.
- Surface stress evaluation is based on the results of Nadai and Wu. Pure shear stress-strain curves of engineering materials Al6061-T6 are obtained and are consistent among different specimens.
- Solid bar torsion provides stable shear deformation and uniform shear stress on the surface of the gage section. Various specimen size could be used depending on torque and DIC capacities.