AC 2011-77: MEASURING ANGLE OF TWIST IN A TORSION EXPERIMENT

Surendra K. Gupta, Rochester Institute of Technology (COE)

"Vinnie" Gupta is a Professor of Mechanical Engineering, and a member of the graduate faculty of Materials Science & Engineering at the Rochester Institute of Technology (Rochester, NY). He is a recipient of the 2000 Eisenhart Award for Excellence in Teaching. At RIT, he teaches undergraduate and graduate courses in Applied Mechanics, Computational Techniques, and Materials Science.

Steven John Kosciol, Rochester Institute of Technology

Senior Mechanical Technician - Mechanical Engineering Department

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Introduction

At our university, every mechanical engineering student must take a sophomore level one quarter-credit hour course titled "Mechanics of Materials Lab". Students take this laboratory course concurrently with a 4 quarter-credit hour Mechanics or Strength of Materials course. One of the five experiments in the laboratory course focuses on the study of elastic and plastic deformation of a circular cross-section metallic rod in torsion.

The objectives of the torsion experiment include determination of shear modulus of elasticity "G" and shear proportional limit "τ_p" of the material. In the torsion test, a torque "T" is applied to one end of a circular cross-section metallic rod while the other end is held fixed in a stationary grip. We use a bench-mounted Tinius Olsen 10,000 in-lb Torsion Tester shown in Figure 1. The tester has a variable speed drive electromechanical loading system with manual controls and LED digital display. We have developed a LabView interface to acquire the torque and grip angular position data using the RS-232 port.

Figure 1: Tinius Olsen 10,000 in-lb Torsion Tester

The shear strain "γ" on the surface of the rod is determined by measuring the relative angle of twist "ϕ_G" over a gage length "L_G". The shear strain $\gamma = c * \phi_G / L_G$ where "c" is the radius of cross-section and ϕ_G is in radians. With shear stress "τ" linearly proportional to shear strain γ for $\tau \leq \tau_p$, the shear stress at the surface is $\tau = 2T/(\pi c^3)$. The shear modulus G is then determined as the slope of the line fitted to τ versus γ data.

Existing Troptometer

Until recently, the relative angle of twist ϕ_G was measured using a troptometer shown in Figure 2 that was designed and fabricated in-house more than thirty years ago. It consists of two halves – each consisting of a 45° plastic protractor attached to a Y-shaped aluminum plate that is clamped onto the specimen using two hexagonal head screws.

Figure 2: Existing Troptometer

Figure 3 shows the troptometer mounted onto a 2024-T351 aluminum alloy specimen.

Figure 3: Troptometer mounted on specimen in Torsion Tester

Students experience several difficulties in using this troptometer: (i) keeping it aligned while mounting it on the specimen, (ii) reading ϕ_G from the protractor scale, and (iii) taking it off when the specimen begins to deform plastically. In clamping onto a specimen, the protractors on the two troptometer halves need to be aligned carefully. If the two halves are clamped too close to each other then the plastic protractors rub against each other. On the other hand, if the two halves are not sufficiently close to one another then it becomes extremely difficult to read the relative angle of twist ϕ_G from the protractor scale. Even when the troptometer is aligned and properly mounted onto the specimen, it is difficult to read the protractor scale from a distance of 2 to 3 feet. The troptometer needs to be removed from the specimen when plastic deformation begins – in any case before ϕ_G reaches 45° since the protractors will lose contact with one another. This removal requires loosening the four clamping screws which is a difficult operation while the specimen is held in the torsion tester's grips. Since the specimen being tested with a troptometer is ductile, this removal operation is quite safe.

Digital Inclinometers

Last year, we designed and fabricated a set of specimen clamps shown in Figure 4 to which a pair of commercially available digital inclinometers can be magnetically attached. The clamps are made of low carbon steel that can be easily machined, formed and welded. Each inclinometer costs about $55.

Figure 4: Inclinometers and Specimen Clamps

It is quite easy to mount each clamp onto a specimen as shown in Figure 5. The distance between the two clamps L_G is kept at approximately 5¼".

Figure 5: Mounting specimen in clamps

The specimen is then mounted in the torsion tester grips. A digital inclinometer is magnetically attached to each clamp as shown in Figure 6, powered on, and initialized to display relative zero degree orientation. This eliminates difficulty (i) experienced with the troptometer.

Figure 6: Inclinometers attached to specimen clamps in Torsion Tester

As the applied torque T is increased on the specimen, the display on the inclinometer on the right "ϕ_R", and on the left "ϕ_L" is read simultaneously. The relative angle of twist $\phi_G = \phi_R - \phi_L$ is thus easily determined. This eliminates difficulty (ii) experienced with the troptometer. In practice, ϕ_R readings are recorded at 0.5° intervals up to 10°, and at 1° intervals up to 20° thereafter.

When ϕ_R exceeds 20°, the two inclinometers are detached from the clamps, and kept aside. The clamps need not be removed from the specimen. This eliminates difficulty (iii) experienced with the troptometer. Since each inclinometer is detached magnetically, the removal operation is very safe. The torsion test continues until the specimen fails so that students can examine the fracture surface and determine whether the failure mode is ductile or brittle.

Experimental Results and Discussion

Torsion tests were conducted on 2024-T351 aluminum alloy specimens using both ϕ_G measuring techniques. Nominal shoulder to shoulder distance and diameter of each specimen was 7⅛" and ½" respectively as prescribed in ASTM E-143 standard. The gage length L_G for troptometer was 5¼". Special effort was made to keep the distance L_G between the two inclinometer clamps to be approximately 5¼" to achieve comparable precision in ϕ_G measurements. Figure 7 shows a plot of shear stress versus shear strain data points in the elastic range with least-square line fits to determine the shear modulus.

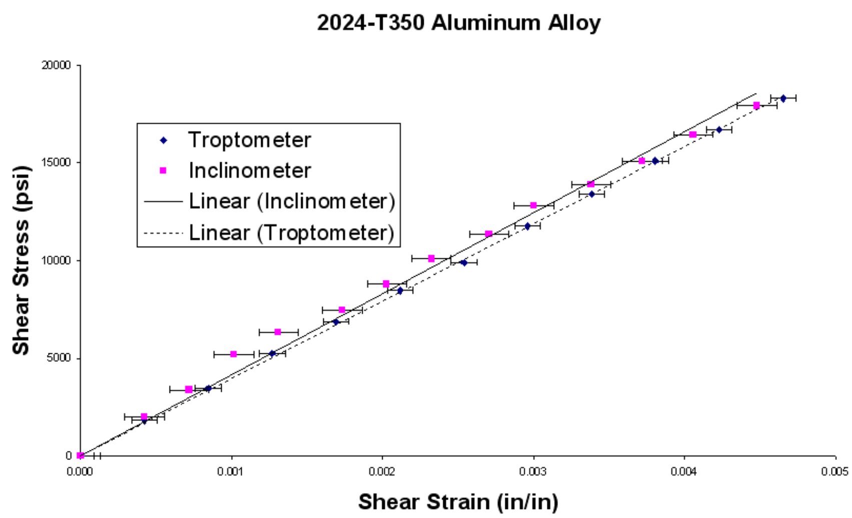

Figure 7: Plot of Shear Stress versus Shear Strain

In the laboratory course, we use 1018 cold rolled steel specimens for demonstration whereas students in groups of three conduct the test on 2024-T351 aluminum alloy specimens. Table 1 below summarizes the results from least-squares line fitting for both steel and aluminum alloy specimens:

Table 1: Results from Experimental Measurements

	2024-T351 Aluminum Alloy		1018 Cold Rolled Steel	
	Troptometer	Inclinometer	Troptometer	Inclinometer
Shear Modulus G (Msi)	3.96	4.15	11.74	12.37
Correlation Coefficient r^2	0.9996	0.9918	0.9990	0.9838

From results of a previous laboratory experiment on tensile testing conducted to determine the elastic modulus and Poisson's Ratio of both these materials, we can compute the shear modulus G to be 4.13 Msi and 11.78 Msi for 2024-T351 Al-Cu and 1018-CRS respectively. Table 1 results are within 5% of these values.

Even though the line fits are excellent in all cases, we find that the correlations coefficient of line fit on data from inclinometers is always less than that from troptometer on a corresponding specimen. Visually also, we see that data from inclinometers show more scatter than that from troptometer on a similar specimen, and this can be seen in Figure 7 as well. We attribute this minor difference to two reasons: (i) there is a small time gap in reading the values from the two inclinometers, and (ii) the inclinometers are sluggish in measuring and displaying the angular tilts. We believe that (i) has negligible effect but the effect of (ii) is observable. The inclinometer display changes by as much as 0.15° often. The inclinometer determines the angular tilt by measuring the capacitance of a liquid column whose height changes with tilt. The inclinometer's electronic equilibration and response is quite sluggish. These inclinometers are designed for applications where either the angle is static or angle changes due to vibrations need to be minimized by damping. In Figure 7, the horizontal error bars for inclinometer data reflect this 0.15° uncertainty whereas the troptometer data error bars reflect the least count of 0.1°. We are hoping to replace each inclinometer by an iPod Touch to remedy the issue of sluggish response, and our initial results appear promising.

Conclusions

1. Students encounter three difficulties in using the existing troptometer: (i) keeping it aligned while mounting it on a specimen, (ii) reading its protractor scale, and (iii) removing it from the specimen during plastic deformation of the specimen.

2. Using commercially available digital inclinometers attached to specimen clamps eliminates all three difficulties identified in item #1.

3. Both techniques to measure the relative angle of twist yield comparable values for shear modulus and linear correlation coefficient.

4. The marginally poorer correlation coefficient obtained with inclinometers is attributed to their sluggish response.

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