Tensile Testing Laboratory

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Executive Summary

Tensile tests are fundamental for understanding properties of different materials, and how they will behave under load. This lab tested four different materials, including A-36 hot rolled steel, 6061-T6 Aluminum, polycarbonate, and polymethylmethacrylate (PMMA). Each material was tested three times using an Instron load frame and the BlueHill data acquisition software. The data from each test was used to determine valuable material properties such as ultimate tensile strength, modulus of elasticity, and yield strength. Other calculated properties included true fracture strength, percent reduction of area, and percent elongation. These material properties were used for comparing the materials to each other, and to define the material as brittle or ductile.

The true stress and true strain were calculated for one sample of 6061-T6 aluminum to show the difference between the engineering stress and strain, and the true values. The engineering stress is an assumption that uses the initial area of the cross section, ignoring the effects of transverse strain and the changing cross section. This assumption results in the drop of the engineering stress-strain curve after the ultimate tensile strength, where necking occurs.

Using the values of the true strain, the true plastic strain was determined for one sample of Aluminum (Sample #2) by subtracting the contribution of the true elastic strain, as outlined in Appendix E. Plotting the logarithm of the true stress versus the logarithm of the true plastic strain allowed the plastic portion of the true stress-strain curve to be modeled by the Ramberg-Osgood model, as detailed in Appendix F. While the model did poorly at low plastic strains near yielding, it did an excellent job just before necking and the ultimate tensile strain.

The results of the tensile tests showed that the A-36 hot rolled steel was the strongest material. It had the highest ultimate tensile strength (527.9 MPa), the greatest modulus of toughness (174.6 MPa), and the largest true fracture strength (1047 MPa). The 6061-T6 aluminum had a higher yield (356.3 MPa) than the steel (355.6), but a lower ultimate tensile strength (374.9 MPa) and true fracture strength (571.8 MPa) due to tempering and precipitation hardening. All of the materials besides the PMMA proved to be ductile, especially the polycarbonate, which had a percent elongation of 82.2%. The PMMA samples averaged a percent elongation of only 0.7333%.
A. Introduction

Tensile testing is one of the most fundamental tests for engineering, and provides valuable information about a material and its associated properties. These properties can be used for design and analysis of engineering structures, and for developing new materials that better suit a specified use.

The tensile testing laboratory was conducted using an Instron load frame and the BlueHill data acquisition software. Four different materials were tested, including 6061-T6 Aluminum Alloy, A-36 hot rolled steel, polymethylmethacrylate (PMMA, cast acrylic), and polycarbonate. The samples were cylindrical in cross section, with a reduced gage section. The reduced gage section ensured that the highest stresses occurred within the gage, and not near the grips of the Instron load frame, preventing strain and fracture of the specimen near or in the grips. The reduced gage section of each specimen was about 12.7 mm (0.5 inches). The samples were already machined to the proper dimensions required for the test, according to ASTM standards.

Three samples of each material were tested in the Instron load frame, and the data gathered into an Excel spreadsheet. The data was used to calculate various properties of each material, including the elastic modulus, yield strength, ultimate tensile strength. The data was then plotted on engineering stress-strain curves to compare the samples. The purpose of this experiment was to gather information about each material so that important mechanical properties could be determined. This experiment also familiarized the students with the Instron load frame, BlueHill data acquisition software, and the general steps to performing a tensile test on a reduced gage section specimen. The data used for this lab report was not gathered from the student run experiments, but rather from standardized testing performed by the laboratory professor, to ensure accurate and consistent results.
B. Procedure

Each specimen was measured with the calipers to determine the diameter of the cross section. A gage length was determined (typically 50.00 mm) and scribed into the specimen so that the distance between the two marks could be measured after the tensile test was completed. A typical reduced gage section specimen is shown in Figure 1, on the following page. The BlueHill data acquisition software was started, and the correct material was chosen. The load cell was zeroed to ensure that the software only measured the tensile load applied to the specimen.

The specimen was loaded into the jaws of the Instron load frame so that it was equally spaced between the two clamps. The axial and transverse extensometers were attached to the reduced gage section of the specimen, ensuring that the axial extensometer was set correctly when attaching it to the gage and that the transverse extensometer was across the complete diameter of the specimen. This precaution results in better data and prevents damage to the extensometers.

The Instron load frame, shown in Figure 2 on the following page, was preloaded using the scroll wheel to ensure that the specimen was properly loaded in the frame, and that it wasn’t slipping in the jaws. The load was released, and the extensometers were zeroed using the software. The test was started, and the specimen was loaded, resulting in a measurable strain. For the steel and aluminum samples, the crosshead was initially set to move upward at 1.27 mm/min, then at 15 mm/min at a specified state beyond yielding. This increase in the rate of strain sped up the test, but may have also introduced some error. The polycarbonate sample started at 5 mm/min and was later sped up to 30 mm/min. The PMMA samples were pulled at a constant rate of 10 mm/min.

The data was gathered using the software, and loaded into a spreadsheet. At a set value of strain (past the yield strain), the software stopped using data from the extensometers, and started gathering the strain information using the position of the moving crosshead. A warning message came up on the computer screen, instructing the operator to remove the
extensometers to prevent damage. The test continued until fracture, where the software stopped the moving crosshead, and finished gathering data. The specimen was removed, and the crosshead was reset to the initial position to start another tensile test. The testing procedure was repeated for the rest of the specimens.

**Figure 1:** A reduced gage section specimen made from 6061-T6 aluminum, ready for tensile testing.

**Figure 2:** A typical Instron load frame used for tensile testing.
C. Results

C.1 Engineering Stress and Engineering Strain

The data from the tensile tests was plotted on separate graphs according to material. Each graph shows the engineering stress versus the engineering strain, as calculated per Appendix A. Figure 3 shows the three tests for the A-36 hot rolled steel samples, and Figure 4 shows the three tensile tests of the 6061-T6 aluminum samples. Figure 5 and Figure 6 show the test results of the polycarbonate and the PMMA, respectively.

![Figure 3: The engineering stress versus the engineering strain for A-36 steel.](image)

![Figure 4: The engineering stress versus the engineering strain for 6061-T6 aluminum.](image)
Figure 5: The engineering stress versus the engineering strain for polycarbonate.

Figure 6: The engineering stress versus the engineering strain for PMMA.
C.2 Material Properties

The ultimate tensile strength for each material is listed in Table 1. The value of the ultimate tensile strength was found using the process in Appendix B. The strain corresponding to the ultimate tensile strength is where necking begins to occur.

Table 1: The ultimate tensile strength for the four materials.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>Ultimate Tensile Strength, $\sigma_u$ (MPa)</th>
<th>Standard Deviation, StDev (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-36 Steel</td>
<td>527.9</td>
<td>1.161</td>
</tr>
<tr>
<td>6061-T6</td>
<td>374.9</td>
<td>2.218</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>59.18</td>
<td>0.3217</td>
</tr>
<tr>
<td>PMMA</td>
<td>77.62</td>
<td>2.606</td>
</tr>
</tbody>
</table>

The modulus of elasticity and the yield strengths were calculated for steel and aluminum. The corresponding standard deviations for both values were also calculated using the procedure outlined in Appendix B. All of these values are shown in Table 2.

Table 2: The modulus of elasticity, yield strength, and standard deviations for steel and aluminum.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>Modulus of Elasticity, $E$ (MPa)</th>
<th>Standard Deviation of $E$ (MPa)</th>
<th>Yield Strength, $\sigma_y$ (MPa)</th>
<th>Standard Deviation of $\sigma_y$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-36 Steel</td>
<td>209300</td>
<td>1966</td>
<td>355.6</td>
<td>1.357</td>
</tr>
<tr>
<td>6061-T6</td>
<td>69460</td>
<td>337</td>
<td>356.3</td>
<td>1.979</td>
</tr>
</tbody>
</table>

The modulus of resilience and the modulus of toughness were calculated from the area under the engineering stress versus engineering strain curves, as outlined in Appendix C. Both are useful for determining the amount of energy the material can absorb before yielding and fracture. The values of both are shown in Table 3.

Table 3: The modulus of resilience and the modulus of toughness for the materials.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>Modulus of Resilience $U_r$ (MPa)</th>
<th>Modulus of Toughness $U_T$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-36 Steel</td>
<td>0.9725</td>
<td>174.6</td>
</tr>
<tr>
<td>6061-T6</td>
<td>1.600</td>
<td>60.03</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.3793</td>
<td>63.73</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.3091</td>
<td>2.475</td>
</tr>
</tbody>
</table>
The true fracture strength provides the actual value of the stress encountered by the sample during the tensile test, just before fracture. The true fracture strength is the greatest stress that the material can handle after yielding. The percent elongation and the percent reduction in area provide information about the ductility of a material, and how much it can be stretched before failure. The calculations of these properties are outlined in Appendix D. The averages of all three values for each of the four materials are shown in Table 4.

Table 4: The average true fracture strength, percent reduction of area, and the percent elongation for all four materials.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>True Fracture Strength, $\sigma_f$ (MPa)</th>
<th>Percent Reduction of Area, %RA</th>
<th>Percent Elongation, %EL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-36 Steel</td>
<td>1047</td>
<td>64.79%</td>
<td>33.47%</td>
</tr>
<tr>
<td>6061-T6</td>
<td>571.8</td>
<td>54.02%</td>
<td>17.30%</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>94.11</td>
<td>44.88%</td>
<td>82.20%</td>
</tr>
<tr>
<td>PMMA</td>
<td>67.29</td>
<td>0.2609%</td>
<td>0.7333%</td>
</tr>
</tbody>
</table>

C.3 True Stress and True Strain

One sample of aluminum was used to find the true stress and the true strain encountered during a tensile test, and to compare both to the engineering stress and the engineering strain. The engineering stress and strain does not account for the change in cross sectional area, and only accounts for the axial strain in the sample. The true stress and strain account for the change in cross sectional area, and therefore the true stress is higher than the engineering stress. The true strain is also greater than the engineering strain due to strains in the transverse direction along the gage of the sample. Figure 7 shows the true stress versus the true strain, along with the engineering stress and the engineering strain for the same sample. The second sample of aluminum was used in this analysis, as defined by Appendix E.
The true stress at the point of maximum load (where the ultimate tensile strength occurs) for the 6061-T6 aluminum sample had a value of 404.9 MPa, compared to a maximum tensile strength of 376.6 MPa. The true strain at this point had a value of 0.0723 m/m, compared to an engineering strain of 0.0750 m/m. The maximum true stress at fracture was 561.5 MPa, with a strain of 0.765 m/m. At fracture, the engineering stress was 261.3 MPa, with a strain of 0.182 m/m.

**Figure 7:** The True Stress versus the True Strain, along with the Engineering Stress and Strain for a sample of 6061-T6 Aluminum.
C.4 The Ramberg-Osgood Model

The behavior of the true stress due to the true plastic strain can be accurately modeled using the Ramberg-Osgood equation. This equation models the stress-strain curve as a power hardening model, after yielding. The resulting equation, as derived in Appendix F, gives rise to Figure 8, where it is plotted against the true stress and strain values derived from the experiment.

![True Stress vs. True Plastic Strain](image)

**Figure 8:** The plot of the true stress versus the true plastic strain for both the experimental values and the calculated values obtained from the Ramberg-Osgood model.

The value of the true stress and strain obtained from the Ramberg-Osgood model at three defined points is compared against the experimental values in Table 5, showing the increasing accuracy of the model as plastic strain increases.

**Table 5:** The true stresses calculated using the Ramberg-Osgood model, compared to the experimental true stress.

<table>
<thead>
<tr>
<th>True Plastic Strain (m/m)</th>
<th>Calculated Stress (MPa)</th>
<th>Experimental Stress (MPa)</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>300.5</td>
<td>360.1</td>
<td>19.84%</td>
</tr>
<tr>
<td>0.01</td>
<td>353.9</td>
<td>364.1</td>
<td>2.886%</td>
</tr>
<tr>
<td>0.05</td>
<td>396.7</td>
<td>396.8</td>
<td>0.01496%</td>
</tr>
</tbody>
</table>
D. Discussion

The test results were consistent for each of the materials, as evident in Figures 3-6, where each of the three stress-strain curves were approximately overlapping. An interesting observation can be made from the PMMA graph, where sample one suddenly loses stress as it is stretched. This sample may have fractured partially across the cross section before complete failure, or a void could have caused a sudden release of stress. All of the other samples exhibited consistent behavior.

From the ultimate tensile strength data in Table 1, it is clear that the A-36 hot rolled steel was the strongest material, followed by aluminum, PMMA, and polycarbonate, respectively. All of the standard deviations were low, not exceeding 2.606 MPa, suggesting that the data was consistent and that the testing procedure was valid and repeatable. The true fracture strength, shown in Table 4, gives a better view of the true stress at fracture. The A-36 steel had the highest true fracture strength, followed by the aluminum, polycarbonate, and PMMA.

Although the A-36 hot rolled steel had a much higher modulus of elasticity (209300 MPa, compared to 69460MPa for the 6061-T6 aluminum), and a higher ultimate tensile strength, the yield strength is about the same as the 6061-T6. The higher ultimate stress is due to work hardening as the material is plastically deformed. The introduction of dislocations reduces their motion, and hardens the material. The 6061-T6 is a tempered and aged alloy that is already precipitation hardened. It will not work harden as much as the A-36 steel, resulting in a lower ultimate tensile strength. The standard deviations for the yield strength and modulus of elasticity are also small compared to the average values, proving the consistency of the data.

The modulus of resilience and the modulus of toughness are important values in determining the energy that a material can absorb before yielding and before fracture. The modulus of resilience is the area under the engineering stress-strain curve up until the yield, and corresponds to the energy per unit volume that a material can absorb before it yields. The 6061-T6 aluminum had the highest modulus of resilience, followed by A-36
steel, polycarbonate, and PMMA. The aluminum had the highest resilience due to the high yield strength, and the low modulus of elasticity (compared to the A-36 steel), as shown in Table 3. The low modulus of elasticity ensured that the aluminum was strained more before yielding, allowing it to absorb more energy.

The modulus of toughness was the highest for the A-36 steel due to the high ultimate tensile strength, and the ductility of the steel. The polycarbonate had a higher modulus of toughness than the 6061-T6 aluminum due to its high ductility, even though it had a lower yield and ultimate tensile strength. The acrylic had the lowest modulus of toughness due to its brittle nature.

The percent reduction of area and the percent elongation are indicators of the ductility of a material. All of these values are located in Table 4. A more ductile material will have a greater percent elongation, and the material will neck down further, resulting in a greater reduction of area. The A-36 steel samples had the greatest reduction of area due to the large amount of necking just before fracture. The polycarbonate had the highest percent elongation due to the straightening of the polymer chains. The polymer chains did not neck down after they were straightened, which resulted in a smaller percent reduction of area compared to the steel and aluminum samples. The aluminum did not elongate as far as the steel due to the alloying of the material and the precipitation hardening that was used to improve other properties. The PMMA had the lowest percent reduction of area and the lowest percent elongation, indicating that it is a brittle material.

The true stress and true strain take into account the changing area of the cross section as it is being elongated, and the strains that accompany the changing area. Accounting for these two effects results in a final true stress that is much higher than the engineering fracture stress and a greater amount of strain. As shown in Figure 7, the true stress reaches a maximum at the point of fracture. At this point, the area is much smaller, so the specimen cannot withstand a large load, which causes the engineering stress-strain curve to drop off after necking. There is no ultimate tensile stress in the true stress-strain curve.
as with the engineering stress-strain curve, and the true stress is always increasing up until fracture.

The Ramberg-Osgood model proved to be excellent at determining the true stress at higher values of true plastic strain, but had higher error at low values of true plastic strain, especially near the yield strain, where plastic strain is essentially zero. Table 5 shows that near the ultimate tensile strain, the error is very small, but near the yield strain, the error is rather high at 19.84%. The aluminum samples did not exhibit the power hardening behavior that is typical of the Ramberg-Osgood model. The engineering stress-strain curve was flat after yielding, and not curved like the model shows in Figure 8. Since the model was fitted to the data between three times the yield strain, and the ultimate tensile strain, it does not fit the sample well at low values of true plastic strain. This error could be alleviated by fitting multiple models to the curve, or by choosing a different model that better fits the shape of the engineering stress-strain curve.
Appendix A: Calculating the Engineering Stress and Strain

Each material was tested three times, and the Engineering stress was plotted against the engineering strain. To calculate the engineering stress and strain, the Instron machine used extensometers up until necking, which measured the strain induced on the sample. Past necking, the Instron machine obtained strain data from the position of the crosshead. The load cell on the moving crosshead measured the vertical load applied to the sample. The diameter of the gage on the sample was measured using calipers, and from there the area was calculated using Equation A.1. The engineering stress is a function of the force applied and the original cross-sectional area of the gage of the sample. Using Equation A.2, the engineering stress was calculated. P denotes the tensile force applied to the specimen.

\[ A_o = \pi \frac{D_o^2}{4} \]  
\[ \sigma = \frac{P}{A_o} \]  

Appendix B: Determining the Modulus of Elasticity and the Yield Stress

The modulus of elasticity and the yield stress was calculated for all three samples of both the aluminum and the steel. To find the modulus of elasticity, a small portion of the stress-strain curve was plotted to only include the linear region around zero strain. The slope of the graph at this point is the modulus of elasticity for that material. Excel was used to plot this portion of the stress-strain curve, and a trend line was added to best fit the data. Using the modulus of elasticity, the yield stress was also found. A line was plotted with the modulus of elasticity as the slope, but it was offset 0.002 mm/mm of strain. The value of the stress where the two lines cross is the corresponding yield stress. This method is the standard 0.2% offset method used to find the yield stress. The average of each value was calculated, along with the standard deviation, using Equation B.1 and Equation B.2, respectively.

\[ \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \]  
\[ StDev = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})} \]
The ultimate tensile strength was found by determining the maximum load, and using Equation A.2 to solve for the maximum engineering stress encountered. The standard deviation was also calculated for the ultimate tensile strength, using Equation B.2.

**Appendix C: Determining the Modulus of Resilience and the Modulus of Toughness**

The modulus of resilience is defined as the area under the engineering stress-strain curve up until yielding. It is the maximum energy per unit volume that the sample can absorb elastically. This energy can be recovered by relaxing the stress. Both Equation C.1 and Equation C.2 can be used to calculate the modulus of resilience.

\[
U_r = \frac{1}{2} \sigma_y \varepsilon_y \quad \text{(Equation C.1)}
\]

\[
U_r = \frac{\sigma_y^2}{2E} \quad \text{(Equation C.2)}
\]

The modulus of toughness is defined as the area under the entire stress-strain curve up until fracture. It is the maximum energy per unit volume that the sample can absorb before it fails completely due to fracture. Unlike the modulus of resilience, most of the energy cannot be recovered by relaxing the stress. The plastic deformation of the material is permanent. The modulus of toughness cannot be calculated using an equation due to the variety of shapes encountered in the stress-strain curves. To find the modulus of toughness for the four materials, one of the three samples was chosen from each material (All of the data was taken from Sample 1 of each material). The data was loaded into MATLAB using XLSREAD, and the area under the curve was evaluated using the TRAPZ command. The cumulative integral from zero strain up until the fracture strain was recorded as the modulus of toughness. The modulus of resilience was also calculated using MATLAB, but the integral was only carried out to the value of the yield strain.
Appendix D: Determining the True Fracture Strength, Percent Reduction in Area, and Percent Elongation

The true fracture strength provides the actual stress at fracture. The engineering stress does not account for the reduction in area due to necking. Equation D.1 provides the true stress at fracture. The diameter of the gage of the specimen was measured after fracture using calipers, and the area of the cross section was calculated using equation A.1. \( P_f \) and \( A_f \) represent the load and the area at fracture, respectively.

\[
\sigma_f = \frac{P_f}{A_f} \quad \text{(Equation D.1)}
\]

The percent reduction in area and the percent elongation provide useful information about the ductility of the material. A more ductile material typically has a higher percent elongation up until fracture, and the reduction in area is greater as the material necks down before fracture. A brittle material will not elongate much past the yield strain, and the percent reduction of area is lower than for a ductile material. Equation D.2 is used to calculate the percent reduction in area. \( A_f \) is the area at fracture, and \( A_o \) is the area of the cross section before testing, both taken from caliper measurements before and after the tensile test.

\[
\% RA = 100 \left( \frac{A_o - A_f}{A_o} \right) \quad \text{(Equation D.2)}
\]

Equation D.3 is used to calculate the true length of the specimen just before fracture. The length measured after fracture is less than the length before due to the elastic recovery when the stress is relieved when the material fractures. \( l_{pf} \) is the length of the gage post fracture, and \( \sigma_f \) is the engineering stress at fracture. The length after fracture was measured by placing the two halves of the specimen back together, and measuring the length of the gage. Equation D.4 is then used to calculate the percent elongation of the material.

\[
l_f = l_{pf} + \frac{\sigma_f}{E} \quad \text{(Equation D.3)}
\]

\[
\% EL = 100 \left( \frac{l_f - l_o}{l_o} \right) \quad \text{(Equation D.4)}
\]
Appendix E: Determining the True Stress and the True Strain

The true stress and true strain was calculated for one sample of aluminum, in this case for the second sample. The engineering stress and strain does not account for the reduction in area as the sample is pulled apart, nor does it account for strains besides the axial direction. The true stress and true strain show the actual stress and strain encountered during the tensile test. The true stress can be calculated at any point using Equation E.1, but since the instantaneous area was not known for this test, other methods had to be incorporated. $\bar{\sigma}$ denotes the true stress. The tensile force is denoted by $P$, and the instantaneous area is shown by $A$.

$$\bar{\sigma} = \frac{P}{A} \quad \text{(Equation E.1)}$$

For strains below two times the yield strain, the true stress is well approximated by the engineering stress, shown by Equation E.2. Between two times the yield strain and necking (the strain at the ultimate tensile stress), the true stress is approximated by Equation E.3. $\sigma$ is the engineering stress, and $\varepsilon$ is the engineering strain.

$$\bar{\sigma} = \sigma \quad \text{(Equation E.2)}$$
$$\bar{\sigma} = \sigma (1 + \varepsilon) \quad \text{(Equation E.3)}$$

The true strain was calculated using Equation E.4, up until necking. From necking until fracture, there was not enough information to fully define the true stress or true strain. The final true stress was calculated using the final area and the tensile force right before fracture, as shown in Equation E.5. The true strain at fracture was calculated using Equation E.6. A final point was plotted, and a straight line was drawn from necking to fracture. $P_f$ is the tensile force at fracture.

$$\bar{\varepsilon} = \ln(1 + \varepsilon) \quad \text{(Equation E.4)}$$
$$\bar{\sigma}_f = \frac{P_f}{A_f} \quad \text{(Equation E.5)}$$
$$\bar{\varepsilon} = \ln\left(\frac{A_0}{A_f}\right) \quad \text{(Equation E.6)}$$
Appendix F: The Ramberg-Osgood Equation for Plastic Deformation

After the true stress and true strain were calculated, the true plastic strain was calculated using Equation F.1. This resulted in the elastic strain being taken out, leaving only the permanent plastic strain. The true elastic strain was calculated using Equation F.2.

\[
\bar{\varepsilon}_p = \bar{\varepsilon} - \bar{\varepsilon}_e \quad \text{(Equation F.1)}
\]
\[
\bar{\varepsilon}_e = \frac{\bar{\sigma}}{E} \quad \text{(Equation F.2)}
\]

A plot was made of the logarithm of the true stress versus the logarithm of the true plastic strain. The plot only concerned the region between three times the yield strain, and the strain corresponding to the ultimate tensile stress. This resulted in a straight line that was fit with a best fit model of the curve, yielding a linear equation, as shown in Figure F.1.

![Figure F.1: The plot of the logarithm of the true stress versus the logarithm of the true plastic strain](image)

Excel was used to create the linear equation, and the slope and y intercept were used to create a model of the true stress encountered, using the true plastic strain, according to Equation F.3.

\[
\bar{\sigma} = H \bar{\varepsilon}_p^n \quad \text{(Equation F.3)}
\]
Using logarithm identities, the slope of the equation (0.07101) became \( n \) in Equation F.3, and 10 raised to the power of the y intercept (2.6909) became \( H \) (490.8) in Equation F.3. The resulting equation is shown as Equation F.4.

\[
\bar{\sigma} = 490.8\epsilon_p^{0.07101}
\]  
(Equation F.4)

Equation F.4 was used to create a plot of the true stress versus the true strain to compare it to the experimental plot of the true stress versus the true strain, as shown in Figure 8. The equation was also used to calculate the true stress at set values of true plastic strain of 0.001, 0.01, and 0.05. The calculated values of the true stress were compared to the true stress values obtained from the experiment in Table 5 using percent error.