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Experiment 1: Tensile Testing

Objectives

The purpose of this report is to describe the methods, results, and improvements upon tensile testing procedures of various metals, in addition to the effects of manufacturing differences on the material structural properties.

Introduction

Tensile tests are used to define a material's structural properties, such that it can be used safely and effectively in various engineering applications. The two most important quantities derived from tensile testing are the engineering stress σ and the engineering strain ε, which are normalized forms of the force and deformation a material sample experiences. The stress and strain are measured using a tensile test fixture, which consists of a load cell to measure force, an extensometer to measure displacement, and a pneumatic piston to provide tensile force. Once the sensor outputs are related to stress and strain, the relationships between these two values give the yield strength, ultimate strength, ductility, and fracture toughness.

A metal's structural properties are primarily dependent on the presence of atomic singularities and their ability to propagate through a material, which vary based on chemical composition and manufacturing processes. Thus, the same material can have wildly different properties if manufactured differently.

Methods

Prior to setting up the pull test, the width and thickness of the unit under test should be measured using calipers or another suitably accurate measurement device. Additionally, a reference length should be marked along the wishbone axially, as shown in Figure 1. This length is used to validate strain measurements. Once this data has been collected, load the sample into the tensile tester by clamping down on the wide ends of the sample.

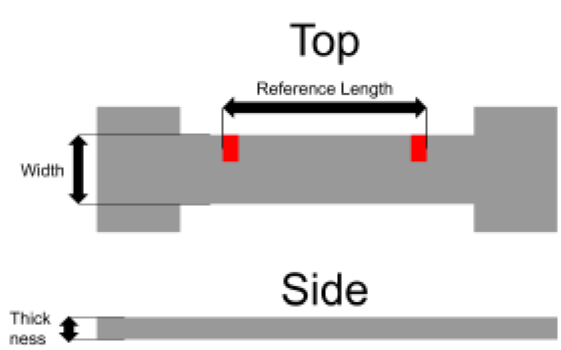


Figure 1: Illustrates the dimensions on the samples that are essential for data collection.

The material sample is secured to the pull tester with two grips, one placed on the stationary bed of the pull tester, and one on the carriage of the fixture. To prevent slipping, it is important to ensure that both grips are making full contact with the entire gripping face of the sample. It is also important to ensure that the sample is aligned to be concentric with the load cell in order to ensure that the load is propagated entirely axially through the sample. This will prevent any of the load from being applied as a shear force in the sample.

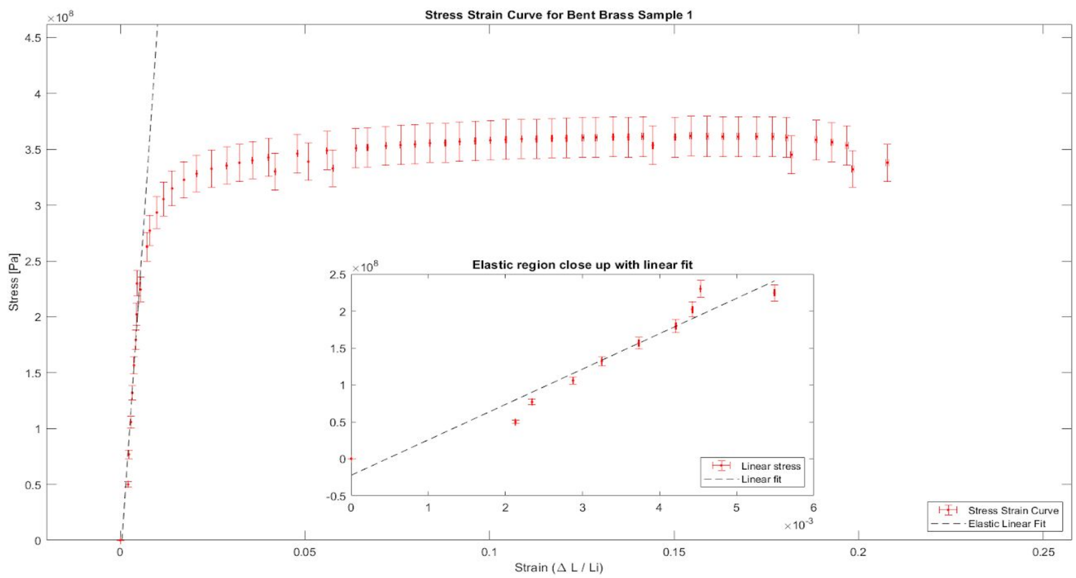
Once the sample is securely held by the two grips, the extensometer can be secured to the unit. This is done simply by mating the bottom ends of the extensometer to the sample using rubber bands that hold down the extensometer. This mating method relies on the friction between the legs of the extensometer and the sample to minimize slipping. This was found to be unreliable at times and will be addressed in the section on extensometer calibration data.

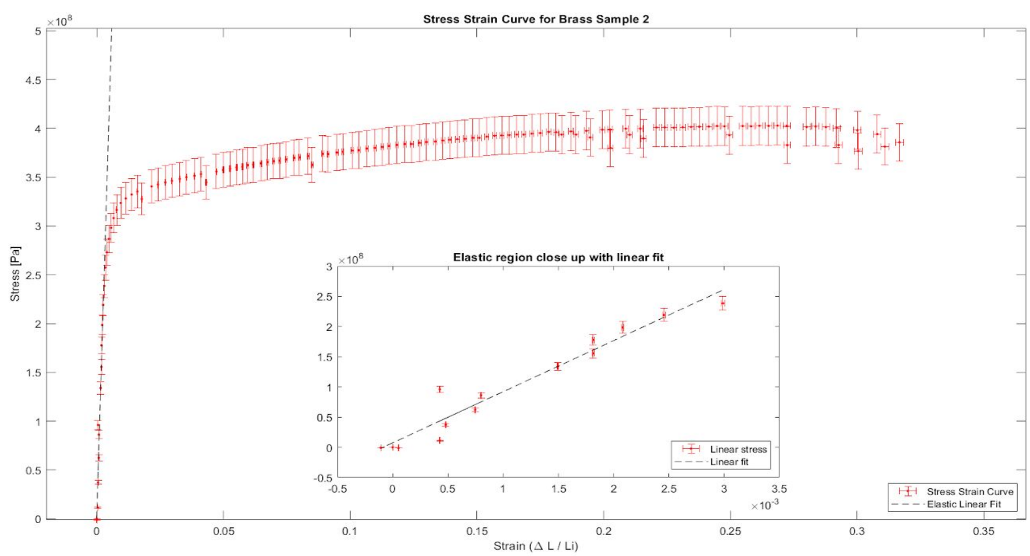
When the extensometer is affixed, a LabVIEW VI is run to collect voltage data from the load cell and the extensometer. A lever is pressed to engage the pneumatic piston, supplying force to the sample under test and fracturing it. This procedure is repeated five times for brass and aluminum samples, and once for an annealed steel sample, an unannealed steel sample, and a brass sample bent 90 degrees and straightened at the center of the gauge length.

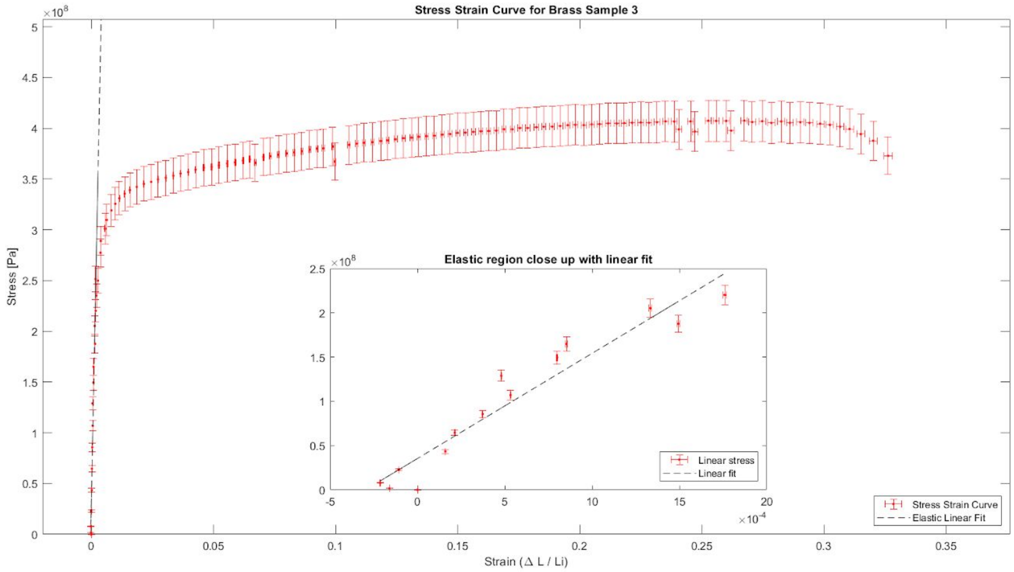
Data

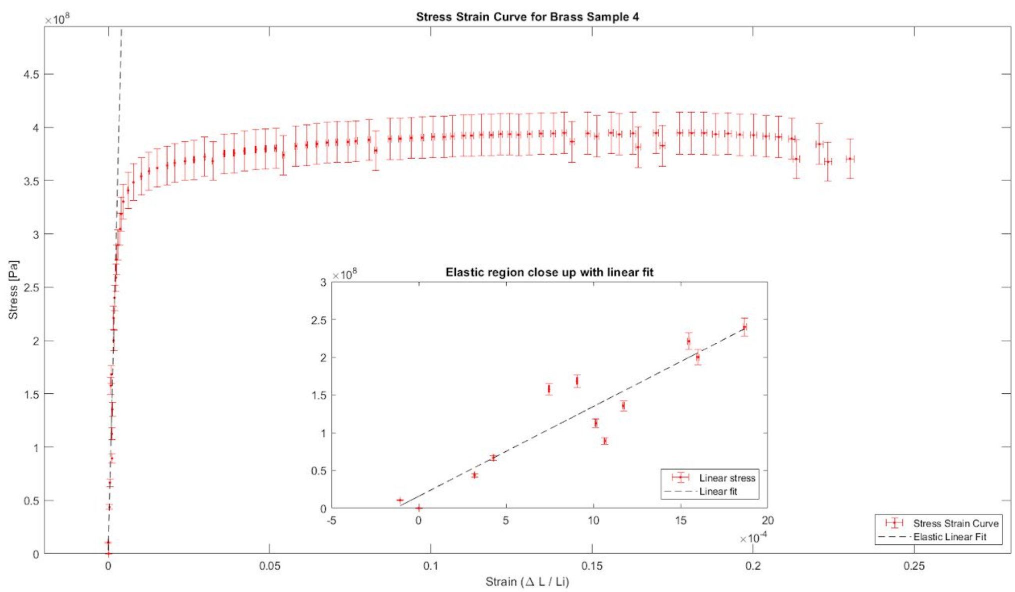
Table 1: Initial and Final dimensions of Brass, Aluminum, and Steel (± 0.01 mm)								
		Initial Dimensions (mm)			**Final Dimensions (mm)**			
Material	**#**	**Length**	**Thickness**	**Width**	**Length**	**Thickness**	**Width**	**Notes**
Brass	1	4.83	0.51	2.08	7.29	0.40	1.52	Plastic flow with necking
	2	4.65	0.51	2.06	6.60	0.38	1.56	Plastic flow with necking
	3	5.79	0.51	2.06	7.44	0.42	1.66	Plastic flow with necking
	4	5.31	0.51	2.06	7.09	0.40	1.60	Plastic flow with necking
	5	4.88	0.51	2.06	6.44	0.42	1.58	Plastic flow with necking
Bent Brass	1	8.08	0.52	2.06	10.26	0.39	1.59	Plastic flow with necking
Aluminum	1	5.28	0.51	2.06	6.22	0.45	1.89	Brittle fracture
	2	5.54	0.51	2.06	6.38	0.46	1.91	Brittle fracture
	3	8.38	0.52	2.06	11.32	0.45	1.86	Brittle fracture
	4	7.76	0.50	2.04	9.38	0.45	1.90	Brittle fracture
	5	7.76	0.52	2.04	8.88	0.45	1.91	Brittle fracture

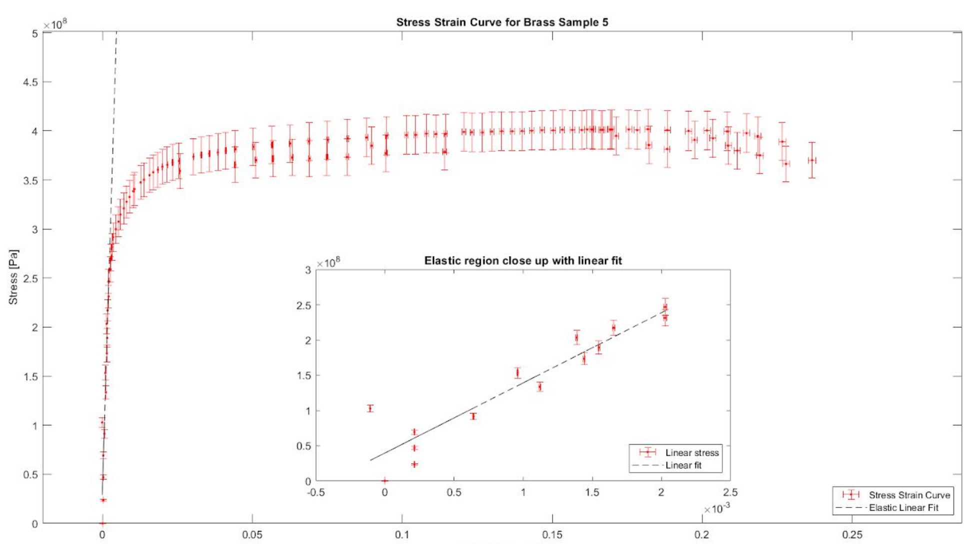
Steel	1	9.02	0.54	2.06	9.28	0.47	1.92	Brittle fracture
Steel (annealed)	1	8.16	0.54	2.08	11.68	0.37	1.18	Plastic flow with extreme necking

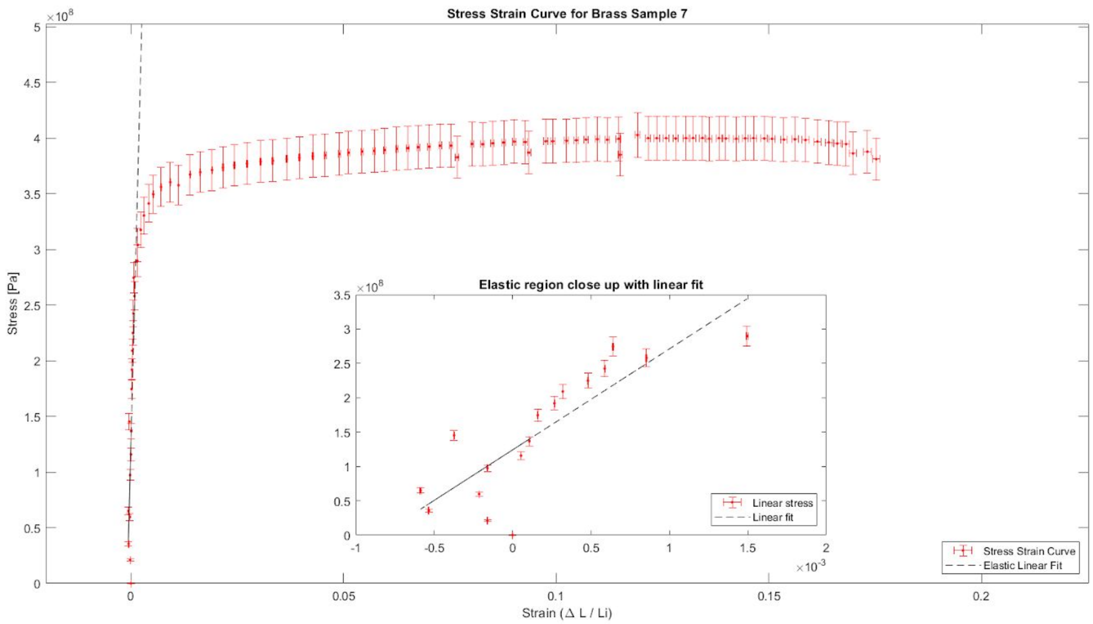




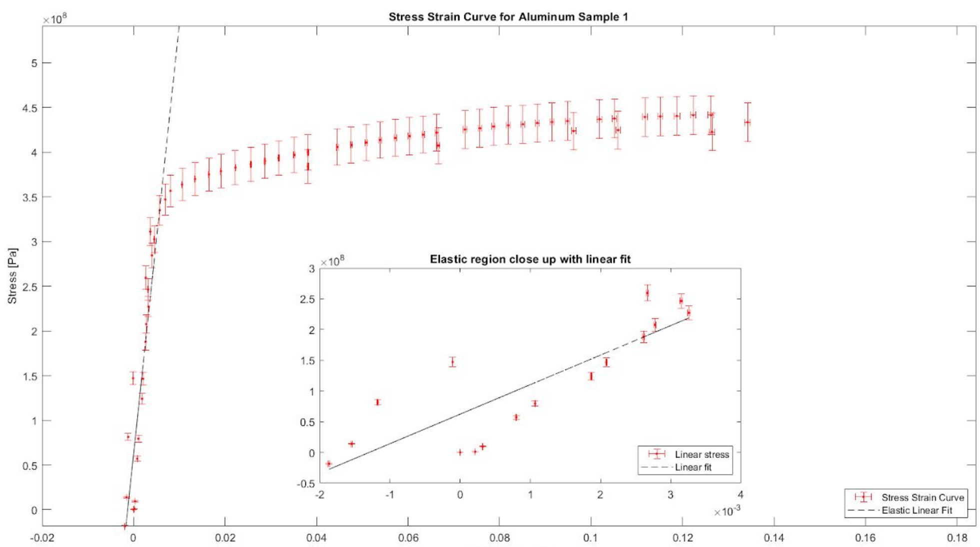

Stress Strain Curve for Brass Sample 3
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)

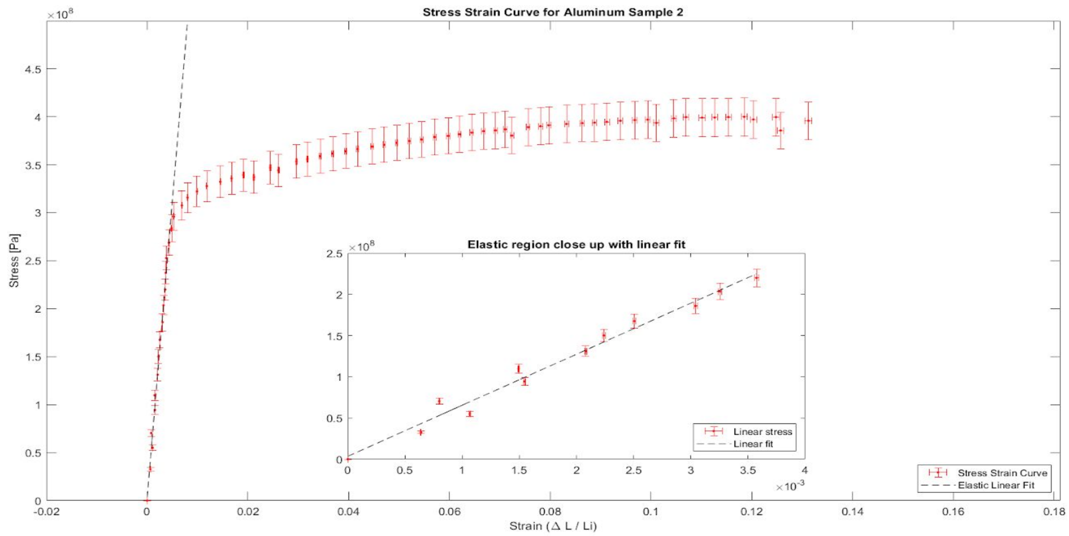

Stress Strain Curve for Brass Sample 4
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)

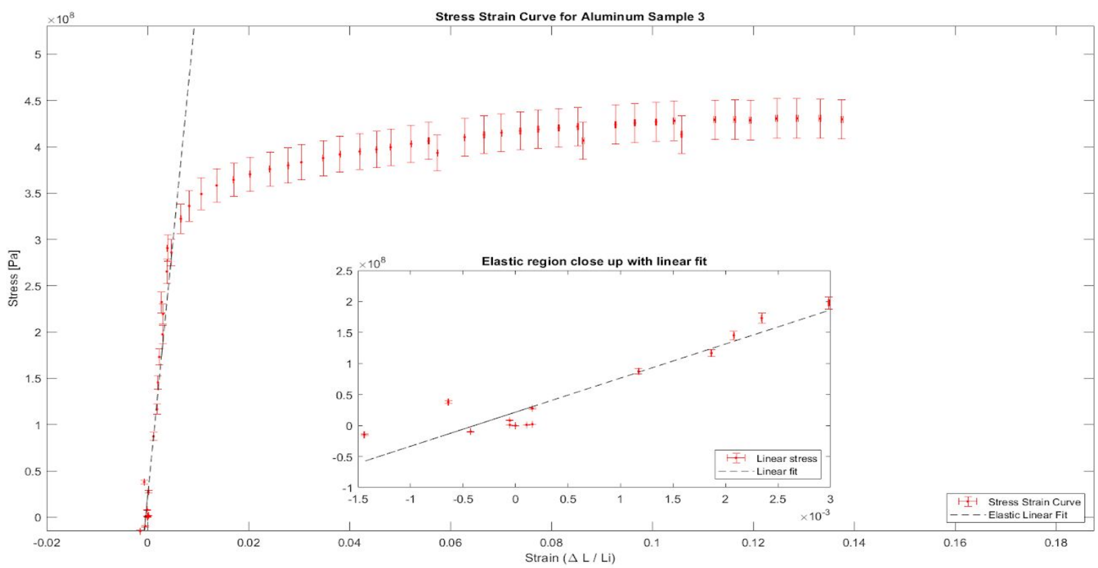

Stress Strain Curve for Brass Sample 5
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)

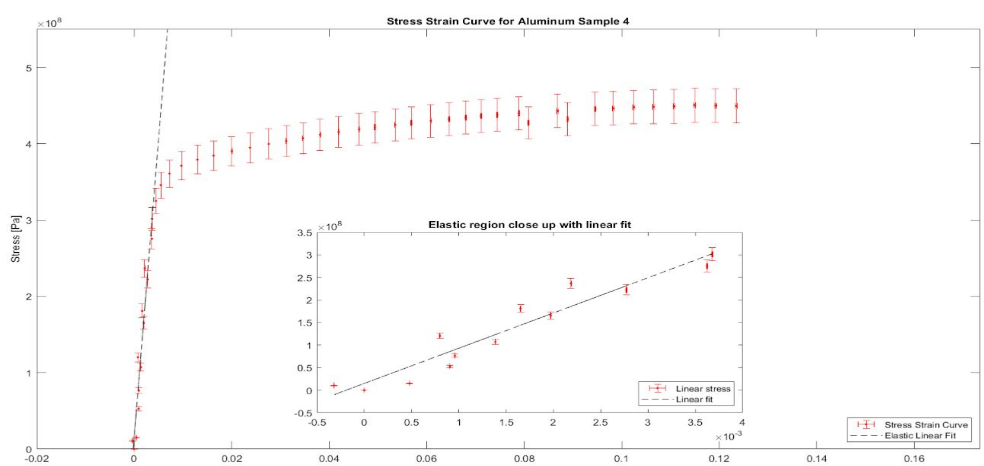


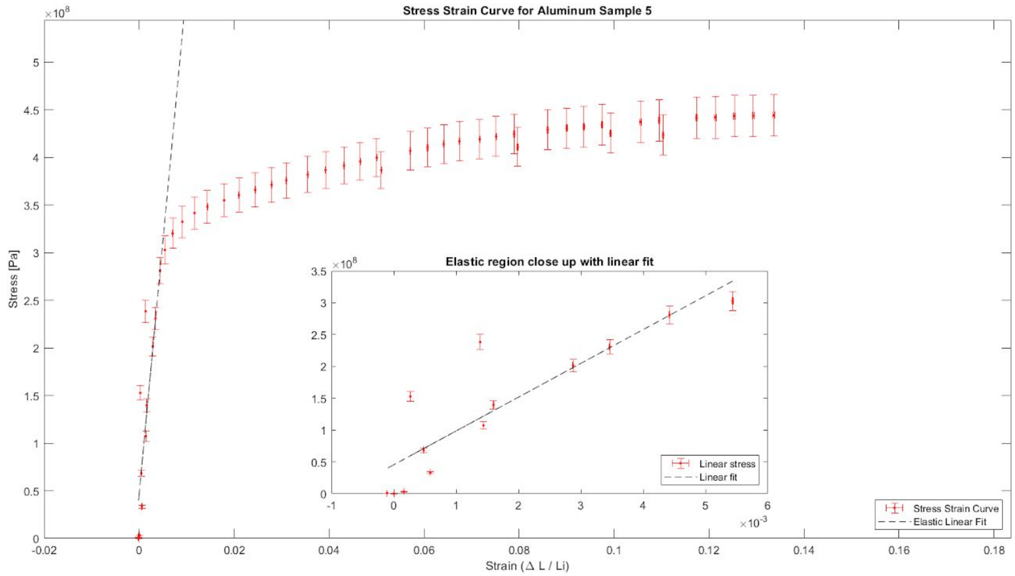
Figures 2-7: From top to bottom, stress-strain data for Brass samples 1-5 and bent Brass sample 1, with linear fit lines in the elastic regime.




Stress Strain Curve for Aluminum Sample 2
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)


Stress Strain Curve for Aluminum Sample 3
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)


Stress Strain Curve for Aluminum Sample 4
Elastic region close up with linear fit
Linear stress
Linear fit
Stress Strain Curve
Elastic Linear Fit
Stress [Pa]
Strain (Δ L / Li)



Figures 8-12: From top to bottom, stress-strain data for Aluminum samples 1-5, with linear fit line shown in the linear elastic region.

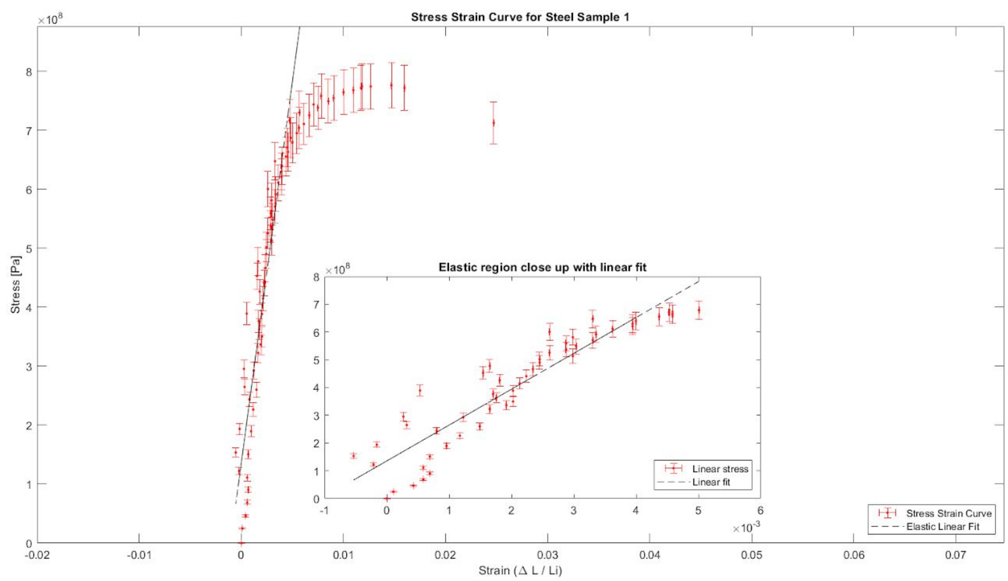


Figure 13: Stress-strain data for unannealed steel, with linear fit shown in the linear elastic region.

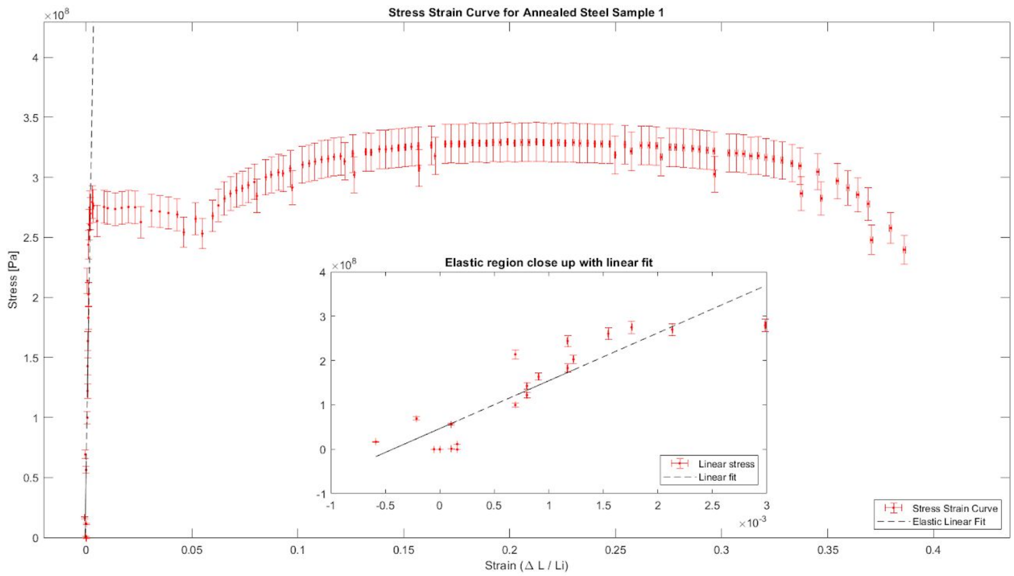
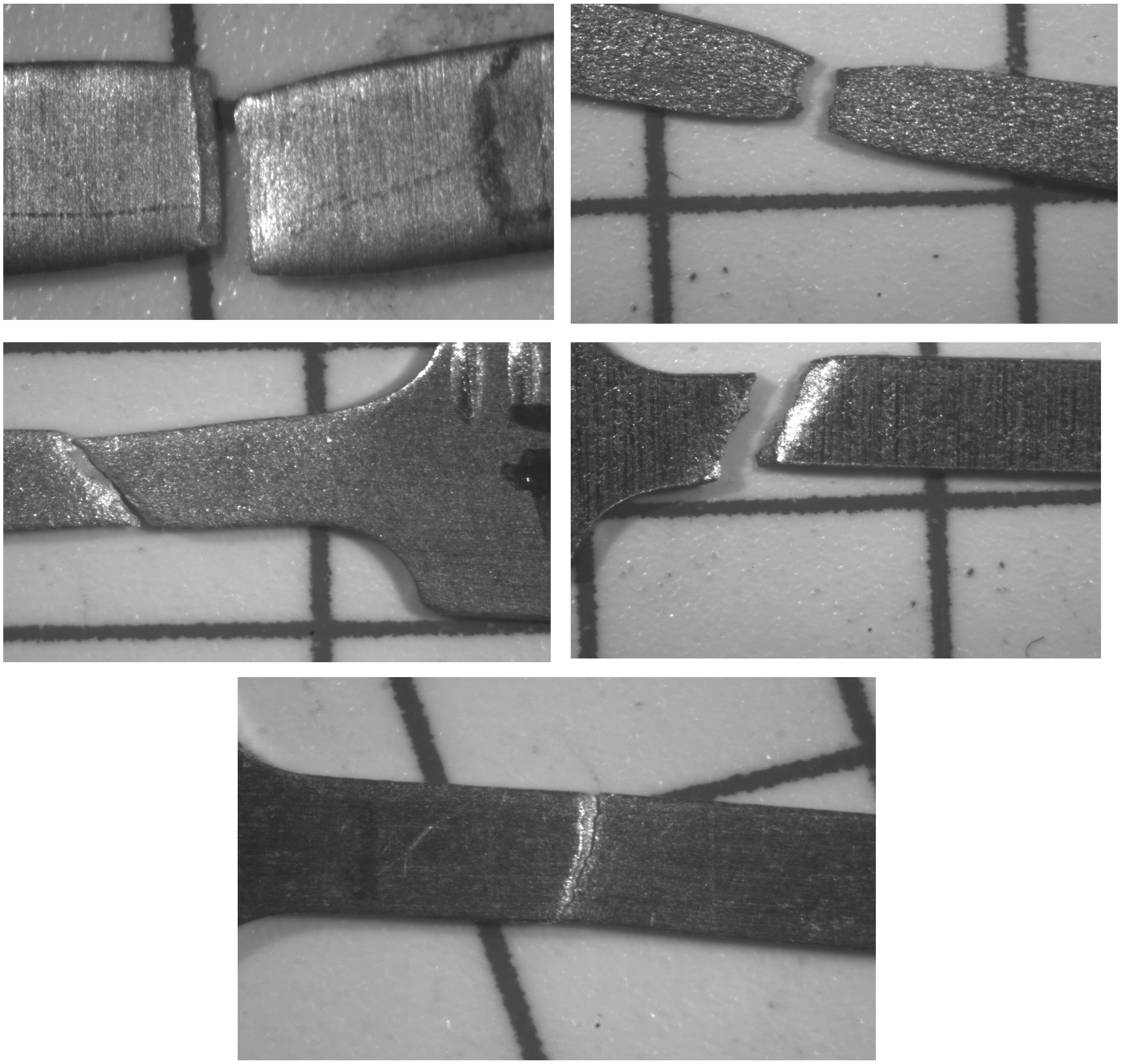


Figure 14: Stress-strain data for annealed steel, with linear fit line shown in the linear elastic regime.



Figures 15-19: Samples after tensile fracture. From top left to bottom, going from left to right, brass sample 1, annealed steel, slipped brass sample, unannealed steel, aluminum sample 4.

Results

Table 2: Cross-sectional area and percent deformation of Brass, Aluminum, and Steel					
Material	#	Initial Area (mm^2)	Final Area (mm^2)	% Elongation	% Reduction of Area
Brass	1	1.061 ± 10.46%	0.608 ± 9.75%	50.932 ± 0.17%	42.68 ± 6.83%
	2	1.051 ± 10.36%	0.593 ± 10.53%	41.936 ± 0.19%	43.58 ± 7.16%
	3	1.051 ± 10.36%	0.697 ± 10.14%	28.497 ± 0.11%	33.64 ± 6.82%
	4	1.051 ± 10.36%	0.640 ± 10.26%	33.52 ± 0.14%	39.08 ± 6.95%
	5	1.051 ± 10.36%	0.664 ± 9.65%	31.967 ± 0.16%	36.84 ± 6.76%
Bent Brass	1	1.071 ± 10.16%	0.620 ± 10.46%	26.980 ± 0.06%	42.11 ± 6.88%
Aluminum	1	1.051 ± 10.36%	0.851 ± 10.77%	17.803 ± 0.13%	19.05 ± 6.85%
	2	1.051 ± 10.36%	0.879 ± 10.65%	15.163 ± 0.12%	16.37 ± 6.83%
	3	1.071 ± 10.16%	0.837 ± 10.60%	35.084 ± 0.06%	21.86 ± 6.60%
	4	1.020 ± 10.46%	0.855 ± 10.83%	20.876 ± 0.06%	16.18 ± 7.18%
	5	1.040 ± 10.26%	0.860 ± 10.88%	14.433 ± 0.06%	17.39 ± 6.96%
Steel	1	1.112 ± 9.79%	0.902 ± 10.48%	2.883 ± 0.04%	18.88 ± 6.18%
Steel (annealed)	1	1.123 ± 9.88%	0.437 ± 8.20%	43.137 ± 0.06%	61.13 ± 6.67%

Table 3: Calculated material properties of Brass, Aluminum, and Steel						
Material	#	Young's Modulus (GPa)	Yield Stress (MPa)	Ultimate Strength (MPa)	Ductility ± 0.5%	Toughnes s (MJ/m^3)
Brass	1	84.7 ± 8.62%	296.7 ± 4.95%	402.8 ± 4.95%	31.6%	119.8
	2	118.8 ± 9.38%	293.5 ± 4.95%	407.5 ± 4.95%	32.6%	125.6
	3	118.8 ± 13.42%	331.6 ± 4.95%	394.7 ± 4.95%	23.0%	87.6
	4	99.5 ± 12.07%	305.2 ± 4.95%	401.7 ± 4.95%	23.7%	90.4

	5	147.1 ± 17.44%	342.1 ± 4.95%	402.7 ± 4.95%	17.5%	67.9
Bent Brass	1	47.9 ± 10.35%	270.4 ± 4.95%	362.0 ± 4.95%	20.8%	71.7
Aluminum	1	48.1 ± 17.37%	360.8 ± 4.95%	441.5 ± 4.95%	13.4%	54.4
	2	61.9 ± 6.74%	308.2 ± 4.95%	399.9 ± 4.95%	13.1%	48.2
	3	55.0 ± 10.88%	334.7 ± 4.95%	430.7 ± 4.95%	13.8%	54.5
	4	78.1 ± 10.09%	354.9 ± 4.95%	450.6 ± 4.95%	12.4%	51.2
	5	53.1 ± 16.99%	326.5 ± 4.95%	444.2 ± 4.95%	13.4%	53.1
Steel	1	129.2 ± 7.84%	758.4 ± 4.95%	776.4 ± 4.95%	2.5%	17.1
Steel (annealed)	1	107.8 ± 13.02%	269.2 ± 4.95%	329.5 ± 4.95%	38.6%	117.7

Discussion

In general, the accepted material properties for each metal are within one standard deviation of the values calculated from the lab data. Some difficulties with lab equipment acted as sources of repeatability error, specifically with the clamps on the tensile test rig and the means of extensometer fastening to the sample under test. It was difficult to verify the clamp is secured evenly on both sides, resulting in an induced moment in some cases, and complete sample slip in the worst cases. Additionally, the rubber bands used to secure the extensometer to the sample under test did not provide sufficient attachment for high strains, resulting in slip at high elongations. To mitigate these errors in the future, the test rig should have a different method of clamping the sample under test, as well as a different method of securing the extensometer to the sample.

Brass

The brass exhibits material behavior comparable to that of other experiments conducted with brass 260 at ½ hard temper. The experimental Young's modulus is 113 ± 23 GPa, while the value reported by AJ Oster is 112 GPa, which is within the standard deviation of the experimental Young's modulus value. Additionally, the experimental yield strength and ultimate strength are 314 ± 22 MPa and 402 ± 5 MPa, which slightly differs from the listed yield value of 350 MPa, but agrees with the listed ultimate strength value of 395-460 MPa. The experimental percent elongation is 25.7 ± 6.4%, which contains the listed percent elongation of 30%. Although the toughness of Brass 260 is not listed on any commonly available sources, the experimental toughness can be found by integrating the stress-strain curve, which gives a material toughness of 98.3 MJ/m^3.

The bent sample, however, has a Young's modulus of 47.9 GPa and a yield stress of 270.4 MPa, which are both significantly lower than the values for the rest of the samples. When the sample is bent into a corner, the top surface of the sample experiences high tensile strain, while the bottom surface experiences high compressive strain. As a result, the final permanent strain is different throughout the sample's cross section, so the uniform strain assumption used to calculate Young's modulus and the engineering stress is invalid. Thus, the calculated Young's modulus for the bent brass brass is vastly different from the rest of the brass samples.

Aluminum

The aluminum exhibits material behavior comparable to that of other experiments conducted with Aluminum 2024. The experimental Young's modulus is 59.2 ± 11.6 GPa, while the value reported by the Aluminum Association is 73.1 GPa. Additionally, the experimental yield strength and ultimate strength are 337 ± 21 MPa and 433 ± 20 MPa, which include the listed values of 324 MPa and 469 MPa, respectively. The experimental percent elongation is 13.2 ± 0.5%, which differs from the listed percent elongation of 19%. Although the toughness of Aluminum 2024 is not listed on any commonly available sources, the experimental toughness can be found by integrating the stress-strain curve, which gives a material toughness of 52.3 MJ/m^3.

Annealed Steel and Unannealed Steel

The annealed steel is significantly more ductile and malleable in comparison to the unannealed steel. The experimental ductility of annealed steel is 38.6% and the experimental ductility of unannealed steel is 2.5%. The experimental Young's modulus of annealed steel is 107.8 ± 13.02% GPa and the experimental Young's modulus of unannealed steel is 129.22 ± 7.84%. The experimental yield strength and ultimate strength of annealed steel are 269.2 ± 4.95% and 329.5 ± 4.95% respectively and for unannealed steel 758.4 ± 4.95% and 776.4 ± 4.95% respectively. As shown in the next section, the annealing the steel reduced its Young's modulus by nearly 18%, the yield stress by nearly 65%, and the ultimate stress by nearly 58%. Clearly, the annealing process significantly reduces the strength of the steel. The difference between the yield stress and ultimate stress is relatively low for unannealed steel which is an indicator that the sample is quite brittle, however the annealed steel behaves more like aluminum in this regard because it sees significant plastic deformation before reaching ultimate stress. This is quantified by the sheer difference in ductility and toughness between the two samples. It's also unsurprising after observing this data that there was significantly more necking observed in the annealed sample than in the unannealed sample.

Appendix

Extensometer Calibration

Table 4: Extensometer calibration data.

Micrometer step (mm)	Extensometer voltage (V)
0	0.31
0.3174	0.42
0.6350	0.52
0.9525	0.63
1.2700	0.73
1.5875	0.83
1.9050	0.93
1.5875	0.83
1.2700	0.72
0.9525	0.61
0.6350	0.51
0.3174	0.40
0	0.30

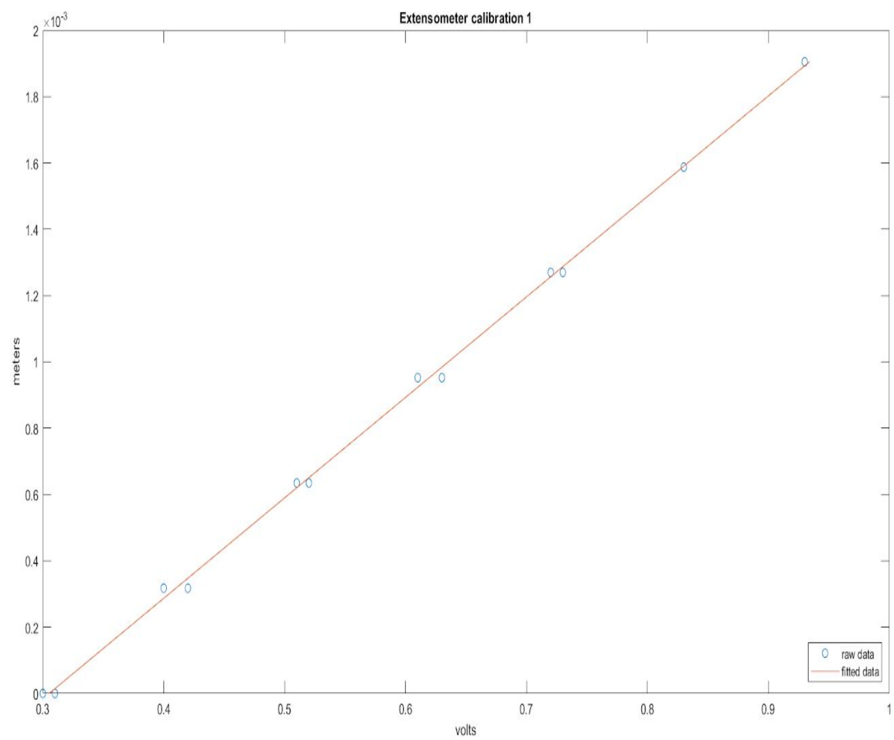


Figure 20: Extensometer calibration data with linear fit. Rsquared=0.9989

The sample strain measurements are recorded by an extensometer, a two-prong sensor with a strain gauge on each prong. The ends of the extensometer affix to the test sample using rubber bands, providing a normal force to prevent slip between the extensometer and the sample under test. When the sample is strained, the extensometer probes extend in proportion to the length extension of the sample, changing the deflection profile of the cantilever probes. The probe deflection causes a change in length in the strain gauges, altering the strain gauge resistance and changing the voltage read by the LabView VI.

In order to calibrate the extensometer, the voltage readings from the extensometer VI must be related to physical changes in the extensometer deflection. The extensometer probes are affixed to the prongs of a desktop micrometer in the same manner as attaching to the test sample. From zero, the micrometer is incremented in steps of 0.3175 mm and the voltage output is obtained from the calibration VI. A linear relationship between the increments and the voltage changes is ensured by cycling up and down through micrometer increments. The extensometer deflection distance is related to the readout voltage by $L = m_L V_L + b_L$ where L is the deflection distance, m_L is the slope of the linear response, V_L is the output voltage, and b_L is the initial voltage at zero deflection. The resting length of the extensometer is measured, and the increments are divided by the resting length to obtain increments of strain.

Sources of Uncertainty

Sources of uncertainty for this experiment include resolution error from the DAQ, the micrometer, and the calipers, random error from extensometer and load cell noise, and repeatability error from extensometer slip and sample misalignment.

DAQ Uncertainty

The resolution uncertainty of the DAQ is on the order of ~1 mV at most, and is not considered in the total uncertainty evaluation since the signal noise from the sensors proves to be much higher.

Micrometer Uncertainty

The resolution error on the micrometer used to conduct the extensometer calibration is neglected for the purpose of this lab, since micrometer displacements much higher than the resolution error resulted in undetectable changes in extensometer voltage.

Caliper Uncertainty

The resolution of the calipers is 0.02 mm, resulting in an uncertainty of ±0.01 mm. This is the most significant source of resolution error, and will affect all geometric measurements of the samples under test.

Extensometer Uncertainty

Noise in the extensometer output voltage scrambled all voltage decimal places after two decimal places, providing an uncertainty of ±0.01 V.

Load Cell Uncertainty

The load cell uncertainty is given as ±1% of the output load cell voltage. In addition to the extensometer uncertainty, the load cell will contribute significantly to the error in the stress-strain plots.

Extensometer Slip

The extensometer is susceptible to slipping during the tensile test if the percent elongation exceeds ~25%, because the device relies on friction to remain fixed on the sample under test. It is difficult to quantify this error, as the amount of slip will change depending on initial extensometer probe deflection, rubber band tension, and surface roughness at the contact point. This source of error can be mitigated in the future by implementing a mechanical fixture point between the extensometer probes and the sample under test.

Sample Misalignment

To ensure all the force applied to the sample is manifested as tensile stress, the sample must be kept as straight as possible, and the ends of the sample must be clamped perfectly evenly. Otherwise, a moment is induced upon the sample, causing the sample to slip out of the clamp, or creating stress concentrations at the sample shoulder and causing a fracture towards the end of the gauge length. If the sample slips and rotates, not all of the force transferred to the sample under test manifests as tensile stress, resulting in unforeseen errors in the derived material properties. If the sample fractures at the shoulder, there is a high likelihood the fracture is outside the portion of the gauge length inside the extensometer, resulting in inaccurate strain data and corrupting the derived material properties. To mitigate this error in the future, a more sophisticated tensile test rig is required to better ensure uniform clamping and closer alignment of the sample with the direction of applied force.

Propagated Uncertainties

Error Measurements

The calipers were made sure to be zeroed with a perceived zero offset. When using the calipers we made sure to take readings from the dial caliper on a flat surface and looked at a perpendicular angle to the dial to limit parallax error. The parallax error from using the calipers is below the resolution of the calipers and are thus excluded from this report.

The length measurements before and after fracture for each sample are taken at the outside of the pen markings to maintain consistency, but there is some error associated with the ability to perfectly line up the caliper jaws to the pen markings. Since the possible deviation from the outer reference length is difficult to quantify, and is small by inspection, alignment error of the calipers to the reference markings is neglected.

The error in the load cells were given to be ±1%. The extensometer correlation was recorded in increments of 0.0125 inch.

The calipers and micrometer were given in inches while the load cell was in newtons per volt, leading us to convert everything into SI units.

Stress error: $\Delta\sigma/\sigma = \sqrt{(\frac{\Delta F}{F})^2 + (\frac{\Delta w}{w})^2 + (\frac{\Delta t}{t})^2}$

Strain error: $\Delta\varepsilon/\varepsilon = \sqrt{(\frac{\Delta m_L}{m_L - L_o})^2 + (\frac{\Delta L_o * m_L}{L_o * (m_L - L_o)})^2}$

Elastic modulus error:

$$\Delta E/E = \sqrt{(\frac{\Delta F}{F})^2 + (\frac{\Delta w}{w})^2 + (\frac{\Delta t}{t})^2 + (\frac{\Delta m_v}{m_v})^2 + (\frac{\Delta m_L}{m_L})^2 + \frac{\Delta Ev}{Ev}}$$

Where F, w, t, mv, mL, Lo, and Ev, represent, force, width, thickness, slope of the voltage voltage plot, slope of the extensometer calibration, gauge length, and slope of the linear voltage-voltage best fit line respectively.

Works Cited:

ASM Metals Reference Book, Third edition, Michael Bauccio, Ed. ASM International, Materials Park, OH, 1993.

"Specification for Cartridge Brass Cartridge Case Cups." doi:10.1520/b0129-02.