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# Solid Cvlindrical Bar Torsion for Characterizing Shear Plastic Deformation and Failure

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## ABSTRACT

The method of thin-wall tube torsion to characterize metal's shear response is well-known. Unfortunately, the thin wall tube specimen tends to buckle before reaching large shear deformation and failure. An alternative technique, which has rarely been considered, is Nadai's surface stress method [1]. It derives shear stress-strain curve from the torque-twist relationship of a solid bar. Although the analysis is more complex due to nonlinear shear stress distribution along the radius, the deformation is stable through large shear deformation to failure.

Solid bar torsion experiments were conducted to study large shear deformation of Al6061-T6. Two experiments were described in this study. Since few tests were available in the literature, these experiments were to explore the large deformation behaviors of an engineering alloy and the application of modern measurement techniques, such as 3D DIC method, under torsion. Results show during twisting, the surface shear strain distribution was uniform initially and then localized on a narrow band; eventually, the specimen was cracked and failed within the band. Depending on the specimen size, the twist could be greater than 360 degrees. Details are discussed.

**Keywords:** ductile failure, large deformation, digital image correlation, shear stress-strain curve, torsion

## INTRODUCTION

Numerous examples have shown that ductile failure of metals is not fully understood. Especially at low triaxial stress state, i.e. shear dominated failure, experimental data are little and inconsistent. Also, stress-strain curves used in computational or hybrid studies are based on tensile data. The shear stress-strain curve and pure shear failure of a metal have hardly been investigated experimentally.

It is well known that large shear deformation and failure are important pieces of information needed in characterizing and modeling engineering metals. Available experimental data in the area, however, are surprisingly limited. Large strain torsion tests and related problems were discussed in detail by Wu et al [2]. The major issue mentioned was the deformation uniformity at the gage section. A well-controlled homogeneous material had to be selected to satisfy the requirement. Little progress has been made since. Motivated by its potential applications, preliminary experiments of solid bar torsion were conducted to observe the deformation and gauge possible challenges and solutions of the test. The first was to explore large deformation torsion qualitatively, focusing on surface deformation uniformity, rotation and torque ranges, etc. In the second experiment, 3D DIC method and IR camera were utilized for quantitative deformation and temperature measurements.

## EXPERIMENT I

The torsion test was performed on a hydraulic axial-torsional testing system. It has the capacities of ±100 mm displacement and ±140$^o$ rotation; the system load cell is rated at ±15 kN (3.3 kips) force and ±170 N-m (1,500 in-lb) torque. A pair of hydraulic grips allow quick installing and releasing specimens.

A Al6061-T6 bar stock was used in this investigation. The specimen geometry is shown in Fig. 1. The gage section dimensions are: 7.62 mm (0.3 in) diameter and 12.7 mm (0.5 in) long. There were six vertical lines painted on the surface of the specimen, which were approximately equally spaced around the circumference. The purpose of these lines was to help visualizing the deformation.

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The test was under biaxial control. The axial control mode was force, which was kept at zero load, $F = 0$ N, throughout the test. At the same time, the torsion went through a loading-unloading cycle. During loading, the control mode was rotation $\Omega$, where the actuator was programmed to rotate 180 degrees, from -90° to 90°, at a constant rate of $\dot{\Omega}$=0.05 degree per second. When loading was done, the torsional control mode was switched to torque $T$ and unloaded to zero torque.

The torque-rotation T-Ω curve of Specimen Solid_Torsion_1 is shown in Fig. 2. The specimen did not fail during the first cycle. After the torque was unloaded to zero at the end of a cycle, the operator manually released the hydraulic grip on the actuator side, returned the actuator to -90° position, regripped specimen, and restarted the program for another loading-unloading cycle. The specimen began to fail at total rotation $\Omega$=194°, i.e. about 14° into the second cycle.

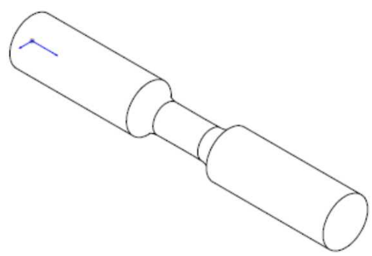


Figure 1: The shape of solid torsion specimen.

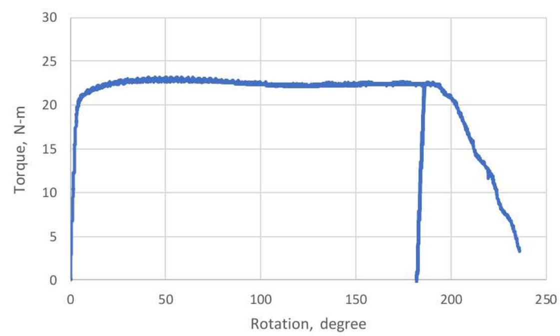
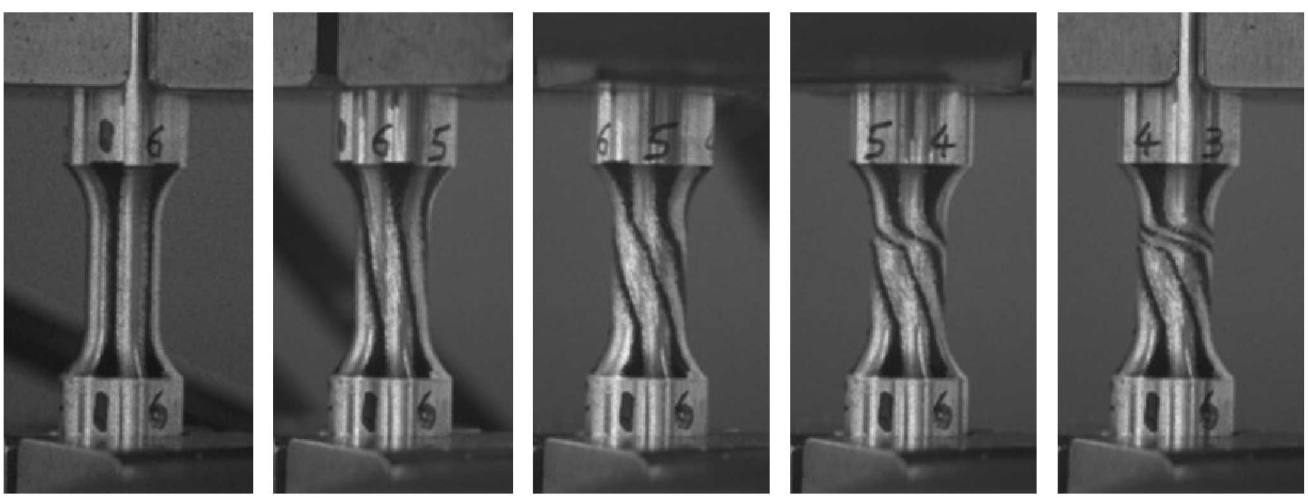



Figure 2: Torque-rotation curve of Specimen Solid_Torsion_1.

Images were taken at every 5 seconds to record the deformation. Figure 3 shows the solid cylinder specimen at selected deformation stages. At $\Omega$=0°, which was the undeformed state, all marked lines were straight and vertical. At Ω=40°, inclined straight lines within the gage section indicated uniform deformation. Lines were kinked at upper part of the gage section at Ω=80°, which denoted surface deformation was not uniform and localization had occurred. The transition from uniform to localization was gradual; it started approximately at Ω=60°. For further rotation, the deformation was evidently concentrated at the localized zone as shown in Ω=120° and 180° images. 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. Change of radius at the shear localized zone was not detectable form this nonquantitative observation.



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

Figure 3: Deformation images of Specimen Solid_Torsion_1.

**EXPERIMENT II**

The setup is shown in Fig. 4. A pair of DIC cameras and IR camera are on the left and right side of the specimen, respectively. Specimen Solid_Torsion_3 was painted with speckles for 3D DIC analysis but left with a vertical unpainted window for IR temperature measurement. The test control was the same as Solid_Torsion_1 except the torsion loading was running at a faster rate of $\dot{\Omega}$=6.67 degree per second and the camera frame rate was 10 Hz.

Figure 4: Test setup for Solid_Torsion_3.

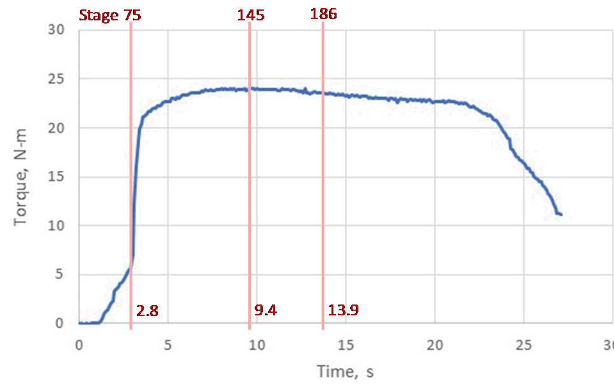
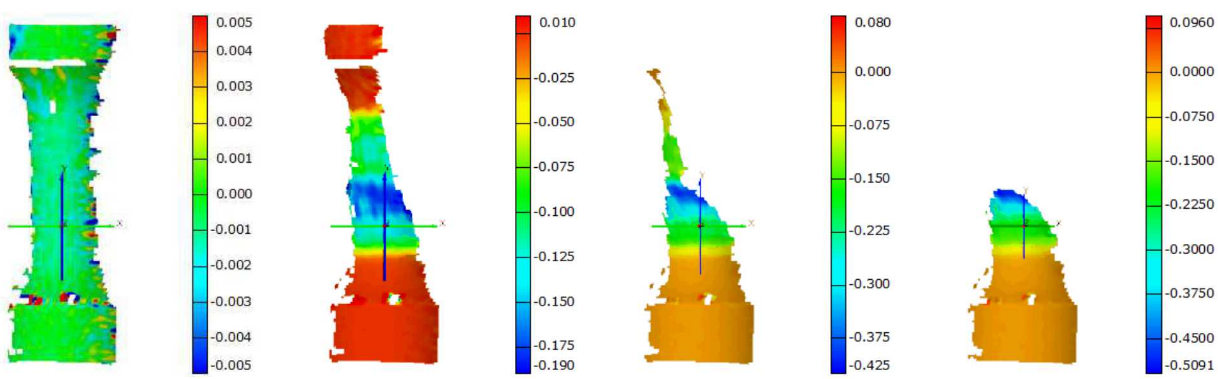



Figure 5: Torque history of Specimen Solid_Torsion_3.

The torque history *T-t* curve is shown in Fig. 5. The specimen failed within the first loading cycle. The shear strain field $e_{xy}$ of selected stages are shown in Fig. 6, where Stage 75, 145, 186 and 198 correspond to rotations, approximately, $0^o$, $42^o$, $72^o$ and $80^o$, respectively. The deformation was clearly localized at Stage 145 and beyond. The figure also shows that the measurable area became smaller and smaller since speckles gradually rotated out of the camera view. At Stage 198, $\Omega$=$80^o$, all top half and most of the localized zone were without data. The specimen failed at rotation $\Omega$=$160^o$. Unfortunately, only the strain data between $0^o$ to $80^o$ are available. Using the average shear strain of localized zone for Nadia's analysis, the initial portion of engineering stress-strain curve is shown in Fig. 7, no data for $\Omega$>$80^o$. The estimated strain rate is about 0.15 $s^{-1}$. Same as Solid_Torsion_1, the separation was in the localized zone, shown in Fig. 8. The width of the localized zone is estimated to be about 1 - 2 mm. IR data show negligible temperature changes.




Stage 75 Stage 145 Stage 186 Stage 198

Figure 6: Solid_Torsion_3 shear strain $e_{xy}$ distributions of selected DIC stages.

**CONCLUSION**

For Al6061-T6, solid bar torsion is stable and do not buckle. It can achieve large shear deformation up to failure. Within the gage section, the deformation is uniform in the beginning, it gradually transitions to deform further in a localized zone, and eventually a crack forms within the zone.

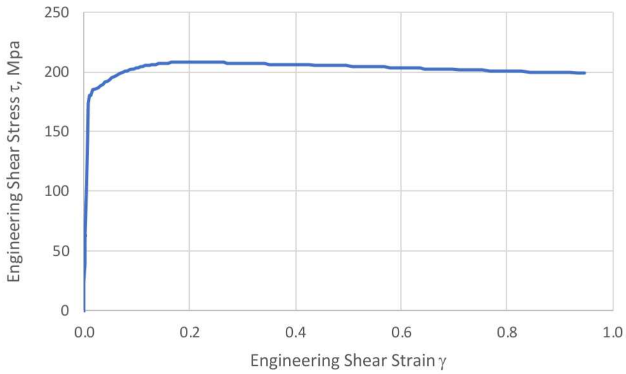



Figure 7: Shear stress-strain curve of Al6061-T6

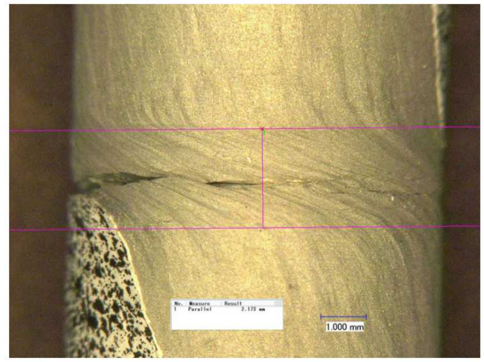



Figure 8: Failed Specimen Solid_torsion_3

Solid bar torsion analyses are no longer limited to the experiments with uniform deformation. Modern 3D DIC method makes up the shortcomings of the mechanical extensometer. Strain fields clearly reveal the deformation uniformity of the gage section. One great advantage of the technique is that the area of interest (AOI) does not need to be identified or guessed before the test, selecting the necessary data to construct shear stress-strain curve are done afterward.

The rotation could be very large. The whole gage section should be painted with DIC speckles; also, the DIC analysis needs to re-establish the reference frame periodically to avoid the reference AOI deforms out of the camera view. Take the current setup for example, about every 60$^{o}$ (i.e. less than 80$^{o}$) rotation is recommended. The re-referenced analyses results need to map back to the original reference frame.

No significant temperature change is observed. Numerical modeling will help to understand and improve the torsion experiment.

**ACKNOWLEDGEMENTS**

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