Lab 3: Tension Test

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Background and Objectives

The design of everything from small instruments to large buildings is informed by the properties of the materials used in construction. It is therefore essential that engineers fully understand the strengths and limitations of these materials to optimize performance and ensure user safety. In this lab, we perform tensions tests to investigate A36 Steel (low carbon), C1050 Steel (hot rolled and annealed), 2024-T351 Aluminum, and Acrylic. Load and displacement data allow us to plot stress and strain to calculate each material's modulus of elasticity, yield stress, ultimate stress, and percent elongation. This will prompt a discussion into various types of material properties (such as ductile and brittle) and methods of measuring displacement (using the LVDT, extensometer, or strain gauge). Overall, our knowledge of such critical material properties is essential for engineers to create advanced structures that can property react to their surroundings and applied loads.

Experimental Methods and Analysis

Performing a tension test to plastically deform and break materials as strong as steel requires heavy machinery. In this lab, we utilized a 100 kips MTS machine with several key features and supporting sensors attached, as shown in figures (1) and (2) below. The upper crosshead of the universal testing machine displaces at a constant 0.00083in/s, an ASTM standard. The slow rate gives atoms in the material time to properly react to the force; any faster and the test would be considered unreliable. The cross head contains a load cell for measuring force applied, later used to calculate stress in the material. An internal linear variable differential transducer (LVDT) also located in the upper crosshead measures its displacement. However, for more accurate strain calculations, we placed an extensometer on the material coupon itself. To compare methods of measuring strain, a strain gauge is used for the C1050 tests. All sensor values are recorded by the connected computer, and information about the test material coupons are recorded by hand (discussed later).

Figure (1): MTS Machine Setup

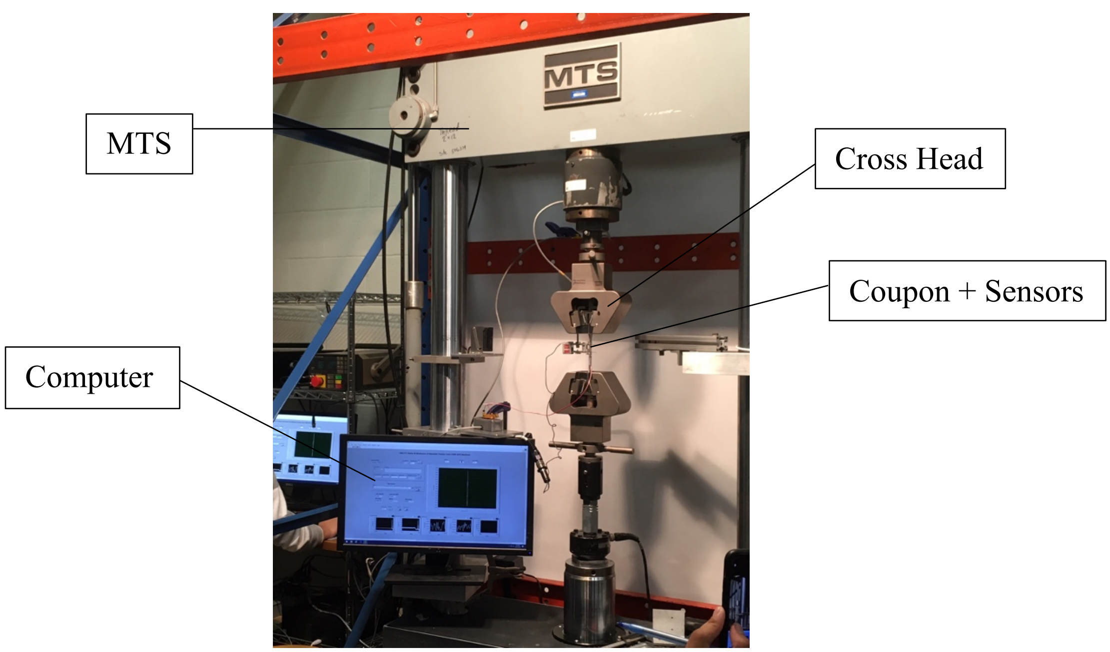


Figure (2): Sensor Setup on Coupon

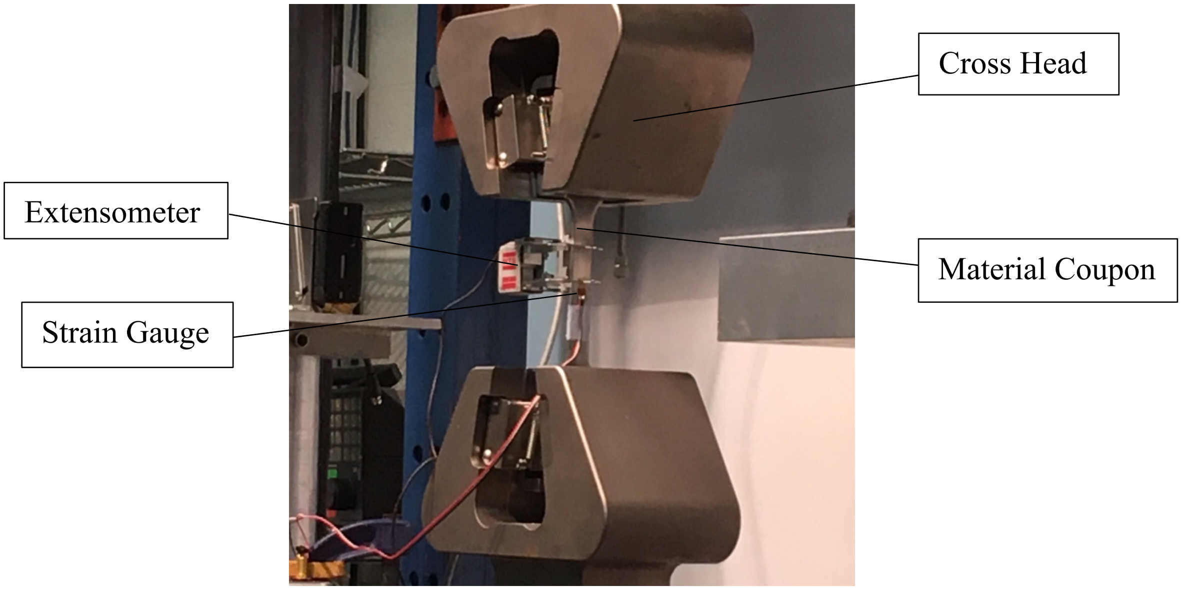
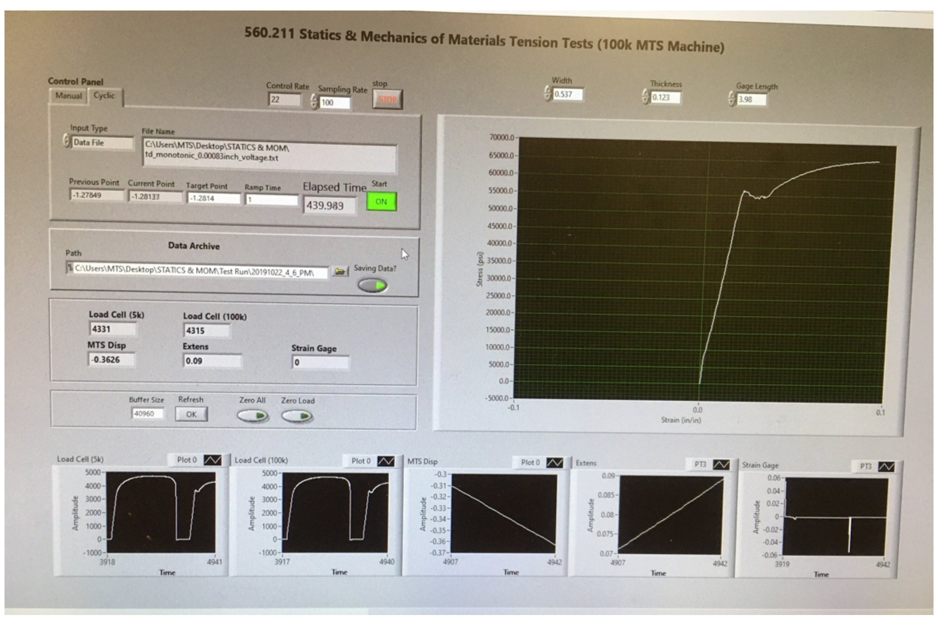
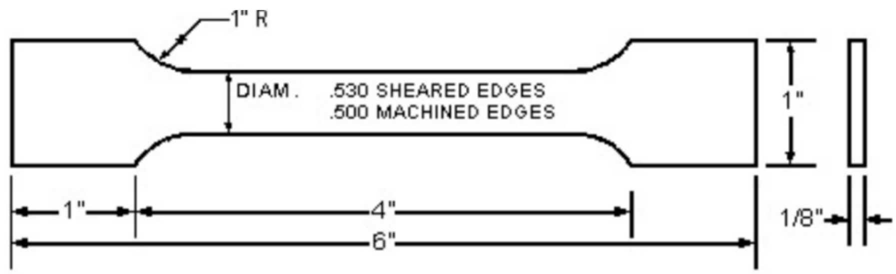


Figure (3): Computer Screen during Tension Test



For this lab, we performed tension tests on four materials: A36 Steel (low carbon), C1050 Steel (hot rolled and annealed), 2024-T351 Aluminum, and Acrylic. While the material itself plays a critical role in the measured results, so does the shape of the test specimen. Therefore, we used pieces of material that are as similar as possible in design, following the ASTM standard for a tension test coupon with the dimensions shown in figure (4).

Figure (4): Dimensions of Standard ASTM Coupon used in Lab



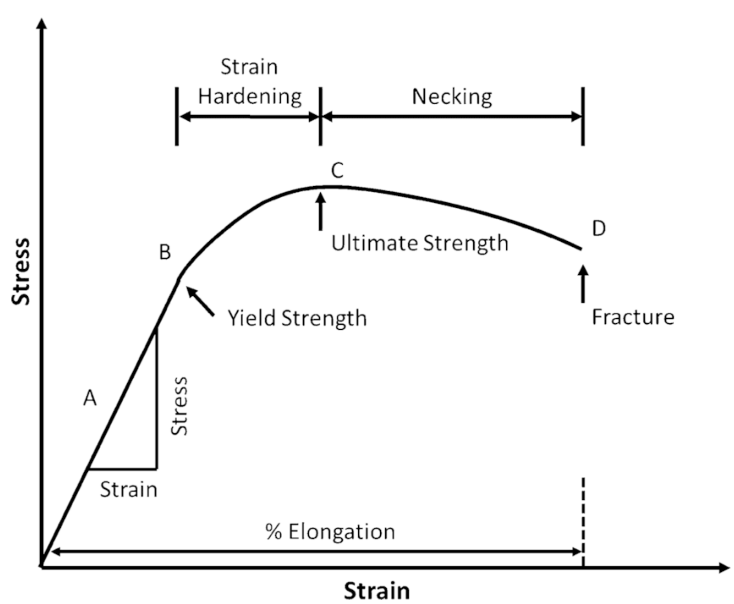
Because we want the most accurate measurements of each coupon used in the test, we additionally measured the dimensions again and calculated various attributes of the material piece, shown below.

Table (1): Dimensions of Coupons Before Test

Material	Width(in)	Thickness (in)	Initial Cross Section Area (in^2)	Gage Length (in)	Weight (lb)
A36 Steel	0.501	0.1250	0.0626	4.035	0.155
C1050 Steel	0.537	0.1235	0.0663	3.980	0.150
Aluminum	0.535	0.1245	0.0666	3.984	0.055
Acrylic	0.525	0.1250	0.0656	3.998	0.020

From both the measurements recorded in the computer and the ones by hand, we can calculate each material's modulus of elasticity, yield stress, ultimate stress, and percent elongation. The graph below displays a standard stress vs. strain curve and the visual representation of the desired values, which the following equations will be used to derive.

Figure (5): Stress Strain Curve Model[1]



[1] https://www.researchgate.net/publication/236924185_Plasticizer_Effects_on_Physical-Mechanical_Properties_of_Solvent_Cast_SoluplusR_Films/figures?lo=1&utm_source=google&utm_medium=organic

The engineering stress (ksi) present in the coupon during the tension test is defined as:

$$\sigma = \frac{P}{A} \tag{1}$$

Where P is the force (kips) and A is the initial cross-sectional area (in^2) of the coupon.

Strain is outputted by the strain gauge (already converted to volts by the computer) and extensometer (where the displacement is divided by factor 1 to be equivalent to strain). Strain ε (in/in) in the material can also be calculated by using the displacement δ (in) measured in the LVDT:

$$\varepsilon = \frac{\delta}{L_o} \tag{2}$$

Where L_o is the initial length of the specimen in inches.

The final length and area of each coupon is measured after its tension test. The percent change in the quantities are given by:

$$\%\ Elongation = \frac{L_f - L_o}{L_o} \tag{3}$$

$$\%\ Reduction\ in\ Area = \frac{A_f - A_o}{A_o} \tag{4}$$

The Modulus of Elasticity is given by the relationship of stress and strain (the slope on plots):

$$E = \frac{\sigma}{\varepsilon} \tag{5}$$

Results

After conducting each tension test, final measurements were taken of the width and length of the two coupon halves rejoined. From these datapoints, final area, gage length, percent elongation, and percent reduction in area were calculated according to equations (3) and (4), as given in the table below.

Table (2): Dimensions of Coupons After Test

Material	Width (in)	Thickness (in)	Area (in^2)	Length (in^2)	Elongation (%)	Reduction (%)
A36 Steel	0.487	0.085	0.0413	4.603	14.08	33.94
C1050 Steel	0.432	0.093	0.0403	4.740	19.09	39.07
Aluminum	0.487	0.114	0.0557	4.445	11.58	16.28
Acrylic	0.529	0.127	0.0672	3.994	0.10	2.44

From this information, stress and strain were calculated according to equations (1) and (2). The following four plots display the stress strain curves of each material: A36 Steel (low carbon), C1050 Steel (hot rolled and annealed), 2024-T351 Aluminum, and Acrylic. The linear portion of which the modulus of elasticity was calculated is highlighted in orange. The green line represents the associated 0.2% offset used to calculate yield strength, determined by the point at which it intersects the stress strain curve. The 0.2% offset method is described in Appendix §A.

A sample of the data recorded by the MTS computer is in Appendix §B.

Figure (6): A36 Steel Stress Strain Curve

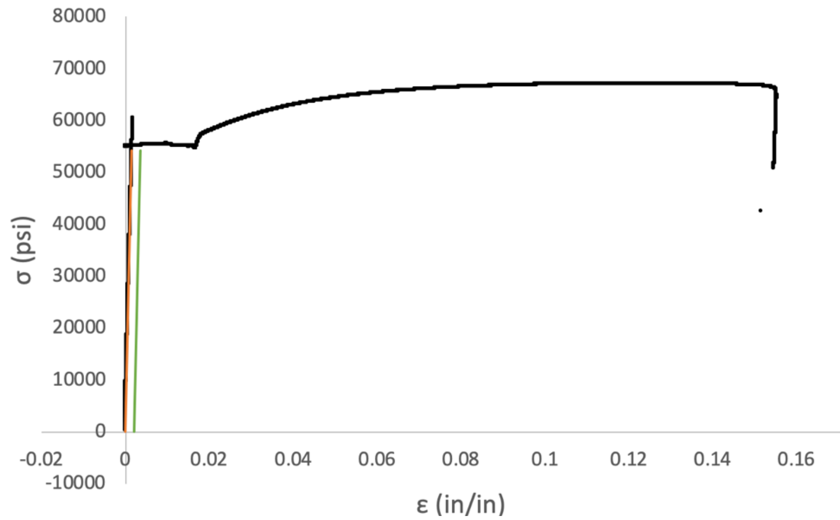


Figure (7): C1050 Steel Stress Strain Curve

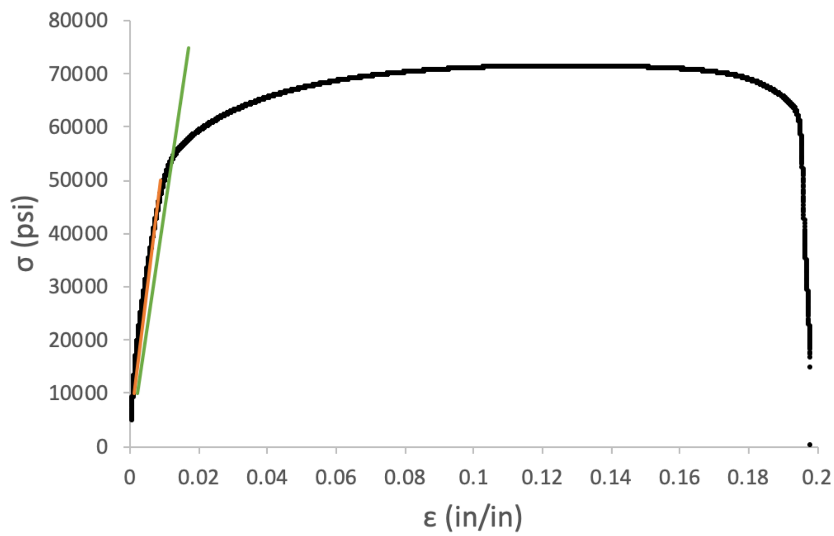


Figure (8): 2024-T351 Aluminum Stress Strain Curve

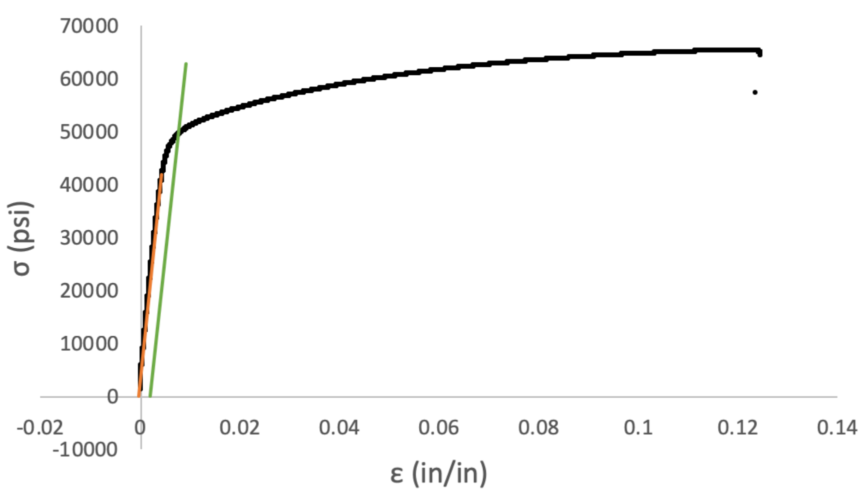
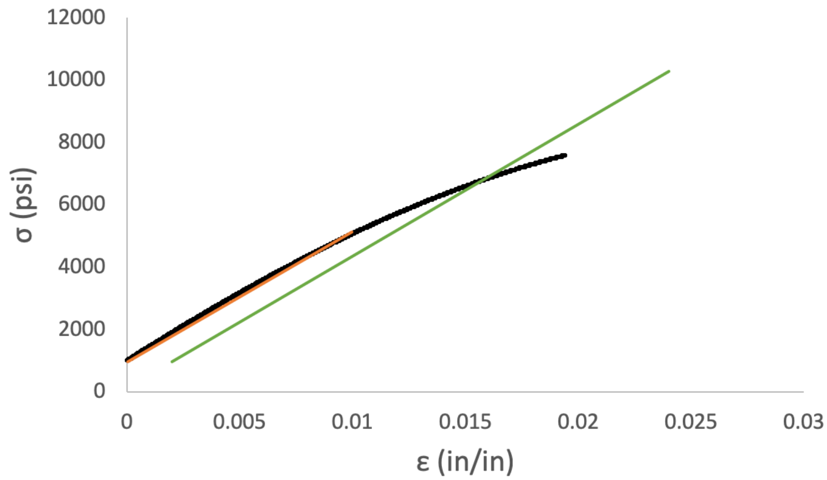
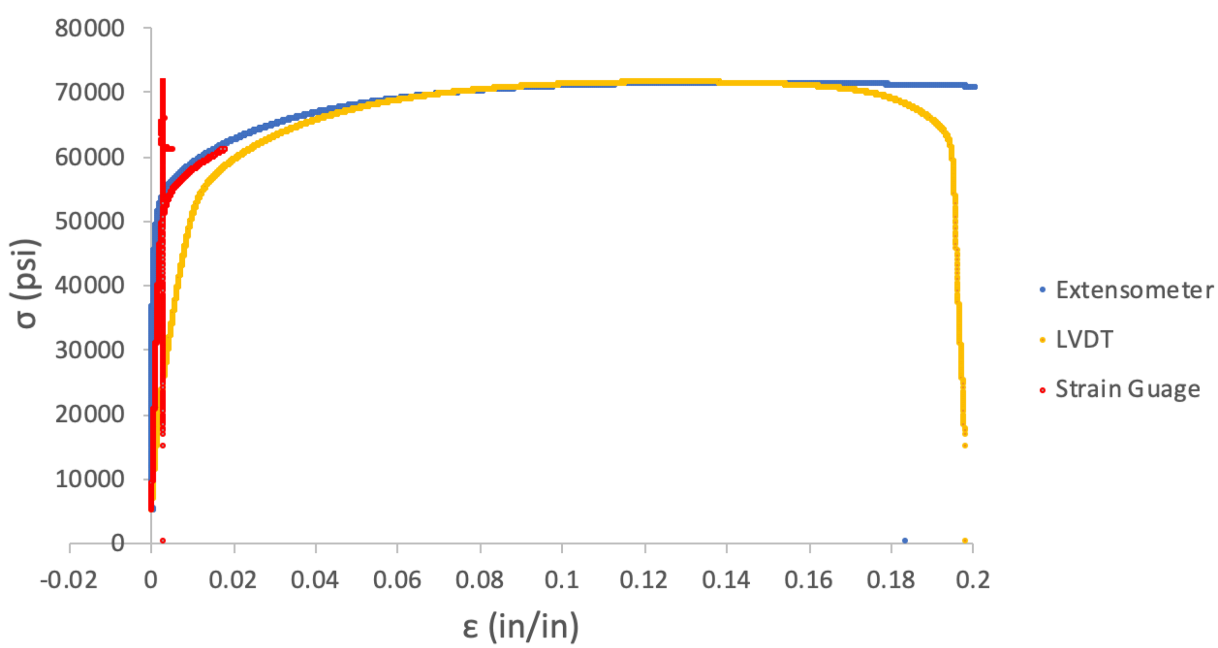


Figure (9): Acrylic Stress Strain Curve



In order to compare methods and types of sensors used to measure displacement, the plot below displays the three overlayed stress strain curves of the C1050 during the tension test, each one using the extensometer, strain gauge, and LVDT calculated strain values on the x axis.

Figure (10): C1050 Stress Strain Curve for Strain Measurement Comparison



From the stress strain plot of each material coupon, the modulus of elasticity is determined by calculating the slope of the linear portion of each stress strain plot (indicated by the orange line). The yield strength is calculated using the 0.2% offset method (described in Appendix §A). Ultimate strength is found by the maximum stress value that the material reaches before entering the necking phase. The material properties calculated in this lab are displayed in table (3) below. These are compared to published values in table (4), from AZO Materials (azom.com), and calculated percent error in table (5).

Table (3): Calculated Material Property Results

Material	E (ksi)	σ_y (ksi)	σ_u (ksi)	Elongation (%)	Area Reduction (%)
A36 Steel	20799	54.939	67.162	14.089	33.942
C1050 Steel	29517	57.185	71.855	19.095	39.077
2024-T351 Aluminum	8179.1	49.194	65.765	11.585	16.28
Acrylic	417.8	6.732	7.542	0.1	2.44

Table (4): Published Material Properties

Material	E (ksi)	σ_y (ksi)	σ_u (ksi)	Elongation (%)
A36 Steel	27000	36	69	20
C1050 Steel	28000	84.1	100	10
2024-T351 Aluminum	10600	41	68	20
Acrylic	400	8.1	9.2	1.5

Table (5): Percent Error of Calculated Material Properties

Material	E (ksi)	σ_y (ksi)	σ_u (ksi)	Elongation (%)
A36 Steel	23.0	52.6	2.7	29.6
C1050 Steel	5.4	32.0	28.1	91.0
2024-T351 Aluminum	22.8	20.0	3.3	42.1
Acrylic	4.5	16.9	18.0	93.3

Table (6): Calculated Strength to Weight Ratios

Material	E (ksi)	Weight (lb)	σ_y / Weight (in^{-2})
A36 Steel	20799	0.155	134,187
C1050 Steel	29517	0.15	196,780
2024-T351 Aluminum	8179.1	0.055	148,709
Acrylic	417.8	0.02	20,890

Note: strength to weight ratio involves density, but it is assumed that the volume of each coupon is the same, and so their mass is sufficient for the calculation.

Discussion

The results obtained from the lab give valuable information about the properties of the materials tested, specifically their ductility, strength, and strength to weight ratio. Ductility is a measure of a material's ability to undergo plastic deformation before rupturing. In the lab, percent elongation and percent reduction in area indicate how ductile a material is (higher percentages mean more ductile), which was exhibited by the necking phase of the tension test. Both elongation and area reduction rankings align in order to show that the C1050 steel is the most ductile material tested, followed by A36 steel and then 2024-T351 Aluminum. A relative note is the known proportional relationship between steel carbon content and ductility, explaining why the high carbon C1050 is more ductile than the low carbon A36 steel. Acrylic displayed very little elongation or reduction in area, and we did not see necking during the tensile test, so it is described as a brittle material. For some materials, ductility is important for structures that must adapt to absorb energy. An engineer designing a building must account for sway due to strong lateral winds and allow for elastic behavior to occur in the frame of the tower, rather than rigidity which could cause collapse. Similarly, ductile structures are essential for engineers to essentially see a failure before it happens: the material visually deforms, causing the structure to be determined unsafe, instead of instantly braking/collapsing.

Material strength is a measure of its ability to withstand various applied loads without failure, a property represented by each material's modulus of elasticity, yield strength, and ultimate strength in the lab. Similar to ranking materials based on ductility, all three metrics computed give the same order of material strength. C1050 steel is the strongest of the materials tested, followed closely by A36 steel. Of slightly less strength is the 2024-T351 Aluminum, and Acrylic is relatively weak. As seen by comparing the ranking of ductility and strength, there is a correlation between the two material properties. An essential measure for engineers designing both strong and light structures is the strength to weight ratio of a material, as displayed in table (6). Based on the measurements in the lab, C1050 steel had the best strength to weight ratio, followed by 2024-T351 aluminum and A36 steel, and acrylic with a relatively low value.

Visually inspecting the stress and strain curves of the four materials in figure (6) to figure (9), we can define the particular regions of the tensile test. The C1050 steel and 2024-T351 Aluminum had rather similar phases during the experiment. Both exhibit an elastic region where linear regression lines were fit for the calculation of modulus of elasticity, followed by the occurrence of the material's yield strength into the plastic region and necking. The C1050 peaked at an ultimate stress of approximately 72 ksi stress at 0.13 in/in strain, and then continued with decreasing stress until the rupture point. Alternatively, aluminum continued in the plastic region until rupturing at its ultimate strength of approximately 66 ksi stress at 0.13in/in strain. Similar to aluminum, acrylic also ruptured at its ultimate strength. As discussed previously, acrylic is brittle and therefore has no indication of the onset of a breaking point. Instead, it increased in stress without a visually clear yield point to an ultimate stress of 7.5 ksi at 0.02 in/in strain before suddenly rupturing. Finally, A36 steel exhibited a different kind of stress strain curve than the other materials. While still a ductile material, A36 steel reached its yield strength of approximately 55 ksi at 0.002 in/in strain, decreased slightly and then increased again in stress during the phase of strength hardening, and finally reached its ultimate strength of approximately 67 ksi stress at 0.12 in/in strain. The material then ruptured soon afterwards. A36 had the clearest defined regions of all the materials, with obvious transitions between the elastic region, yield plateau, strain hardening, and ultimate stress.

The values for each material's modulus of elasticity, yield stress, ultimate stress, and percent elongation are moderately close to the published values, as displayed in table (4). Percent errors, displayed in table (5), for modulus of elasticity and ultimate strength are relatively accurate with values under a 30% error. Yield strength values range from approximately 15% to 50% error. Percent elongation calculations are relatively inaccurate, ranging from approximately 30% to 90% error. No material stands out among the others as being significantly more or less accurate, indicating that none of the tensile tests should be considered outliers in the experiment. Some error during the experiment derives from the sensors used to measure the various values, which prompts the discussion in the next paragraph about types of sensors used to measure strain. Error also propagates with the placement of the material coupons in the MTS machine. If the specimen is slightly off center, then the machine would apply tension at a slight angle, or even apply a torsion. Possible non-axial forces are important to note especially because the coupons break exactly at a 45-degree angles due to the internal shear stresses, which could be altered by imperfect axial loads. Lastly, the preparation of the specimens effects their properties: some may have been die cut / punched, while others were milled / laser cut. Specimens that were punched may have had additional internal imperfections introduced during the manufacturing process.

As a secondary objective in the experiment, we seek to compare strain measuring devices. Figure (10) gives three stress strain curves of C1050, each one plotted using a different source of strain data, and the same method of calculating stress. The LVDT and extensometer yield very similar curves, only slightly varying with their slope of the elastic region. Because the percent error of the modulus of elasticity of the stress strain curve using the extensometer is only around 5%, we can conclude that the extensometer gives the most accurate strain values, with the LVDT providing similar measurements. While both the extensometer and LVDT curves can measure for the entire tensile test, the strain gauge cannot provide such information. A strain gauge by design is attached to the coupon with adhesive that, when the specimen is elongated, breaks. This hinders the ability of the device to measure strain at points past the yield stress of the material, once it starts necking. However, during the elastic region of the stress strain curve, the strain gauge can accurately measure strain, indicated by the similarity of its curve and that of the extensometer.

An alternative experiment with similar objectives would be to do the same tests but with different differences between the coupons. In this lab, we compared several different materials. In the alternative experiment, we could compare a specific difference between specimens. For example, observe the change in modulus of elasticity or yield strength relative to carbon levels in steel or compared to the process by which the material was heat treated. This would demonstrate the same concept of axial loads creating axial stress-strain curves but focus on the variation of a specified independent variable.

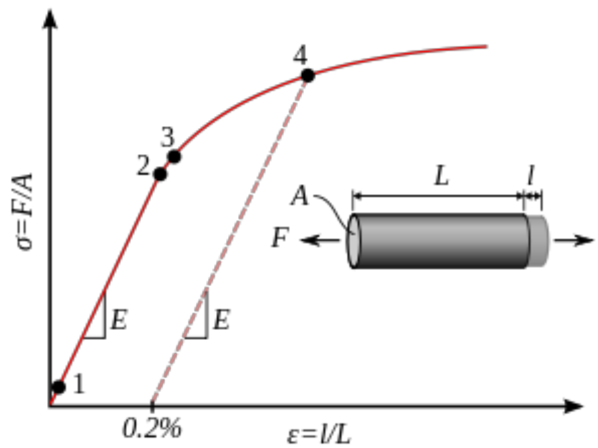
Conclusion

The primary objective of this experiment was to determine the modulus of elasticity, yield stress, ultimate stress, and percent elongation of four materials: A36 Steel (low carbon), C1050 Steel (hot rolled and annealed), 2024-T351 Aluminum, and Acrylic. An MTS machine was used to provide large tensile forces on ASTM standard coupons. The stress and strain on the specimen were derived from recorded values during the test and used to plot curves to calculate the desired material properties. Comparing these properties to published values, we see moderately accurate results, ranging from 5% to 50% error. We also wanted to investigate the accuracy of different strain measuring devices and compared the strain measurements from an extensometer and LVDT with a strain gauge, revealing that the extensometer is the most reliable and accurate device. Overall, the experiment granted unique insight into the properties of the four materials and reveled special trends that materials follow, important concepts for engineers to understand when building safe and sturdy structures.

Appendix

Appendix §A: 0.2% Offset Method

The 0.2% offset is a standard method used to calculate the yield strength of a material from the stress strain curve. After regressing a line to determine modulus of elasticity, its formula is used to graph a new line that has an x-intercept of exactly 0.2% more (0.002 in/in strain value). This process is visualized by the figure below,[2] where point 4 corresponds to the yield strength.



Appendix §B: Sample of MTS Computer Recorded Data

Table A.1: Example of Data Recorded During the C1050 Steel Tension Test

Time sec	**Load** lbf	**Crosshead** in	**Extensometer** in/in	**Strain Gauge** in/in	**ε = ΔL/L** unitless	**σ = (P/A)** lb/in^2
0.16700000	359.64944048	0.00009145	-0.00004251	0.00001840	0.00002298	5424.57677942
0.26699999	374.28957404	0.00017352	-0.00004748	0.00002361	0.00004360	5645.39327368
0.36700001	389.01793525	0.00025559	-0.00005033	0.00003325	0.00006422	5867.54050143
0.46700001	403.26050935	0.00033766	-0.00005672	0.00003502	0.00008484	6082.36062363
0.56699997	416.89081388	0.00041972	-0.00005805	0.00005283	0.00010546	6287.94591067
0.66700000	429.53851233	0.00050179	-0.00006267	0.00006242	0.00012608	6478.71059316
0.76700002	443.75976361	0.00058386	-0.00006649	0.00006576	0.00014670	6693.20910418
0.86699998	458.28806900	0.00066828	-0.00007169	0.00007095	0.00016791	6912.33889891
0.96700001	471.76453088	0.00074800	-0.00007512	0.00007667	0.00018794	7115.60378408
1.06700003	485.90685754	0.00083241	-0.00007878	0.00008947	0.00020915	7328.91187845
1.16700006	500.19479409	0.00091448	-0.00008209	0.00009499	0.00022977	7544.41620049
1.26699996	514.14277298	0.00099655	-0.00008569	0.00010289	0.00025039	7754.79295594
⋮	⋮	⋮	⋮	⋮	⋮	⋮

[2] https://en.wikipedia.org/wiki/Universal_testing_machine