Lab 2: Torsion Test

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Section AC

Abstract

This experiment involves the application of torque onto 1018 steel and 6061-T6 Aluminum in order to determine the accuracy of the Power-Hardening model by comparing the theoretical and experimental values of the shear modulus *G* and the torque *T*. In addition, this experiment serves to determine the nature of failure for each specimen and determine the sensitivity of the strength coefficient *H* and strain hardening exponent *n* in the Power-Hardening model. In order to perform the torsion test, one must obtain long thin rods of the material of choice. Next, one must record the length and diameter of the specimen. Then one must acquire the proper torsion testing equipment and set up the torsion testing apparatus. The actual experiment involves incrementing the angle of twist on the torsion specimen and recording the force for the corresponding angle of twist up until fracture. In order to carry out the data analysis, one must first have on hand the Modulus of Elasticity *E*, Poisson's ratio υ, yield strength σ_y, *H*, and *n* for the corresponding material. These can be obtained via a third-party index or can simply be measured and calculated with a tensile test. Afterwards, one can calculate the applied torque and experimental torque as the sum of the elastic and plastic torque. One can also calculate the theoretical shear modulus as a function of *E* and *v* and compare it to the experimental value calculated by determining the slope of the equation $\tau = G\gamma$ where τ is the shear stress and γ is the shear strain. For the raw aluminum species, the percent difference between the theoretical and experimental shear modulus around 9.1%. For the clean aluminum species, the percent difference was 0.86%. In terms of the theoretical and experimental torque, the raw aluminum had an average percent difference of 12.12% while the clean aluminum had an average percent difference of 4.77%. For the raw steel species, the percent difference between the theoretical and experimental shear modulus around 14.78%. For the clean aluminum species, the percent difference in the shear modulus was around 12.88%. The sensitivity of H was much higher than that of n. When we increased H by 5%, we changed the torque by roughly +700Nmm, and when we decreased H by 5%, we changed the torque by roughly -700Nmm. When we increased n by 5%, we changed the torque by around -5Nmm. When we decreased n by 5% we changed the torque by around +100Nmm. The experimental model that we used in this experiment did a relatively good job in predicting the behavior of the elastic and plastic behavior of both metals by showing the same shape of all measured data sets. Although, it must be noted that the Power-Hardening model is

far from perfect, as it is constantly increasing in the plastic region despite the fact that real mechanical behavior tends to flatline or decrease after reaching ultimate tensile stress.

1. Introduction

The purpose of the torsion test is to induce a state of pure shear in specimens. Torsional testing plays an important role in allowing us to understand the failure of ductile materials, as they tend to resist normal stress by undergoing large plastic deformations. The torsion test is also useful in determining certain material properties such as the shear stress, shear strain, and shear modulus. In this lab, by recording the force versus angle of twist data and utilizing some geometric measurements, we will calculate the experimental torque as the sum of the elastic and plastic torques. We will also be able to calculate the experimental shear modulus as the slope of the shear stress vs. shear strain. There are certain advantages as to why we would conduct a torsion test over a tensile test. Firstly, no necking occurs, therefore the torque can constantly increase up until the moment of failure. Secondly and most importantly, plastic deformation is almost uniform over the entire length of the specimen which enables the determination of deformations and stresses reliably for highly ductile materials. Lastly, brittle or low ductility materials, that are often difficult to test in tension, can undergo quite measurable deformation in torsion test, which enables the determination of their mechanical properties. For the purposes of our experiment, we are only interested in the first and second advantage.

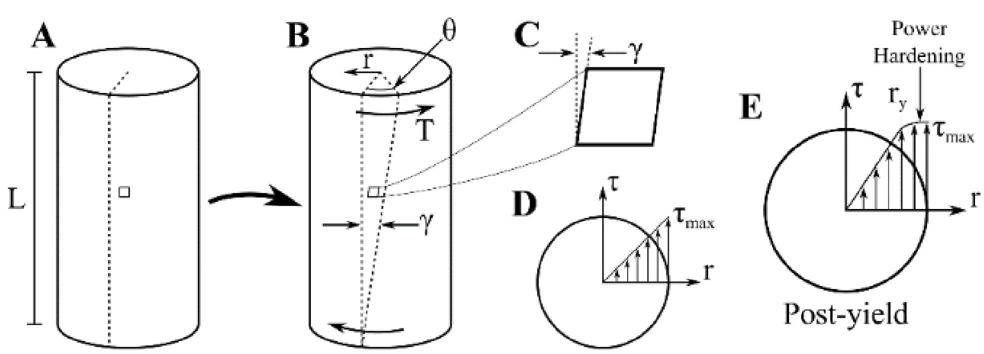

Figure 1*: Schematic of a tensile test illustrating the pure shear that develops in a specimen. A) initial specimen, B) sheared specimen, C) close up showing simple shear state on the surface, D) shear stress distribution prior to yielding and E) shear stress distribution after yielding.*

2. Procedure

2.1 Sample Preparation

Torsion specimens are typically long, slender rods. Their diameters must be small enough such at the grips will not affect the stress state in the specimen. The specimens should have a uniform diameter along their length, however, minor modifications can be made in order to grip the specimen better towards the ends of the rod. The importance of having a straight specimen is immense, as any deformation that exists in the specimen before the test will lead to pre-mature failure, thus leading to inaccurate readings.

The specimens can be created through any sort of machining method so long as the cross-sectional area of the specimen remains uniform. The most common fabrication methods for achieving this result are extrusion and pultrusion molding. Whatever fabrication method one decides to use, the important thing to keep in mind is that changes to the microstructure of the material can occur during such a process and post heat treatment might be necessary if one desires a specific type of microstructure.

2.2 Equipment

1) Technovate torsion testing setup

2) Troptometer (to measure angles)

3) Digital load readout

4) Constant diameter rods of specimens of interest

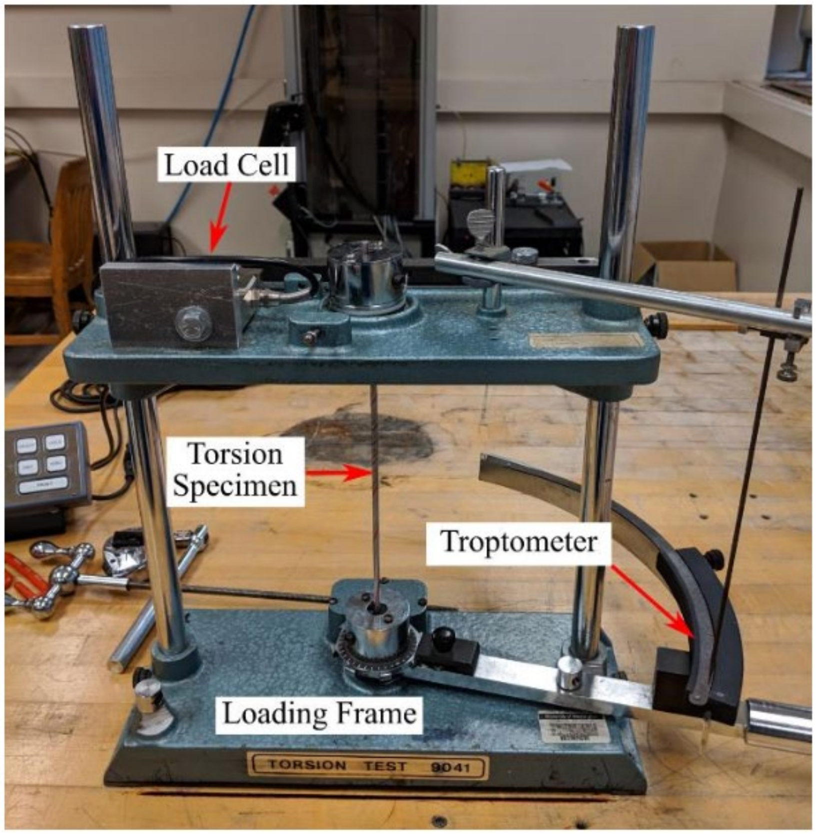

Figure 2: *Schematic of torsion testing apparatus*

2.3 Setup

a. Take multiple measurements of the diameter of the specimen throughout its length using calipers; average the diameter and record it.

b. Measure and record the distance between grips. Notice that the bottom face of the upper jaw is recessed into the upper plate. Make sure to account for this recessed distance in your measurement. Draw two lines perpendicular to the longitudinal line on each end of the thin portion of the specimen. Measure and record the length. (i.e. the true length grip-to-grip is found by adding 20.6mm to the length measured to account for the portion hidden by the grip.)

c. Draw a longitudinal line on the specimen using a sharpie.

d. Very tightly clamp one end of the specimen to the bottom grip of the test machine.

e. Pull forward the pin that is located behind the bottom grip. This engages the ratchet mechanism.

f. Unthread the horizontal drive rod until the end of the threaded rod is almost disconnected from the base. Then twist the lever arm counter-clockwise as far as possible.

g. Look at the top grip and locate the wire ropes that transfer torque to the top grip/specimen. Unscrew the two nuts as far as possible.

h. Rotate the top grip clockwise in order to remove any slack in the wire ropes. While the grip is in this position, hold the grip and tighten it. Make sure the specimen is securely clamped in the top grip.

i. While monitoring the force sensor, remove any remaining slack in the wire ropes by re-tightening the two nuts that were loosened during step (e). In the case that there is still slack even after fully tightening the two nuts, tighten the threaded horizontal driver until an increase in load is sensed.

j. Adjust the pointer so as to indicate “zero” degrees. Make sure the pointer is not touching the troptometer.

k. Use the threaded drive rod to apply an angle of twist to the lower grip until the first “click” sound is heard from the ratchet.

l. Zero the output of the force sensor.

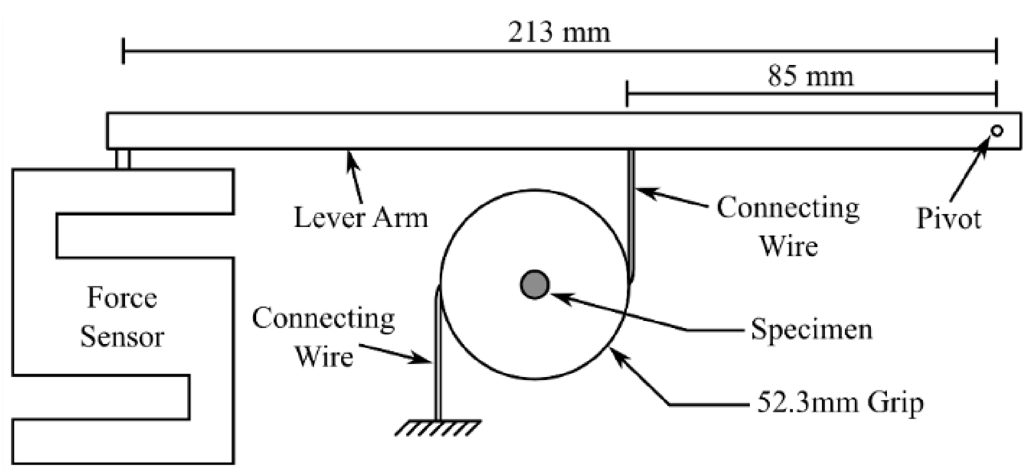

***Figure 3**: Schematic of the torsion load measurement configuration.*

2.4 Procedure

a. Using the threaded drive rod, increase the angle of twist in increments of 2°, up until 30° is reached. Record the force displayed on the force gage at each increment.

b. Next, increase the angle of twist in increments of 5°. Continue to record the force displayed for every increment of 5° until a total angle of twist of 45° is reached.

c. Next, increase the angle of twist in increments of 45° four times. Record the force displayed on the force gage at each increment.

d. Next, increase the angle of twist in increments of 90° four times. Record the force displayed on the force gage at each increment.

e. Next, increase the angle of twist in increments of 180° four times. Record the force displayed on the force gage at each increment.

f. Next, increase the angle of twist in increments of 360° until specimen failure occurs. Record the force displayed on the force gage at each increment.

g. After the specimen fails, remove the broken halves.

h. Make note of the specimen and its fracture surface so that they can later be described.

3. Results

3.1 – Applied Torque Derivation

The force delivered via the user to the threaded drive rod is equivalent to the force delivered by the wire rope to where it is connected to the threaded drive rod. The force delivered via the user is measured by the force displayed on the sensor. Solving for the force in the wire rope, we get the follow equation.

$$F_{sensor} * (213mm) = F_{wire\ rope} * (85mm) \quad (1)$$

$$F_{wire\ rope} = F_{sensor}\ (213 / 85) \quad (2)$$

The torque on the specimen is equal to the two contributions from $F_{\text{wire rope}}$ multiplied by the radius of the grip.

$$\text{Torque} = 2 * F_{\text{wire rope}} * \frac{52.33\text{mm}}{2} \tag{3}$$

$$\text{Torque} = 2 * F_{\text{sensor}} * \frac{213}{85} * 52.33 \tag{4}$$

3.2 – Analysis Based on Power-Hardening Law

a. Calculating E, ν, H, and n for aluminum & steel: The calculations for these values for the purpose of this lab were given to us by the TA's. In order to calculate them, the easiest approach would probably be to conduct a tensile test in order to easily calculate stress and strain values.

Material	E (MPa)	ν	H (MPa)	n
Aluminum	70000	0.38	416	0.0588
Steel	200000	0.37	828	0.0875

Table 1: *Table with E, ν, H, & n values for aluminum & steel*

Young's Modulus, *E*, is the slope (constant of proportionality) of the linear region of the stress ($\sigma_{engineering}$) vs. axial strain ($\varepsilon_{engineering}$) curve.

$$E = \frac{\sigma_{engineering}}{\varepsilon_{engineering}} \tag{5}$$

Poisson's Ratio, υ is the ratio of transverse strains (ε_t) to axial strains (ε_a). Since the load is tensile stress, the relation is $\varepsilon_t = -\upsilon\varepsilon_a$. Thus, we end up with the follow equation(s).

$$\upsilon = -\frac{\varepsilon_{transverse}}{\varepsilon_{axial}} = \frac{|\varepsilon_t|}{\varepsilon_a} \tag{6}$$

H & *n* are derived from the Power-Hardening law which allows us to linearly fit the logarithmic stress vs. logarithmic strain, where n is the slope of the linear fit, and log *H* is the y-intercept. In general, *H* represents the strength index or strength coefficient, and n is the strain hardening exponent. Note that the Power-Hardening law is only applicable in the plastic region.

$$\sigma = H\varepsilon^n \equiv \tau\sqrt{3} = H\left(\frac{\gamma}{\sqrt{3}}\right)^n \quad (7)$$

$$log(\sigma) = n*log(\varepsilon) + log(H) \quad (8)$$

In Eq. 7, the Power-Hardening relationship can also be expressed with the variable γ, also known as the shear strain, which is defined as

$$\gamma = \frac{\theta r}{L} \quad (9)$$

b. Calculating shear modulus (G), tensile yield stress (σ_Y) & shear yield stress (τ_Y):

Tensile yield stress $\boldsymbol{\sigma_y}$ is obtained by the 0.2% offset line method. Draw a 0.2%ε (0.002ε) offset line parallel to the slope of E, the point of intersection between engineering stress-strain curve and offset line is σ_y.

The shear yield stress is simply equal to $\frac{\boldsymbol{\sigma_y}}{\sqrt{3}}$, which is a relationship that is derived from the Von Mises yield criterion, applied to a state of pure shear.

$$\sigma_y \leq \sqrt{\frac{1}{2}(\sigma_{xx} - \sigma_{yy})^2 + \frac{1}{2}(\sigma_{yy} - \sigma_{zz})^2 + \frac{1}{2}(\sigma_{zz} - \sigma_{xx})^2 + 3(\sigma_{xy} + \sigma_{xz} + \sigma_{yz})^2} \quad (10)$$

$$\sigma_y = \tau_Y\sqrt{3} \quad (11)$$

In order to calculate G, we have two methods. The first method relies simply on the shear modulus' relationship to Young's Modulus & Poisson's ratio.

$$G = \frac{E}{2(1+\varepsilon)} \quad (12)$$

The second method relies on the relationship between the shear stress τ and the shear strain γ. Note that this method only works within the elastic regime.

$$\tau = G\gamma \tag{13}$$

By plotting the shear stress versus shear strain and fitting a linear graph, we can determine *G*, which will be the slope. Calculations of G using the latter method are shown below.

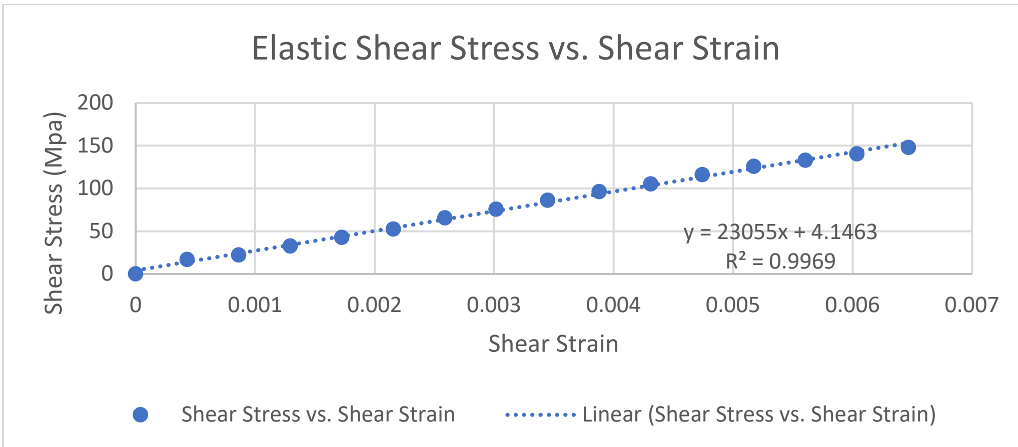

Figure 4: *Shear stress vs. shear strain curve for Raw_Aluminum specimen*

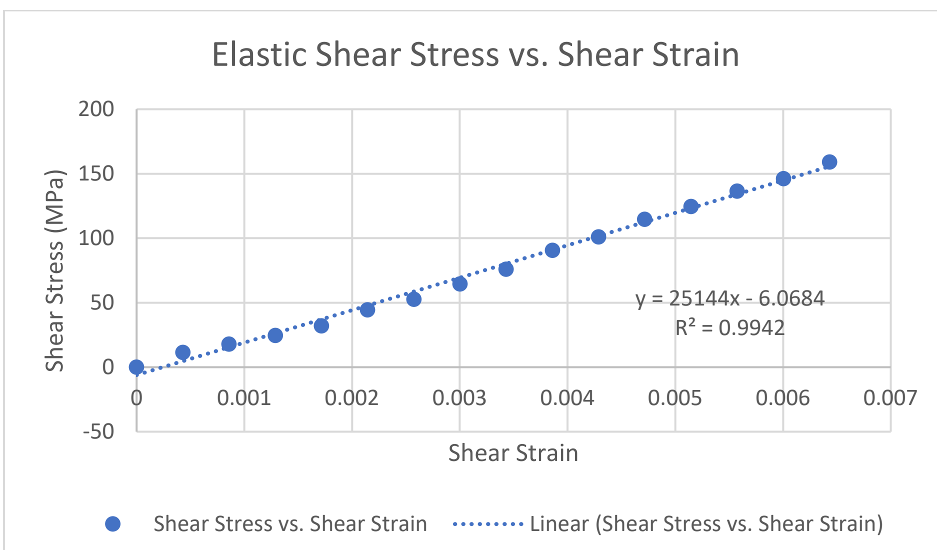

Figure 5: *Shear stress vs. shear strain curve for Clean_Aluminum specimen*

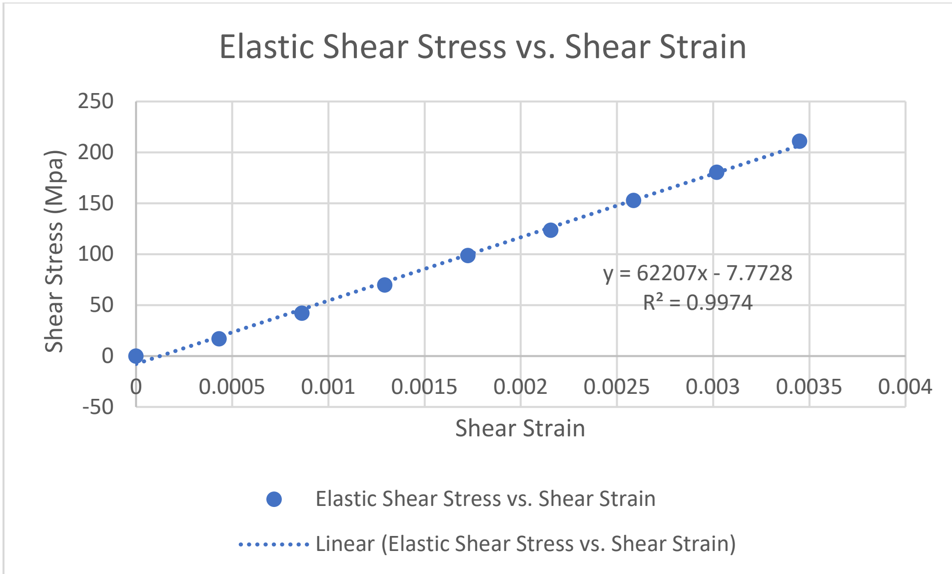

Figure 6: *Shear stress vs. shear strain curve for Raw_Steel specimen*

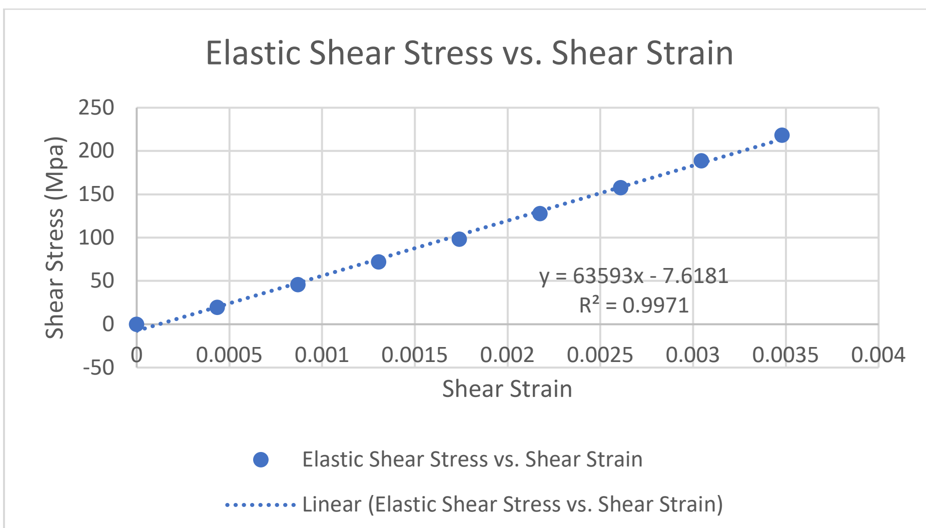

Figure 7: *Shear stress vs. shear strain curve for Clean_Steel specimen*

c. Calculating the radius of elastic zone for each angle of twist: Once the maximum shear stress passes the yield limit of the material, the rod will begin to deform plastically starting at the outer surface of the sample and moving into the plastic radius, r_y, which is defined as the following:

$$r_y = \frac{\gamma_y L}{\theta} = \frac{\tau_y L}{G\theta} \quad (14)$$

d. Calculating elastic and plastic torque for each angle of twist: The experimental torque in the specimen can be calculated as the sum of the torque in the elastic (T_{el}) and plastic (T_{pl}) region which are equal to the following:

$$T_{el} = \frac{\pi \tau_y r_y^3}{2} \quad (15)$$

$$T_{pl} = \frac{2\pi H}{\sqrt{3}(n+3)} \left(\frac{\theta}{\sqrt{3}L}\right)^n \left(r_o^{n+3} - r_y^{n+3}\right) \quad (16)$$

e. Comparing measured (applied) torque to experimental torque: Shown below are graphs of torque vs. angle of twist that illustrate the difference between our theoretical and observed values.

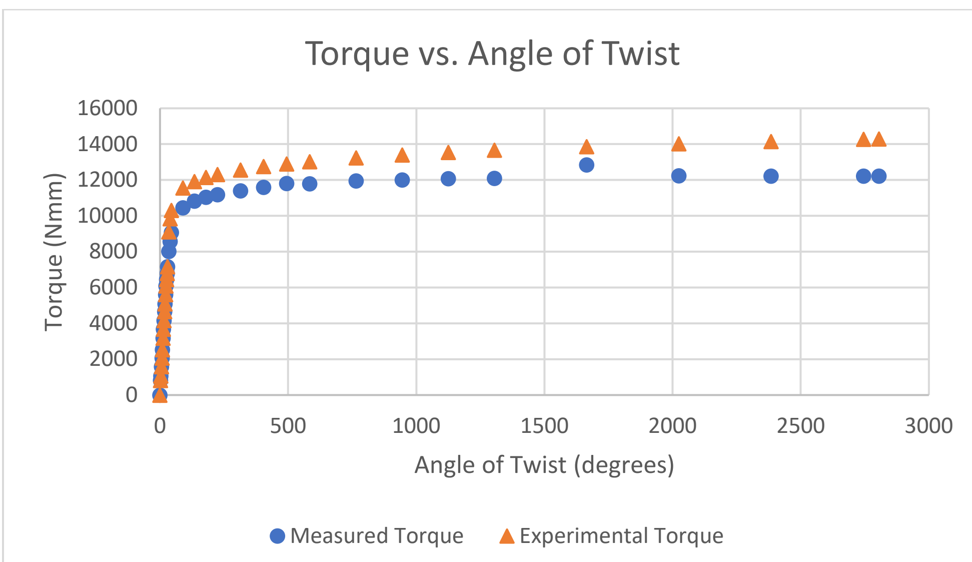

Figure 8: *Measured vs. experimental torque for Raw_Aluminum specimen*

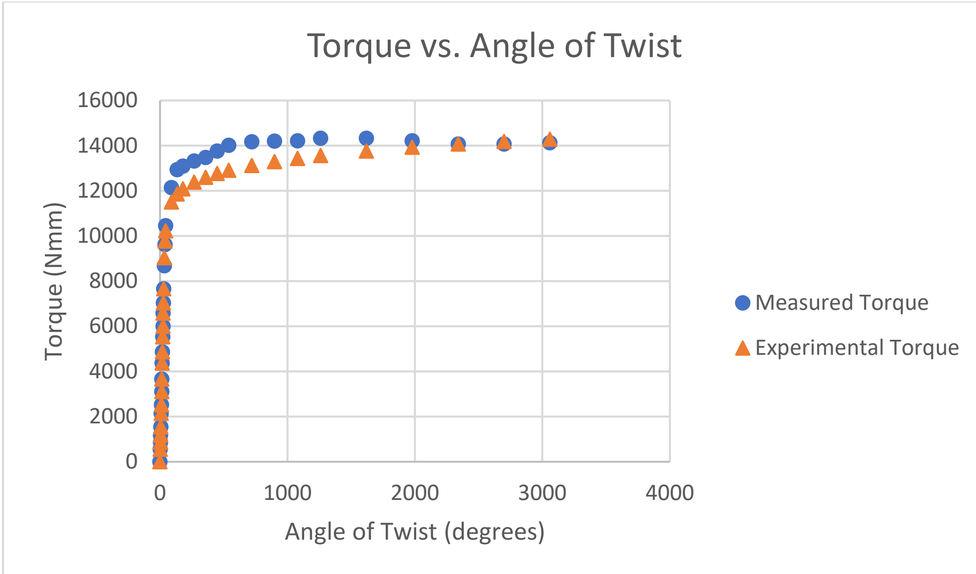

Figure 9: *Measured vs. experimental torque for Clean_Aluminum specimen*

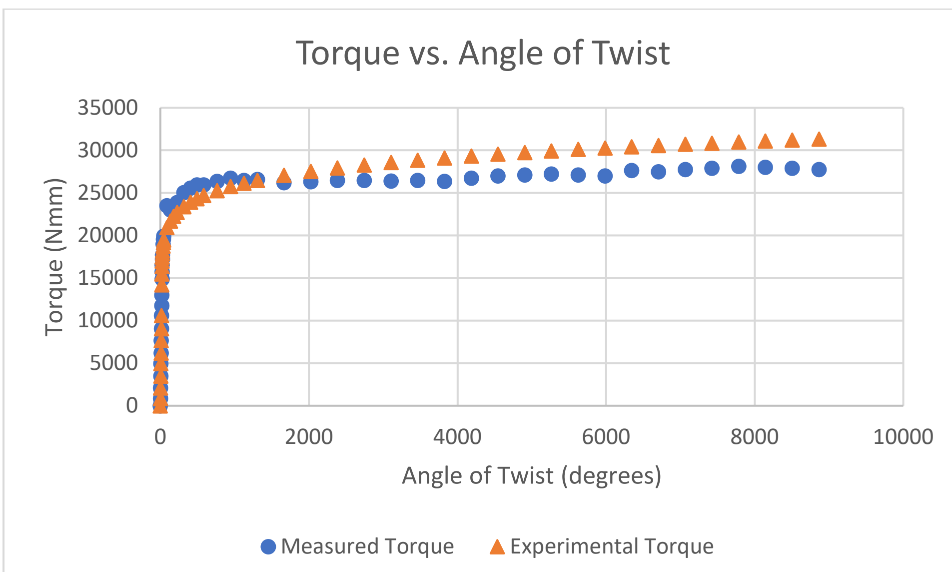

Figure 10: *Measured vs. experimental torque for Raw_Steel specimen*

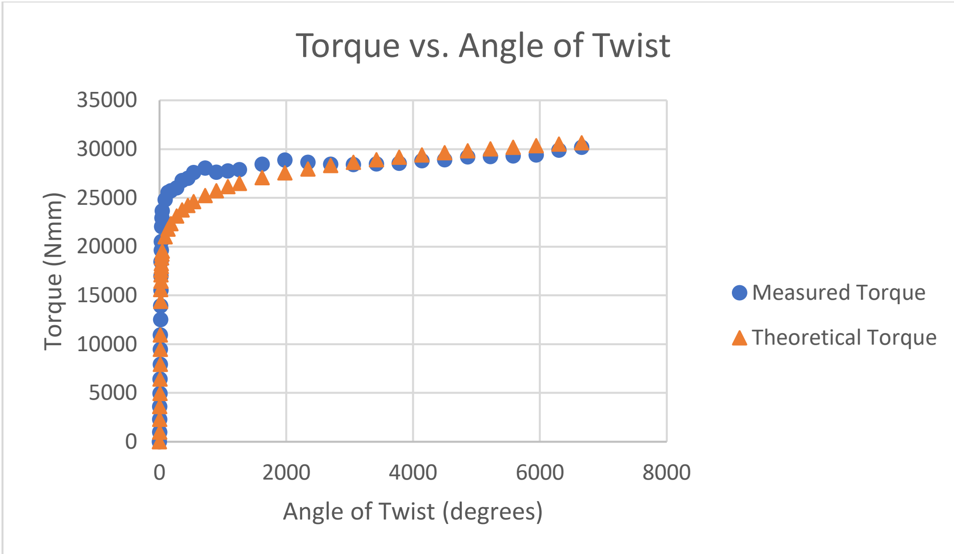

Figure 11: *Measured vs. experimental torque for Clean_Steel specimen*

f. Calculating percent difference for theoretical vs. experimental values: In order to quantitatively compare the theoretical and experimental values, we will treat the theoretical values as the true values and calculate the percentage of how much our experimental values deviate from that. We will utilize the percent error equation:

$$\% \text{ Error} = \left| \frac{Theoretical\ value - Experimental\ Value}{Theoretical\ Value} \right| * 100\% \tag{17}$$

From this equation, we can now compare the theoretical and experimental values of the shear modulus. For the torque, since it is dependent on the angle of twist, we must sum up the percent differences of the torques for every angle of twist within the plastic region and take the average.

	Raw_Aluminum	Clean_Aluminum	Raw_Steel	Clean_Steel
Theoretical G	25362.31884	25362.31884	72992.70073	72992.70073
Experimental G	23055	25144	62207	63593
% Error	9.097428571	0.8608	14.77641	12.87759

Table 2: *Theoretical vs. experimental G*

	Raw_Aluminum	Clean_Aluminum	Raw_Steel	Clean_Steel
Avg % Error for T	12.11799578	4.766538767	7.71569606	7.109176619

Table 3: *Average percent error for theoretical vs. experimental torque values.*

4. Discussion

a. Comparison between measurement and prediction based on power hardening law for aluminum:

For our raw aluminum species, the percent difference between our theoretical and experimental shear modulus around 9.1% (Table 2). For our clean aluminum species, the percent difference is 0.86%. In terms of our theoretical and experimental torque, the raw aluminum had an average percent difference of 12.12% while the clean aluminum had an average percent difference of 4.77% (Table 3). If we examine the graphs (Fig. 8 & 9), we can see that the Power-Hardening model does a decent job at capturing the plastic behavior of the aluminum specimens based on its similarity to the overall shape of the experimental torque vs. angle of twist graph.

b. Comparison between measurement and prediction based on power hardening law for steel:

For our raw steel species, the percent difference between our theoretical and experimental shear modulus around 14.78% (Table 2). For our clean aluminum species, the percent difference is 12.88%. These percentage differences are much larger in comparison to those of the aluminum species. In terms of our theoretical and experimental torque, the raw steel had an average percent difference of 7.7% while the clean steel had an average percent difference of 7.1% (Table 3). By examining Figure 10 & Figure 11, we can see that the Power-Hardening model yet again does a decent job at capturing the plastic behavior, this time for the steel specimens.

c. Nature of failure for each specimen

Both the aluminum and steel specimens are ductile metals. Under only torsion, these specimens experience a state of pure shear. Ductile metals in pure shear will fail under the maximum shear, which occurs at the orientation perpendicular to the longitudinal axis of the specimen itself.

d. Sources of error and noise in the data

The primary source of error would have to be the limitations of the testing equipment. When incrementing to an angle of twist, the force that the sensor displays would change frequently. In addition, the troptometer's level of precision and the amount of accuracy that the pointer can provide is not ideal. Also, the caliper used to measure the diameter of the specimens had a built-in amount of error. Lastly and most importantly, the amount of grip applied onto the metals varied, and this leads to two potential errors. If there was not enough grip, the material would be prone to slipping and the device would not be able to apply torque to the material to its fullest potential. This actually happened in our experiment, causing section AC to repeat our trials twice, only to end up having to utilize another group's data because the metal kept slipping. The other scenario involves gripping the metal in place too tightly, which can alter the stress state of the material and cause an early fracture that is not caused by pure torsion.

The secondary source of error would have to be human error. There are a lot of areas where things can go wrong on our part such as measuring the diameter of the specimen, calling out the force appearing on the sensor, or making sure there is no slack in the wire ropes.

The tertiary source of error would have to be thermal fatigue. The stored energy in the twisting metal actually accumulates a lot of heat. When touching the middle of the specimen immediately after it fractured in torsion, one would find that it is actually very hot to the touch. This rise in temperature can contribute to weakening the integrity of the specimen and influencing where or when the fracture occurs.

e. Sensitivity of H & n:

In order to evaluate the sensitivity of H & n, the experimental torque of clean aluminum was utilized. The method to check sensitivity was to plot the original torque with the torque when H is changed while n is held constant, and with the torque when H is held constant while n is changed. When changing the H or n values by +/- 5%, we observe the following.

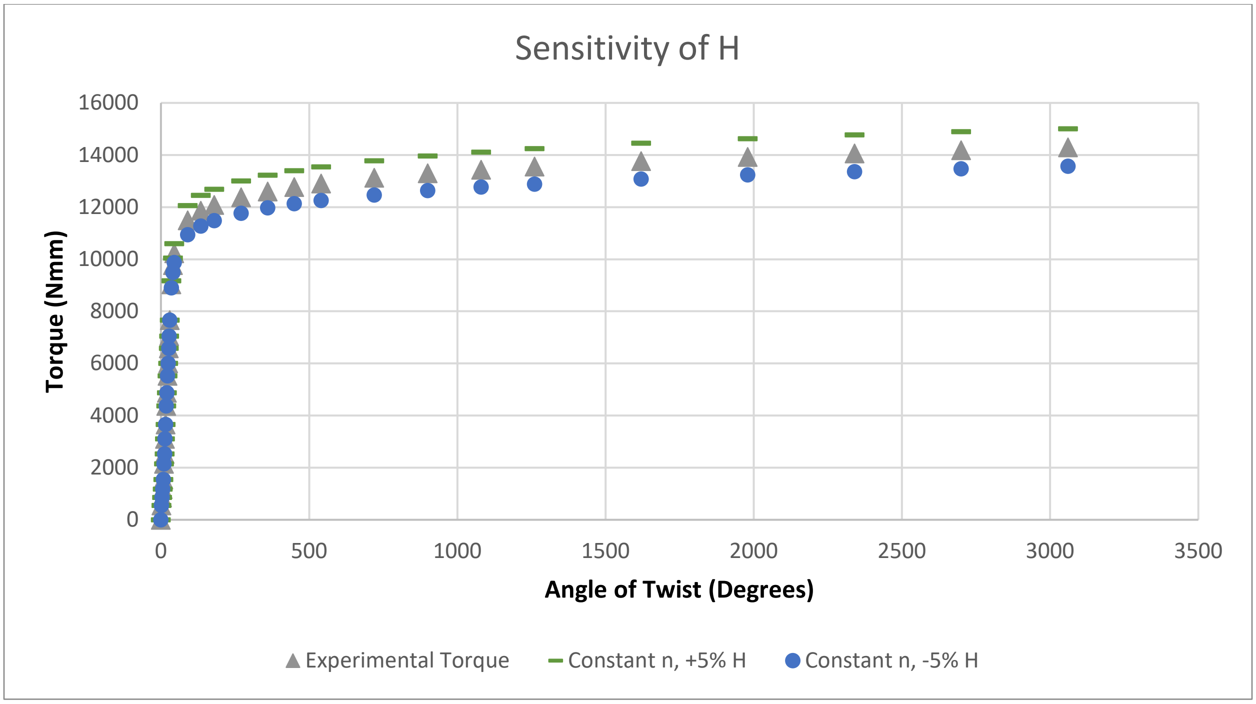

Figure 12: *Sensitivity of H for Clean_Aluminum*

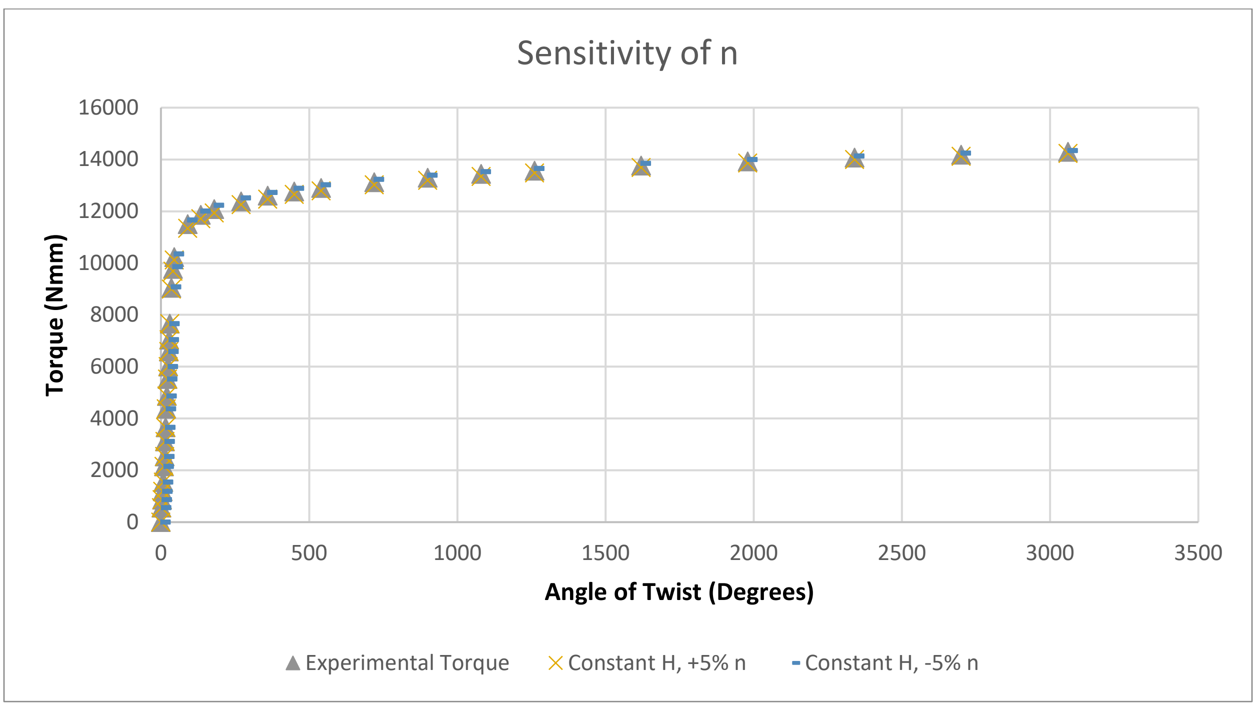

Figure 13: *Sensitivity of n for Clean_Aluminum*

As evident from our graphs (Fig. 12 & 13), the sensitivity of H was much higher than that of n. When we increased H by 5%, we changed the torque by roughly +700Nmm, and when we decreased H by 5%, we changed the torque by roughly -700Nmm. When we increased n by 5%, we changed the torque by around -5Nmm. When we decreased n by 5% we changed the torque by around +100Nmm.

f. Surprisingly results:

Interestingly enough, there was a difference between the accuracy of the Power-Hardening law for the experimental vs. theoretical torque between our clean and raw datasets. As seen in Figure 8 & Figure 10, the Power-Hardening model (experimental torque) overshot the measured torque in both graphs. However, as seen in Figure 9 & Figure 11 for the clean datasets, the Power-Hardening models often times intersect the data points of the measured torque and end at the same fracture torque. This might simply just be due to the fact that the clean data has more accurate values and better represents the relationship between torque and angle of twist in each material, and thus better illustrates the usefulness of the Power-Hardening model.

In addition, the Power-Hardening model constantly increases slightly in the plastic region while for the measured values, there is more of a flat-line behavior after the ultimate tensile stress has been reached.

5. Conclusion

In this lab, we performed torsion tests to induce a state of pure shear in ductile metals, specifically 1018 steel and 6061-T6 Aluminum samples. What we found was that the Power-Hardening model values of torque were not too different from the measured values because the maximum average percent error for the torque measurements was around 12.11%. The experimental value of the shear modulus G was relatively similar to that of the theoretical value with a percent error of 0.86% for the clean aluminum and 9.1% for the raw aluminum. However the percent error of G for the steel specimens were noticeably larger, with a deviation of 12.88% for the clean steel and 14.78% for the raw steel. In addition, we learned that within the Power-Hardening law, the strength coefficient H is much more sensitivity and influential than the strain hardening exponent n. Changing H by 5% resulted in an approximate +/- 700Nmm change in the experimental torque, whereas changing n by 5% resulted in a -5Nmm and +100Nmm change in the experimental torque. The experimental model that we used in this experiment did a relatively good job in predicting the behavior of the elastic and plastic behavior of both metals by showing the same shape of all measured data sets. Although, it must be noted that the Power-Hardening model is far from perfect, as it is constantly increasing in the plastic region despite the fact that real mechanical behavior tends to flatline or decrease after reaching ultimate tensile stress.

6. References

[1] A. Pundle, *ME 354 Laboratory Manual: Torsion Testing Formal Lab Report*. Seattle, WA, U.S.A: University of Washington, 2019

Appendix:

E5 =$F$2 * $B$2 / ($F$1 *D5)

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Aluminum		E (Mpa) =	70000	G (Mpa) =	25362.31884	(Sigma)y (Mpa)=	300	n =	0.0588			
2	L (mm)=	253.85	Poisson =	0.38	(Tau)y (Mpa	173.2050808	H (Mpa) =	416	n + 3 =	3.0588			
3	D (mm) =	6.27	r0 =	3.135	Experimental G (Mpa) =		23055						
4	Angle (deg)	Force (kgf)	Force (N)	Angle (rad)	Ry (mm)	Measured Torque(Nmm)	T_el (Nmm)	T_pl (Nmm)	Total Torque (Nmm)	Shear Strain	Shear Stress	% DIFF	AVG % DIFF
5	0	0	0	0	#DIV/0!	0	0	0	0	0	0	#DIV/0!	12.117996
6	2	0.64	6.276256	0.0349066	49.663975	822.5513437	822.5513437	0	822.5513437	0.00043109	16.99536529	0	
7	4	0.835	8.18855275	0.0698132	24.831987	1073.172456	1073.172456	0	1073.172456	0.00086218	22.17364066	0	
8	6	1.23	12.0621795	0.1047198	16.554658	1580.840864	1580.840864	0	1580.840864	0.001293269	32.66296767	0	
9	8	1.615	15.83773975	0.1396263	12.415994	2075.656906	2075.656906	0	2075.656906	0.001724359	42.88674211	0	
10	10	1.975	19.36813375	0.1745329	9.9327949	2538.342037	2538.342037	0	2538.342037	0.002155449	52.44663509	0	
11	12	2.465	24.17339225	0.2094395	8.2773291	3168.10791	3168.10791	0	3168.10791	0.002586539	65.45871164	0	
12	14	2.855	27.99798575	0.2443461	7.0948535	3669.350135	3669.350135	0	3669.350135	0.003017629	75.81526236	0	
13	16	3.24	31.773546	0.2792527	6.2079968	4164.166177	4164.166177	0	4164.166177	0.003448718	86.0390368	0	
14	18	3.62	35.500073	0.3141593	5.5182194	4652.556038	4652.556038	0	4652.556038	0.003879808	96.13003494	0	
15	20	3.965	38.88336725	0.3490659	4.9663975	5095.962622	5095.962622	0	5095.962622	0.004310898	105.291599	0	
16	22	4.365	42.80602725	0.3839724	4.5149068	5610.057211	5610.057211	0	5610.057211	0.004741988	115.9137024	0	
17	24	4.74	46.483521	0.418879	4.1386646	6092.020889	6092.020889	0	6092.020889	0.005173078	125.8719242	0	
18	26	5.01	49.1313165	0.4537856	3.8203057	6439.034737	6439.034737	0	6439.034737	0.005604167	133.0418439	0	
19	28	5.285	51.82814525	0.4886922	3.5474268	6792.474768	6792.474768	0	6792.474768	0.006035257	140.34454	0	
20	30	5.57	54.6230405	0.5235988	3.3109316	7158.767163	7158.767163	0	7158.767163	0.006466347	147.9127886	0	
21	35	6.235	61.14446275	0.6108652	2.8379414	8013.449419	6218.573618	2898.662772	9117.23639	0.007544071		13.7741803	
22	40	6.665	65.36132225	0.6981317	2.4831987	8566.101103	4165.958498	5673.658616	9839.617114	0.008621796		14.86692716	
23	45	7.065	69.28398225	0.7853982	2.2072878	9080.195693	2925.885804	7374.911767	10300.79757	0.00969952		13.44246225	
24	90	8.125	79.67903125	1.5707963	1.1036439	10442.54636	365.7357255	11193.67606	11559.41178	0.019399041		10.69533608	
25	135	8.425	82.62102625	2.3561945	0.7357626	10828.1173	108.3661409	11812.34351	11920.70966	0.029098561		10.09032621	
26	180	8.59	84.2391235	3.1415927	0.5518219	11040.18132	45.71696568	12098.31894	12144.0359	0.038798081		9.998518652	
27	225	8.705	85.36688825	3.9269908	0.4414576	11187.98351	23.40708643	12288.11112	12311.51821	0.048497602		10.04233422	
28	315	8.87	86.9849855	5.4977871	0.3153268	11400.04753	8.530279311	12553.74106	12562.27134	0.067896642		10.19490317	
29	405	9.02	88.455983	7.0685835	0.2452542	11592.833	4.013560773	12746.70982	12750.72338	0.087295683		9.987984643	
30	495	9.185	90.07408025	8.6393798	0.2006625	11804.89702	2.19826131	12900.44423	12902.64249	0.106694724		9.299068586	

Excel Formulas (by Column)

A: Angle (deg)

B: Force (kgf)

C: Force (N) = B6 * 9.80665

D: Angle (rad) = A6 * (PI() / 180)

E: Ry (mm) =$F$2 * $B$2 / ($F$1 *D6)

F: Measured Torque (Nmm) =C6 * (213 / 85) * (52.3)

[*]G: T_el (Nmm) =(PI() * $F$2 * (E21^3)) / 2

[*]H: T_pl (Nmm) = (2 * PI() * $H$2) / (SQRT(3) * $J$2) * ((D21 / (SQRT(3) * $B$2))^ $J$1) * ((($B$3/2) ^ $J$2) - E21^$J$2)

I: Total torque (Nmm) =SUM(G6+H6)

J: Shear strain = D6 * $D$3 / $B$2

K: Shear stress (Mpa) =2 * G6 / (PI() * $D$3 ^ 3)

L: % DIFF =ABS(F21 - I21) / F21 * 100

[**]M: AVG % DIFF =AVERAGE(L21:L40)

* = only applicable in plastic region where Ry < R0

** = only averaging non-zero integers

7. Extra Credit

In order to obtain the strength coefficient H and strain hardening exponent n, the stress and strain data were taken from the tensile test for the Aluminum1 species and Steel2 species. The log stress vs. log strain was plotted against each other in order to obtain H and n. The range of the values taken were from the yield stress up until the ultimate tensile stress. For Aluminum1, $n = 0.04$, and $H = 10^{2.5834} = 383.178$. For Steel2, $n = 0.056$, and $H = 10^{2.8621} = 727.95$.