Tension

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Contents

Abstract

In this experiment, seven specimens of differing metals and heat treatment were fixed into a Hydraulic Tension Testing Machine and placed under increasing load until fracture. The seven materials tested were 1018 Cold Rolled Steel, A36 Hot Rolled Steel, Grey 20 Cast Iron, and four AA6061 Aluminum Alloys with zero, two, four, and six hour heat treatments. After the tensile tests were completed and results analyzed, it was found that A36 Hot Rolled Steel was both the most ductile and toughest material, with a percent elongation and modulus of toughness of 33.20% and 126.43 MJ/m^3, respectively, and 1018 Cold Rolled Steel had the highest ultimate tensile strength at 658.91 MPa. Grey 20 Cast Iron had the lowest ductility, toughness, and ultimate tensile strength with corresponding tensile property values of 2.00% elongation, 1.24 MJ/m^3 modulus of toughness, and 181.92 MPa ultimate tensile stress. Comparing the different heat treatments of AA6061 Aluminum Alloy, it was found that a longer heat treatment generally coincided with greater ductility, lower strength and toughness, and little to no change in elasticity.

1 Introduction

1.1 Apparatus

The apparatus used in the experiment is a device called a Hydraulic Tension Testing Machine. This machine took dog-bone shaped specimens of the tested material and applied an increasing, uni-axial load until fracture. To measure the strain in the specimen, a Linear Variable Differential Transformer (LVDT) was attached to the specimen with it's two fittings positioned 50 mm apart. As the specimen elongated, the LVDT recorded the change in length into a computer which then saved the data into a text file [1].

1.2 Engineering Stress and Strain

Once the load and elongation data from the tensile test was saved, the engineering stress and strain were calculated. The engineering stress and strain are a good approximation of the true stress and strain, and can be used to estimate the material's physical properties. The engineering stress is calculated by the equation:

$$\sigma = \frac{F}{A_0} = \frac{F}{\frac{\pi}{4} D_0^2} \tag{1}$$

where F is the load force, and A_0 is the initial area, and the engineering strain is calculated by the equation:

$$\epsilon = \frac{\Delta L}{L_0} \tag{2}$$

where ΔL represents the change in length (or elongation) of the specimen, and L_0 is the initial length.

Engineering stress and strain are related to each other by Hooke's Law, which states:

$$\sigma = E\epsilon \tag{3}$$

where E is the modulus of elasticity; however, this is only true in the elastic region, before the material starts to deform [2]. This will be explained in further detail in Section 1.4.1.

Graphing the engineering stress against the engineering strain gives a plot similar to the one shown in Figure 1. The graph can be separated into two main regions: the elastic region, where stress and strain are linearly proportional, and the plastic region, which includes the region where deformation starts until fracture. The specific shape of the stress-strain curve relates to the material's properties, like ductility, resilience, and toughness.

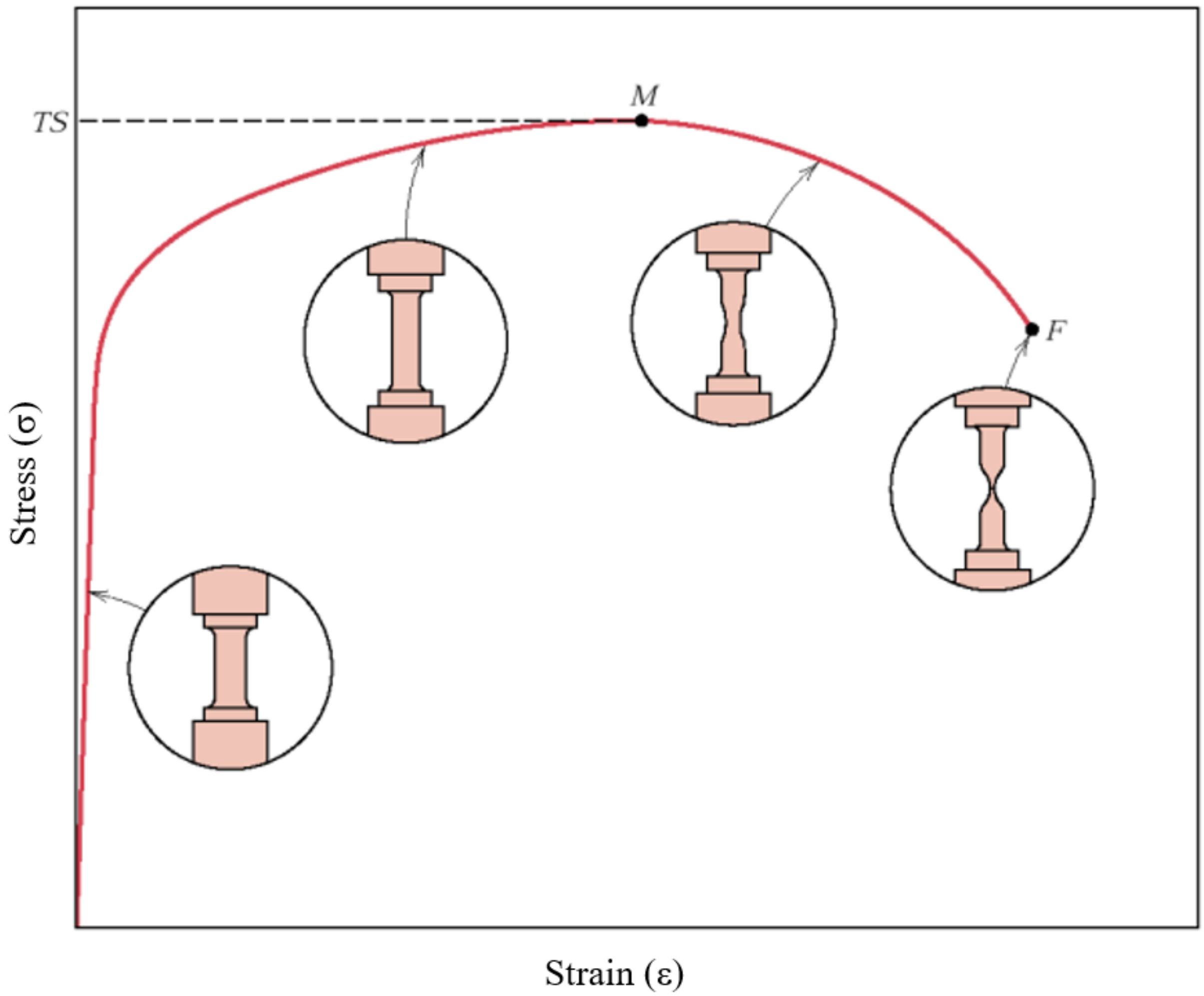

Figure 1: Conventional Stress vs. Strain Diagram and the evolution of the specimen shape under tension [2].

As the specimen elongates, the body stretches uniformly until reaching its maximum stress, or ultimate tensile strength (*M*), then undergoes a necking phase before fracturing (*F*). During necking, a localized region of the specimen's body will constrict and drastically reduce in diameter as shown by the drawings in Figure 1. Necking only occurs in ductile materials, whereas a brittle material will fracture at its ultimate tensile strength point [3].

1.3 True Stress and Strain

The true stress and strain are determined similarly to the engineering stress and strain, but involve the instantaneous area and length. This differs from the engineering stress and strain in that it considers how the stress-strain curve evolves as the specimen undergoes elongation and constriction. The equations for true stress and strain are:

$$\sigma_T = \frac{F_i}{A_i} \tag{4}$$

and

$$\epsilon_T = \ln \frac{L_i}{L_0} \tag{5}$$

where F_i, A_i, and L_i represent the instantaneous values of the load, area, and length, respectively.

The problem, however, is that the diameter is not measured continuously during the tensile test and therefore the instantaneous area is unknown. Fortunately, some algebra can be used to relate the engineering stress and strain to the true stress and strain. Foremost, the knowledge that the instantaneous length is the summation of the initial length (L_0) and change in length (ΔL), and using Equation (2), the true strain can be rewritten in terms of the engineering strain by the equation:

$$\epsilon_T = \ln(1 + \epsilon) \tag{6}$$

Furthermore, by assuming the volume of the specimen does not change during deformation, expressed as $A_i L_i = A_0 L_0$, a relationship can be established between the true stress and engineering stress and strain, which can be written in the equation:

$$\sigma_T = \sigma(1 + \epsilon) \tag{7}$$

This assumption only holds true until necking occurs, at which point the true stress and strain should be computed from actual load, area, and length measurements [4].

Compared to the engineering stress-strain curve, the true stress-strain curve is nearly identical in the elastic region and it's not until the plastic region, between the yield point and ultimate tensile stress, where a noticeable difference can be seen between the two. In the plastic region, the true stress-strain curve tends to demonstrate greater stress than its engineering counterpart. This difference will be shown in detail in Section 3, where the results of the tensile tests are analyzed.

1.4 Tensile Properties

Every material has a unique set of properties that define how they act under tension. These properties include the material's elasticity, strength, ductility, energy capacity, and strain hardening. Engineers use these properties during the material selection phase to maximize the efficiency, safety, and quality of their designs. The tensile properties of a tested material are found by analyzing it's stress and strain in the different regions of tension.

1.4.1 Elasticity

The elasticity of a material describes the relationship between the stress applied to the material and it's elongation. Previously mentioned in Section 1.2, Hooke's Law (Equation (3)) relates the material's stress and strain in the elastic region. The modulus of elasticity (E) corresponds to the linear relationship between the stress and strain which, from Hooke's Law, can be expressed as:

$$E = \frac{\sigma}{\epsilon} = \frac{\Delta\sigma}{\Delta\epsilon} \tag{8}$$

A material with a high modulus of elasticity will require a greater amount of stress to achieve the same elongation as a material with a lower modulus of elasticity. The modulus of elasticity is in units of pressure, and it's typical values for metals range between 45 GPa (6.5×10^6 psi), for magnesium, and 407 GPa (59×10^6 psi), for tungsten [4].

Another physical property defined by the material's elasticity is Poisson's ratio (ν). Poisson's ratio is the relationship between the strain of the material lateral to the force and the material's elongation along the axis of the force. It is expressed using the equation:

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z} \tag{9}$$

where ϵ_x and ϵ_y are lateral strains, and ϵ_z is the axial strain (elongation). For most metals, values of Poisson's ratio ranges from 0.25 to 0.35 [4].

1.4.2 Strength

A material's strength is determined by the amount of stress required for it to deform and the maximum stress it can handle before fracturing. Knowing the strength of a material is important to engineers because it determines in which conditions, and at what level of stress, a material can be used without deformation or failure.

The proportional limit of a material (σ_p) is the upper limit of stress that can be applied to a material before it begins to yield, or deform. The region of stress below the proportional limit is the elastic region, where Hooke's Law is stated to be true. After the proportional limit is reached, the material is considered to be in the plastic region of deformation, where the stress is no longer linearly proportional to the strain, as shown in Figure 2. The proportional limit is conventionally defined as the stress at an elongation of 0.2% ($\epsilon = 0.002$) [4].

Yield strength (σ_y) is another property relating a material's resistance to deformation. The yield strength of a material is defined as the stress required to permanently elongate the material by 0.2%. In the case when a material has entered the plastic region and the load is then released, the material will not return to its original state, but instead to an elongated length where the stress and strain are linearly proportional by the modulus of elasticity until that point. Therefore, by starting at a strain of 0.002 and tracing a line parallel to the stress-strain curve of the elastic region, the yield point can be found where the line meets the stress-strain curve in the plastic region (Shown by the dashed line in Figure 2).

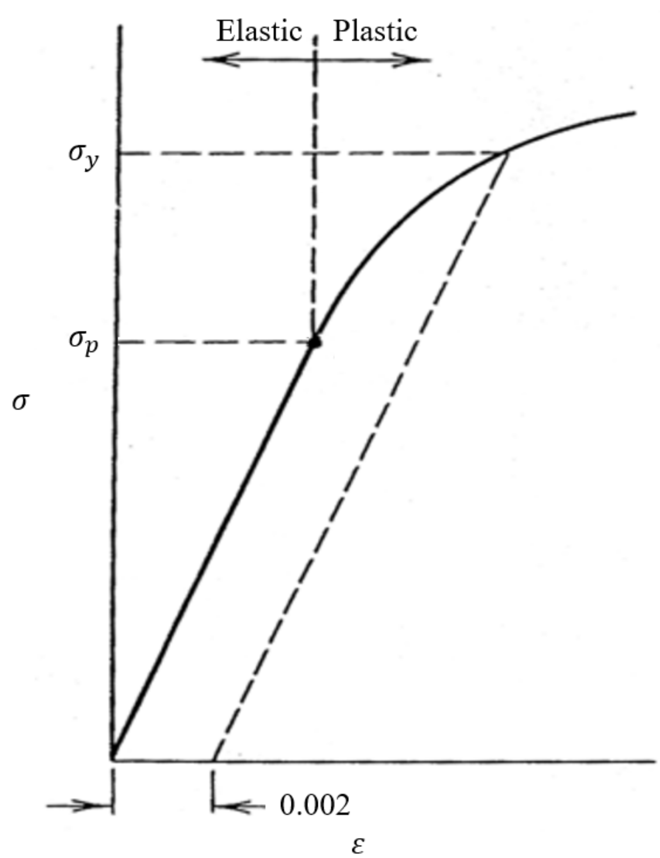

Figure 2: Proportional limit and yield stress shown on the stress-strain diagram [2]

Other physical properties that characterize the material's strength include the ultimate tensile strength (σ_μ) and the fracture strength (σ_f). The ultimate tensile strength is the maximum stress that a material can undergo before it necks, and then fractures. The value for the ultimate tensile strength can be found at the peak of the stress-strain diagram, shown by point M in Figure 1. Engineers use the ultimate tensile strength as the stress where the material has experienced so much deformation, that it becomes practically useless [4]. The fracture strength, shown in Figure 1 as point F, is the stress when the material fractures, and is simply the last stress reading on the stress-strain diagram.

1.4.3 Ductility

Ductility relates to the degree of plastic deformation a material undergoes up until fracture. A ductile material, or one with high ductility, will experience more elongation at fracture than a brittle material, one with low ductility.

The ductility of a material is expressed by its percent elongation ($\%EL$) and reduction in area ($\%RA$). The percent elongation is calculated by the equation:

$$\%EL = \frac{L_f - L_0}{L_0} \times 100 \tag{10}$$

where L_f and L_0 are the final and initial lengths, respectively, and the reduction in area is calculated in a similar fashion by the equation:

$$\%RA = \frac{A_0 - A_f}{A_0} \times 100 \tag{11}$$

where A_f and A_0 are the final and initial lengths, respectively.

The ductility of a material is important in design and used to determine how "forgiving" a material is, relating to how much deformation it can undergo before complete failure [4]. Typical ductile metals will elongate in the range of 20-50% before fracture, whereas a brittle metal will elongate less than 5% before fracturing.

1.4.4 Energy Capacity

The tensile properties that relate to a material's energy capacity are resilience (U_r) and tensile toughness (U_t), and describe the amount of energy the material can absorb before yielding and fracturing, respectively. Both the material's resilience and toughness use the area under the stress-strain curve to determine their values and are expressed in units of energy per unit volume.

Resilience is calculated using the area under the stress-strain curve up to the point of yielding, mathematically expressed as:

$$U_r = \int_0^{\epsilon_y} \sigma d\epsilon \tag{12}$$

where ϵ_y is the strain at which yielding occurs. If the assumption is made that the stress-strain curve follows Hooke's Law, and is linearly proportional, the resilience of a material simplifies to the expression:

$$U_r = \frac{\sigma_y^2}{2E} \tag{13}$$

where σ_y is the yield stress and E is the modulus of elasticity. This expression shows that resilient materials are ones with a high yield stress and low elasticity, meaning they are springy in nature [4].

The toughness of a material is calculated similarly to resilience, but differs in that it uses the total area under the stress-strain curve, up to the fracture point [3]. For ductile metals, an approximation of the toughness can be made using the equation:

$$U_t = \frac{\sigma_y + \sigma_u}{2} \epsilon_f \tag{14}$$

where σ_y and σ_u are the yield and ultimate tensile stress, respectively [2]. The stress-strain curve for a brittle material follows the shape of a parabola, so the area under it's curve, and therefore it's toughness, can be expressed as:

$$U_t = \frac{2}{3} \sigma_u \epsilon_f \tag{15}$$

Toughness is a measure of both a material's ductility and strength, which makes it a desirable property for designs that deal with high stress and movement, such as gears and chains [2].

1.4.5 Strain Hardening

In the plastic region, before the ultimate tensile point, the stress and strain is no longer linearly proportional, thus it can no longer be described by Hooke's Law. Instead, a new relationship between the true stress and strain can be used that states:

$$\sigma_T = H\epsilon_T^n \tag{16}$$

where H is the strength coefficient, and n is the strain hardening exponent. By taking the natural logarithm of both sides of Equation (16), the relationship can be rewritten as:

$$\ln \sigma_T = \ln H + n \ln \epsilon_T \tag{17}$$

commonly known as Hollomon's Equation [2].

Hollomon's Equation is useful when determining the values of the strength coefficient and strain hardening exponent because it relates the natural logarithms of the true stress and strain linearly, with a slope of n and an intercept of $\ln H$. Therefore, when the natural logarithms of the true stress and strain are plotted against each other, a strength coefficient and strain hardening exponent can be found that best matches the resulting line.

1.5 Heat Treatment

Variation in tensile properties are not only found in different materials, but also in materials of the same type that have undergone differing heat treatments. The heat treatment process, also called annealing treatment, changes the microstructure of a material, therefore modifying the tensile properties of that material. The main effect of annealing is the restoration of a metal back to its precold-worked state, reducing dislocations and stored internal strain energy in the microstructure of the material [4].

The effect of reducing dislocations and strain energy from a material is a decrease in ultimate tensile strength, but an increase in ductility. This is useful because it allows an engineer to have control over the specific tensile properties of the material and trade off strength and ductility when needed.

2 Experimental Procedure

The experiment involved seven different metal specimens that were placed in a Hydraulic Tension Testing Machine (HTTM) called the MTS Criterion 43 and pulled until fracture. The seven specimens tested were 1018 Cold Rolled Steel, A36 Hot Rolled Steel, Grey 20 Cast Iron, and AA 6061 Aluminum Alloy of 0, 2, 4, and 6-hour heat treatments. The initial diameters and lengths of the specimens were measured using calipers (I.L.E = 0.01 in) before they were placed in the HTTM. The HTTM was connected to a computer which saved the load force applied, crosshead position, and time throughout the experiment. A Linear Variable Differential Transformer called the MTS Axial Extensometer 634.25F-54 was attached to the specimen by two fittings spaced 50mm apart, and saved the elongation of the specimen to the computer as well. The data was saved from the moment the load force was first applied to the exact moment of fracture. This data was then exported to a text file and loaded into MATLAB for analysis. The specimens were taken out of the HTTM and its final diameter and lengths were measured [5].

3 Results and Discussion

3.1 1018 Cold Rolled Steel

Figure 3: 1018 Cold Rolled Steel after fracture. Cup and cone fracture shape is characteristic of ductile metals.

The first material analyzed was 1018 Cold Rolled Steel. The average initial and final measurements of the diameter and length, from the tables in Appendix A, are shown in Table 1.

Table 1: 1018 Cold Rolled Steel Measurements

Quantity	**Symbol**	**Value**
Initial Length	L_0	50.0 mm
Initial Diameter	D_0	8.65 mm
Final Length	L_f	56.4 mm
Final Diameter	D_f	5.80 mm

The raw data from the experiment, given by the load force and change in length, is as shown in Figure 4.

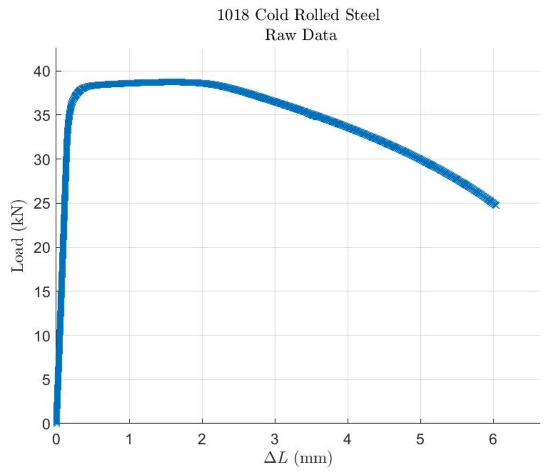

Figure 4: Raw data for 1018 Cold Rolled Steel

Using Equations (1) and (2) with the initial length and diameter measurements, the engineering stress and strain can be calculated and plotted against each other to create the engineering stress-strain curve shown by Figure 5.

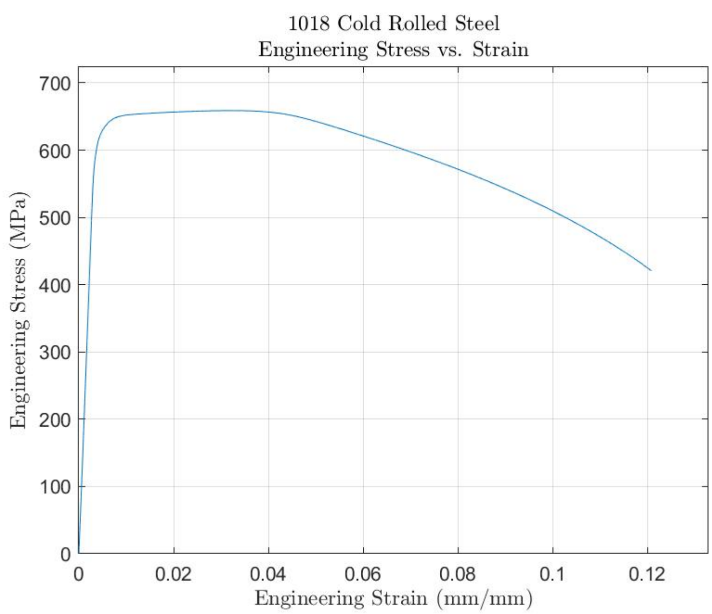

Figure 5: Stress-strain curve for 1018 Cold Rolled Steel

From Figure 5, the ultimate tensile strength (σ_u) and fracture strength (σ_f) can be determined to be:

$$\sigma_u = 658.91 \text{ MPa}$$
$$\sigma_f = 420.75 \text{ MPa}$$

Figure 5 can also be used to find the toughness (U_t) of the material, as described in Section 1.4.4. Using Equation (14), the toughness of 1018 Cold Rolled Steel is found to be:

$$U_t = 78.11 \ \frac{MJ}{m^3}$$

To determine the elastic properties of the steel, the elastic region of the stress-strain curve, shown in Figure 6, must be considered.

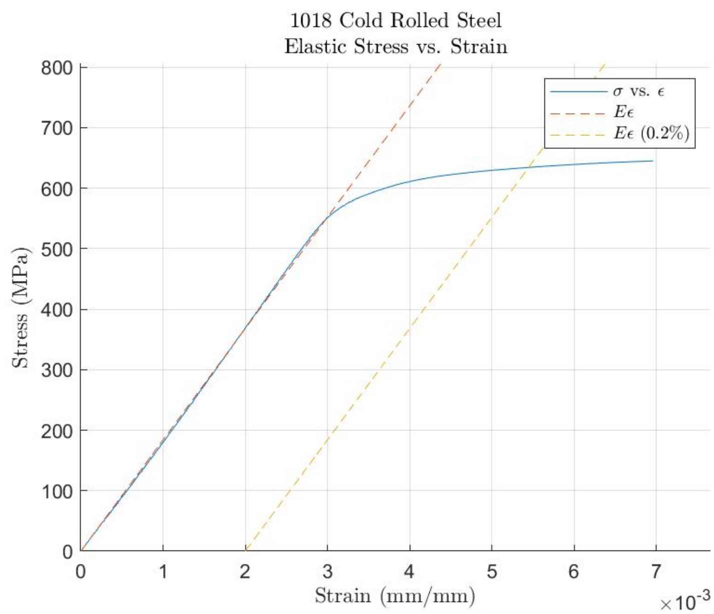

Figure 6: Elastic region of the stress-strain curve. Red dashed line represents the linear relationship between the stress and strain in the elastic region. The yellow dashed line is the same linear relationship with a 0.2% offset along the strain axis.

Using the methods described in Sections 1.4.1 and 1.4.2, the proportional limit (σ_p), yield strength (σ_y), and modulus of elasticity (E) can be found to be:

$$\sigma_p = 368.50 \text{ MPa}$$
$$\sigma_y = 634.32 \text{ MPa}$$
$$E = 184.05 \text{ GPa}$$

The modulus of resilience (U_r) can also be found. Using Equation (13) the resilience is determined to be:

$$U_r = 1.723 \ \frac{kJ}{m^3}$$

The relationships found in Equations (6) and (7) can be used to find the true stress-strain curve, which is graphed in Figure 7.

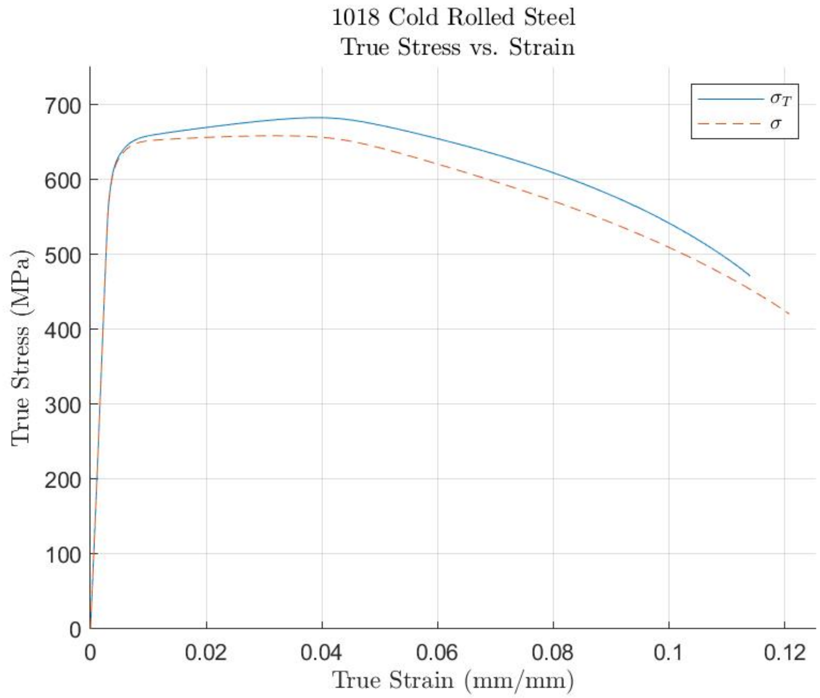

Figure 7: True stress-strain curve for 1018 Cold Rolled Steel. The red dashed line is the engineering stress-strain curve.

Figure 7 shows that the true stress is greater than the engineering stress. This is because as the specimen elongates, lateral strain causes the cross-sectional area of the specimen to decrease, which corresponds to a increase in stress. The true stress-strain curve is used until the point of ultimate tensile strength. Afterwards, the specimen begins to neck and the curve is no longer accurate.

The part of the true stress-strain to consider is the plastic region, before the ultimate tensile point. By taking the natural logarithm of both the true stress and strain, the stress-strain curve takes a form similar to a line and can be evaluated using Hollomon's Equation (Equation (17)). The natural logarithm plot is shown in Figure 8.

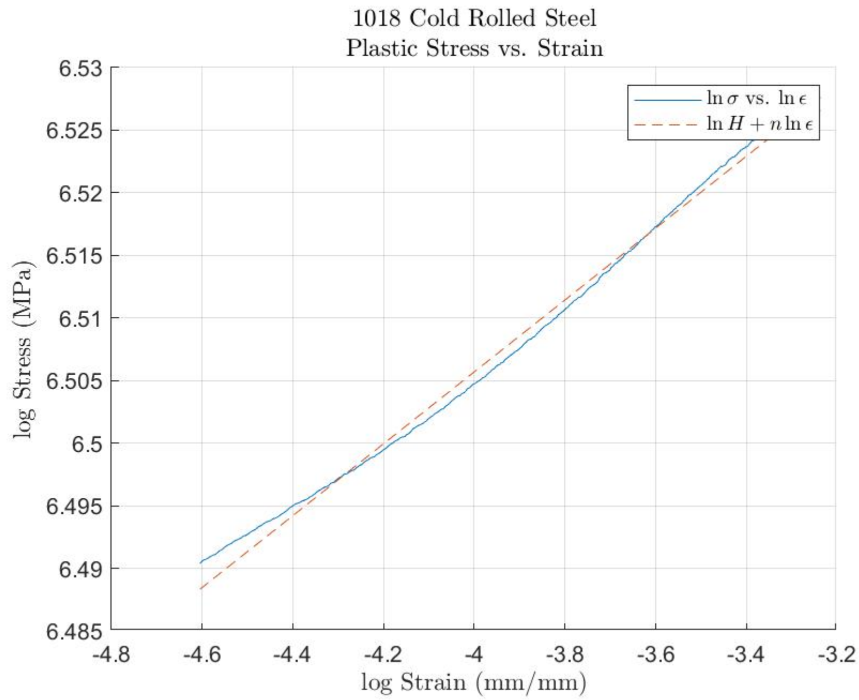

Figure 8: LogLog plot of true stress vs. strain. Red dashed line represents the best fit line with a slope of n and a intercept of $\ln H$

Using the best-fit line, the strain hardening exponent (n) and strength coefficient (H) can be determined to be:

$$n = 0.0287$$
$$H = 750.36 \text{ MPa}$$

Other tensile properties that can be found are the percent elongation ($\%EL$), reduction in area ($\%RA$), and Poisson's Ratio (ν), and are determined using the measured initial and final lengths/diameters of the specimens. Equations (9), (10), and (11) can be used to find the values of the properties which are:

$$\%EL = 12.80 \text{ \%}$$
$$\%RA = 55.04 \text{ \%}$$
$$\nu = 2.57$$

Poisson's ratio for typical metals tends to range from 0.25-0.35; however, because the lateral strain is not measured during the experiment and the final lateral strain is measured after necking, the calculated Poisson's ratio is higher than its true value.

The values found for the tensile properties of 1018 Cold Rolled Steel are similar to the accepted values for some properties, but significantly different for others. For example, the calculated modulus of elasticity of 184.05 GPa has only a 7.98% error from the accepted value of 200 GPa, but the calculated yield strength of 634.32 MPa is 71.44% off the accepted yield strength of 370 MPa. Other differences in the calculated values and accepted values of some tensile properties are: 658.91 MPa vs. 440 MPa (49.75% error) for fracture stress, 12.80% vs. 15% (14.67% error) for percent elongation, and 0.03 vs. 0.23 (87.52% error) for the strain hardening exponent.

Table 2: 1018 Cold Rolled Steel Tensile Properties

Quantity	**Symbol**	**Value**
Modulus of Elasticity	E	184.05 GPa
Proportional Limit	σ_p	368.50 MPa
Yield Strength	σ_y	634.32 MPa
Ultimate Tensile Strength	σ_u	658.91 MPa
Fracture Strength	σ_f	420.75 MPa
Strain Hardening Ratio	σ_u/σ_y	1.04
Modulus of Resilience	U_r	1.723 $\frac{kJ}{m^3}$
Modulus of Toughness	U_t	78.11 $\frac{MJ}{m^3}$
Strain Hardening Exponent	n	0.0287
Strength Coefficient	H	750.36 MPa
Elongation	$\%EL$	12.80%
Reduction in Area	$\%RA$	55.04%
Poisson's Ratio	ν	2.57

3.2 A36 Hot Rolled Steel

Figure 9: A36 Hot Rolled Steel after fracture. Cup and cone fracture shape is characteristic of ductile metals.

The A36 Hot Rolled Steel specimen had initial and final length/diameter measurements as listed in Table 3, and the raw data of the tensile test is graphed in Figure 10.

Table 3: A36 Hot Rolled Steel Measurements

Quantity	**Symbol**	**Value**
Initial Length	L_0	50.0 mm
Initial Diameter	D_0	8.65 mm
Final Length	L_f	66.6 mm
Final Diameter	D_f	5.30 mm

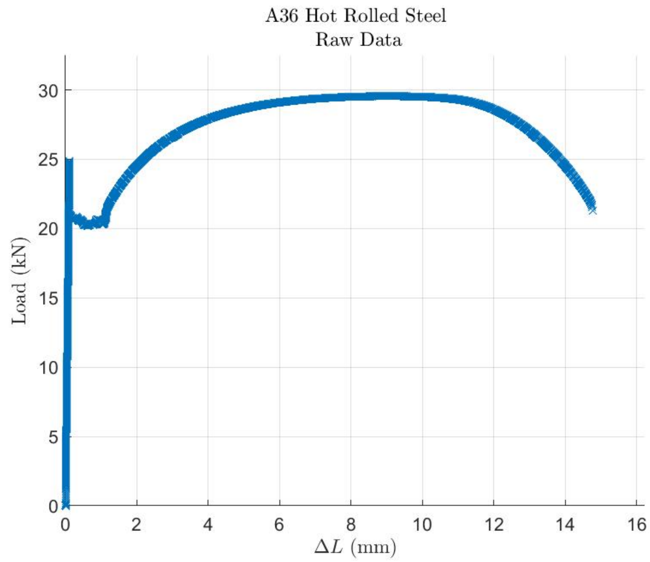

Figure 10: Raw data for A36 Hot Rolled Steel

Applying the same methods used in Section 3.1, the engineering stress-strain curve can be graphed as shown in Figure 11.

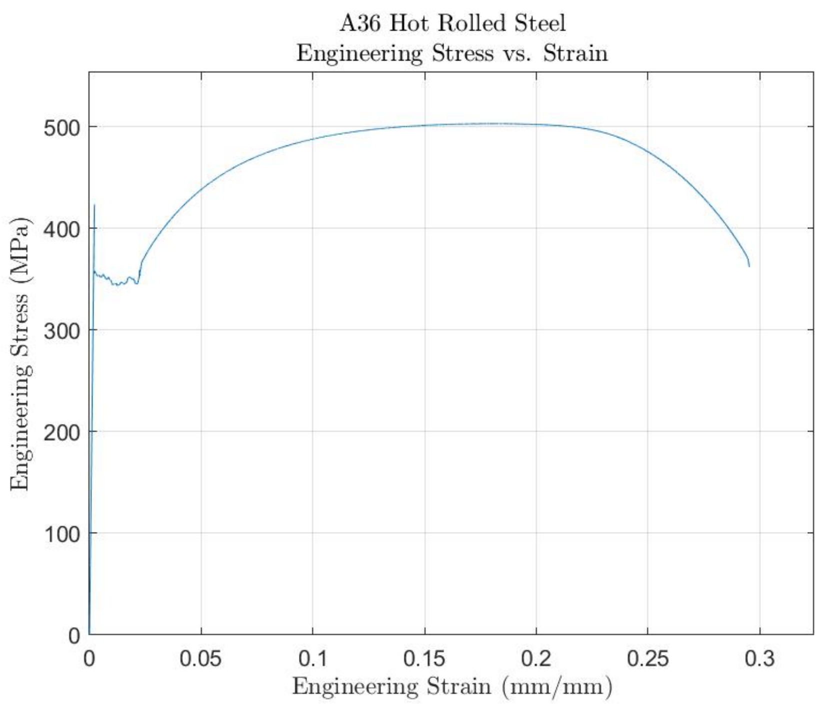

Figure 11: Stress-strain curve for A36 Hot Rolled Steel

From Figure 11, the values for the ultimate tensile stress and fracture stress are found to be:

$$\sigma_u = 502.82 \text{ MPa}$$
$$\sigma_f = 361.87 \text{ MPa}$$

and, using Equation (14), the modulus of toughness of A36 Hot Rolled Steel can be calculated as:

$$U_t = 126.42 \ \frac{MJ}{m^3}$$

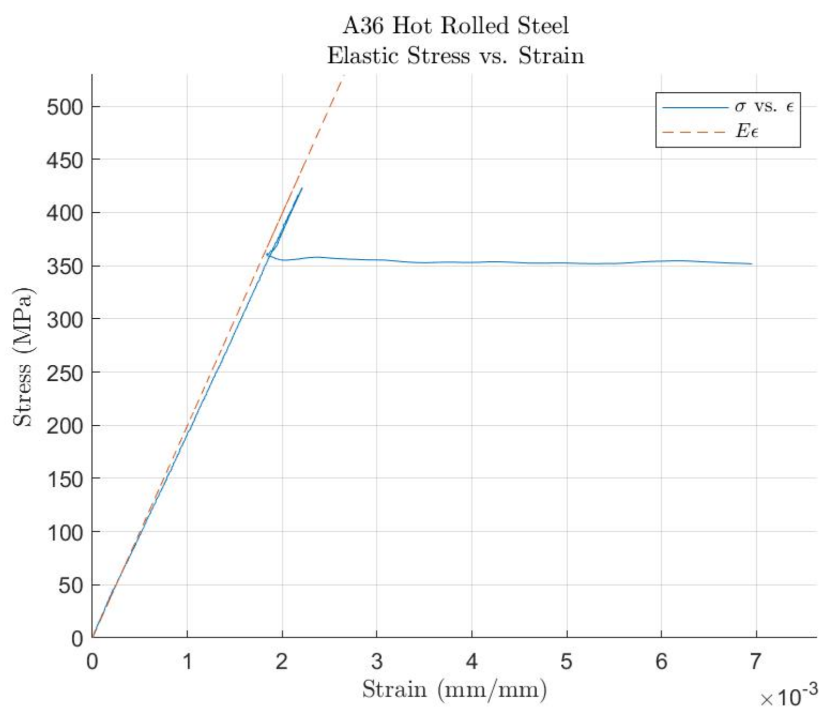

Figure 12: Elastic region of the stress-strain curve. A36 Hot Rolled Steel has an upper and lower yield point, which is characteristic of mild steels due to interstitial and substitutional impurities in the microstructure. [4]

Focusing on the elastic region of the engineering stress-strain curve, displayed in Figure 12, the values for the proportional limit, yield strength, and modulus of elasticity can be determined to be:

$$\sigma_p = 414.09 \text{ MPa}$$
$$\sigma_y = 353.30 \text{ MPa}$$
$$E = 199.58 \text{ GPa}$$

and after applying Equation (13), the modulus of resilience is calculated as:

$$U_r = 0.885 \ \frac{kJ}{m^3}$$

The true stress-strain curve can be found using Equations (6) and (7), which, when plotted, have a curve matching the one shown in Figure 13.

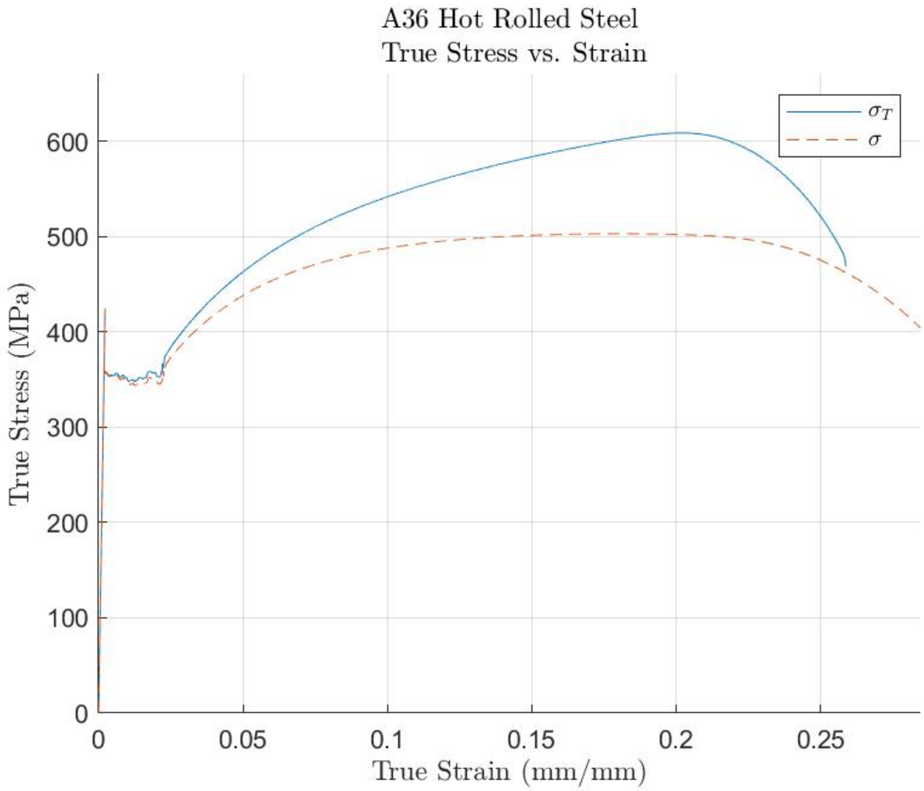

Figure 13: True stress-strain curve for A36 Hot Rolled Steel. The true stress-strain curve reaches its ultimate tensile stress when the strain is over 0.2 mm/mm (20% elongation), making it a relatively ductile material.

By taking the natural logarithm of the true stress and true strain in the plastic region (Figure 14), the true stress-strain curve can be modelled in the form of Hollomon's Equation, and the values of the strain hardening exponent and strength coefficient can be determined.

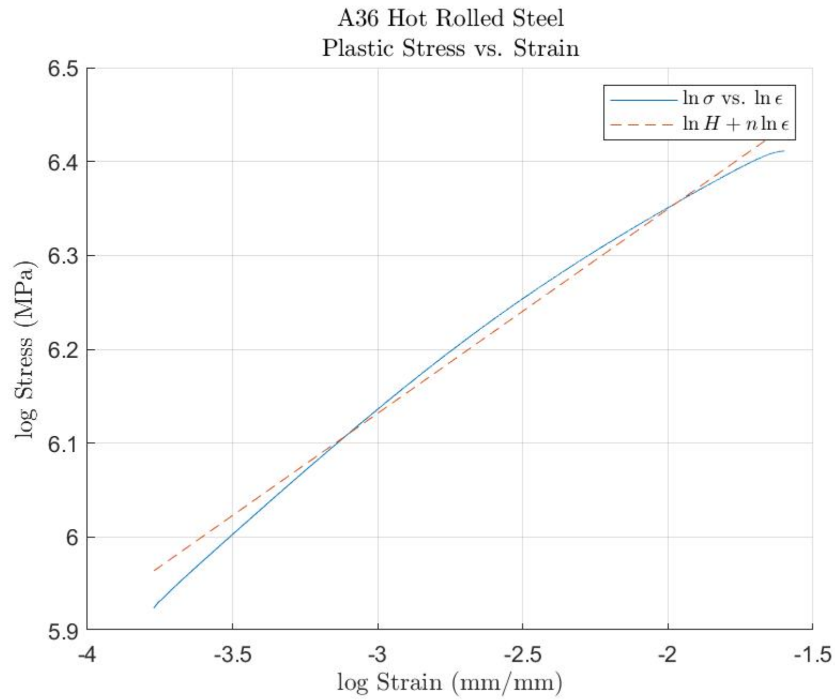

Figure 14: LogLog plot of true stress vs. strain. Red dashed line represents the best-fit line with a slope of n and a intercept of $\ln H$

Using a best-fit line and Hollomon's equation, the values for the strain hardening exponent and strength coefficient are found to be:

$$n = 0.2176$$
$$H = 884.24 \text{ MPa}$$

The final tensile properties are found using the measured initial and final lengths/diameters from Table 3. These properties are percent elongation, reduction in area, and Poisson's ratio, and can be calculated using Equations (9), (10), (11) to be:

$$\%EL = 33.20 \ \%$$
$$\%RA = 62.46 \ \%$$
$$\nu = 1.17$$

As stated in Section 3.1, the calculated Poisson's ratio is higher than its true value due to necking.

The results for the tensile properties were similar to their accepted values. The difference in calculated values vs. accepted values for some tensile properties were: 199.58 GPa vs. 200 GPa (0.21% error) for the modulus of elasticity, 353.30 MPa vs. 250 MPa (41.32% error) for the yield strength, 502.82 MPa vs. 475 MPa (5.86% error) for ultimate tensile strength, and 33.20% vs. 23% (44.35% error) for the percent elongation.

Table 4: A36 Hot Rolled Steel Tensile Properties

Quantity	**Symbol**	**Value**
Modulus of Elasticity	E	199.58 GPa
Proportional Limit	σ_p	414.09 MPa
Yield Strength	σ_y	353.30 MPa
Ultimate Tensile Strength	σ_u	502.82 MPa
Fracture Strength	σ_f	361.87 MPa
Strain Hardening Ratio	σ_u/σ_y	1.42
Modulus of Resilience	U_r	0.885 $\frac{kJ}{m^3}$
Modulus of Toughness	U_t	126.42 $\frac{MJ}{m^3}$
Strain Hardening Exponent	n	0.2176
Strength Coefficient	H	884.24 MPa
Elongation	$\%EL$	33.20%
Reduction in Area	$\%RA$	62.46%
Poisson's Ratio	ν	1.17

3.3 Grey 20 Cast Iron

Figure 15: Grey 20 Cast Iron after fracture. Flat fracture face is characteristic of brittle metals.

The specimen of Grey 20 Cast Iron had initial and final measurements for its length and diameter as listed in Table 5, and the raw data is graphed in Figure 16.

Table 5: Grey 20 Cast Iron Measurements

Quantity	**Symbol**	**Value**
Initial Length	L_0	50.0 mm
Initial Diameter	D_0	8.65 mm
Final Length	L_f	51.0 mm
Final Diameter	D_f	8.50 mm

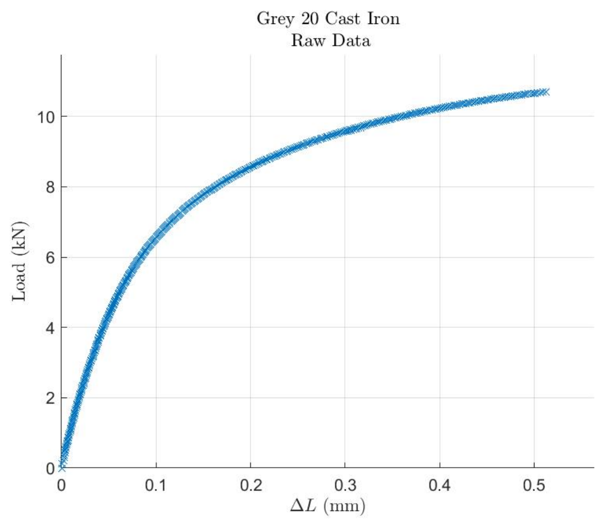

Figure 16: Raw data for Grey 20 Cast Iron

Using Equations (1) and (2) with the initial measurements, a stress-strain curve can be generated as shown in Figure 17.

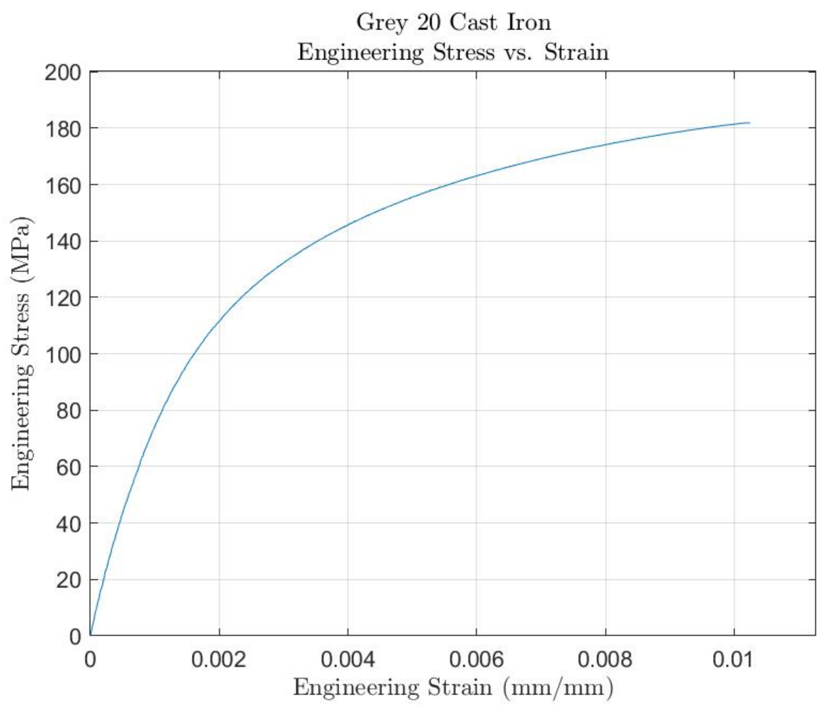

Figure 17: Stress-strain curve for Grey 20 Cast Iron. Due to the brittle nature of Grey 20 Cast Iron, the material fractures without necking, therefore its values for the ultimate tensile stress and fracture stress are the same.

The ultimate tensile stress and fracture stress are found to be:

$$\sigma_u = 181.92 \text{ MPa}$$
$$\sigma_f = 181.92 \text{ MPa}$$

and the modulus of toughness is calculated using Equation (15) as:

$$U_t = 1.24 \, \frac{MJ}{m^3}$$

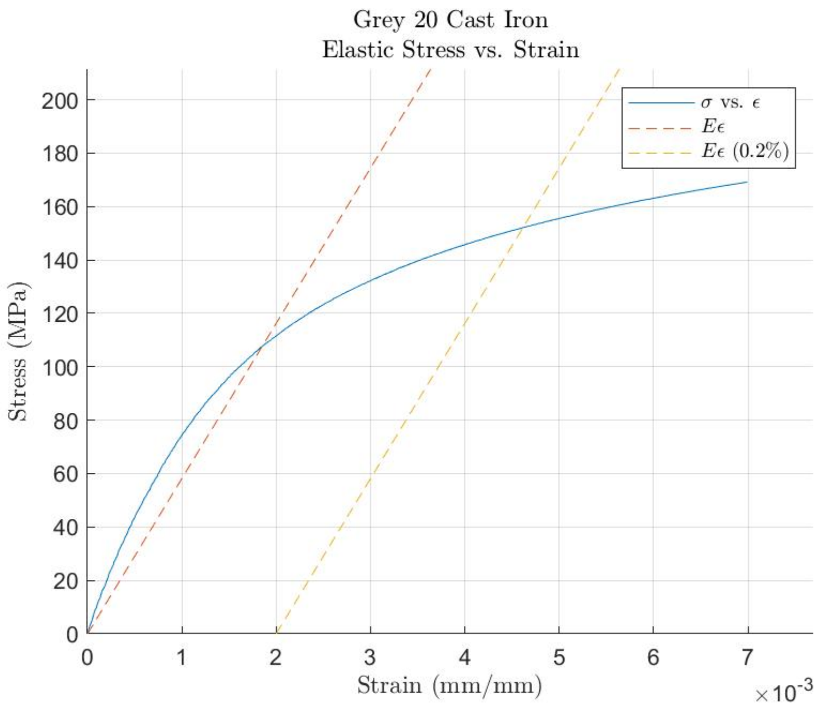

Figure 18: Elastic region of the stress-strain curve. The proportional limit is determined to be the stress at a strain of 0.002 mm/mm

The results from the analysis of the elastic region in Figure 18 give values for the proportional limit, yield strength, and modulus of elasticity of:

$$\sigma_p = 111.20 \text{ MPa}$$
$$\sigma_y = 151.94 \text{ MPa}$$
$$E = 58.14 \text{ GPa}$$

and a modulus of resilience of:

$$U_r = 1.307 \, \frac{kJ}{m^3}$$

The true stress-strain curve, calculated from Equations (6) and (7), is displayed in Figure 19.

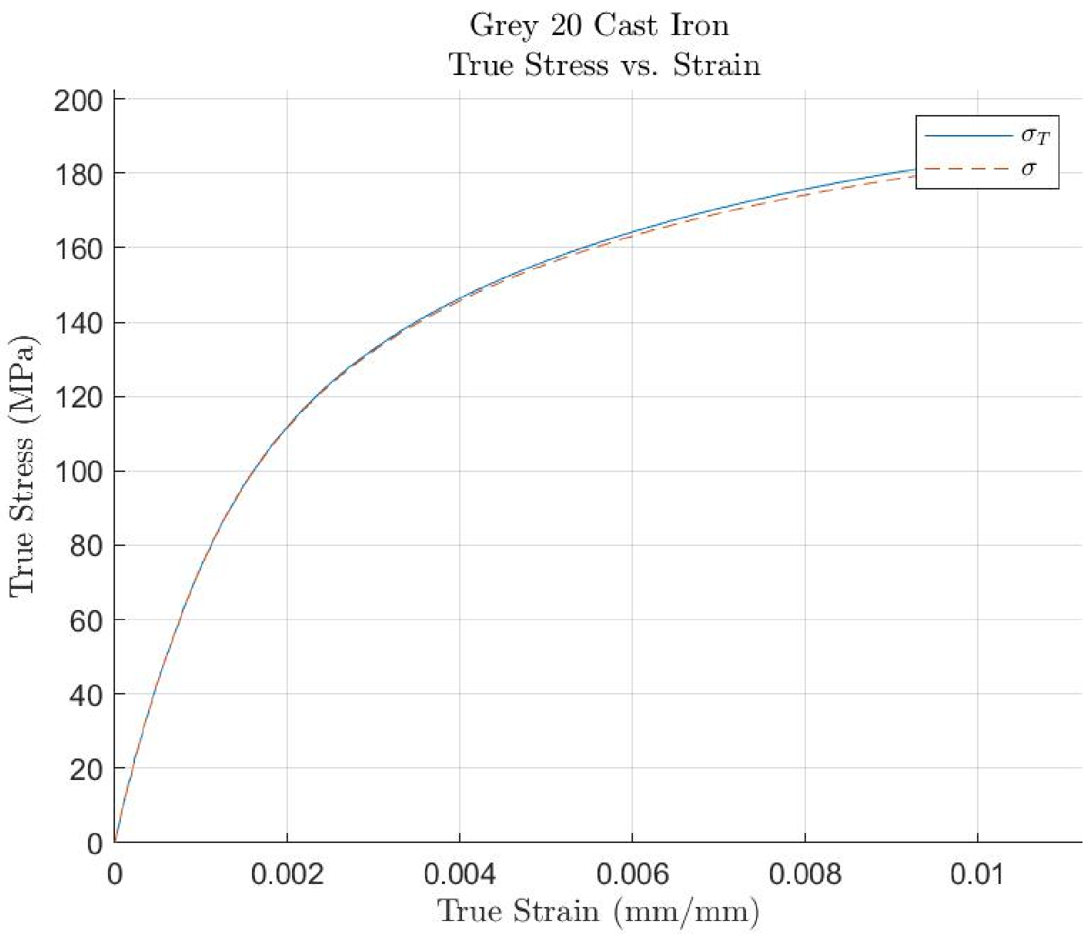

Figure 19: True stress-strain curve for Grey 20 Cast Iron. The true stress-strain curve is nearly identical to the engineering stress-strain curve.

Plotting the plastic region of the true stress-strain curve in logarithmic form gives the curve shown in Figure 20.

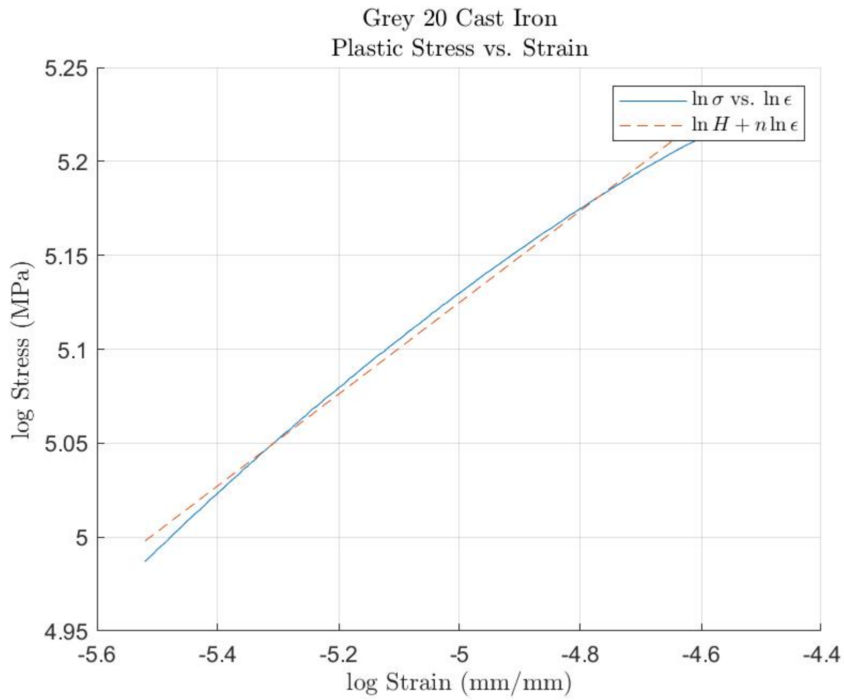

Figure 20: LogLog plot of true stress vs. strain. Red dashed line represents the best fit line with a slope of n and a intercept of $\ln H$

From Figure 20 and Equation (17), the values for the strain hardening exponent and strength coefficient are determined to be:

$$n = 0.2441$$
$$H = 569.77 \text{ MPa}$$

The percent elongation, reduction in area, and Poisson's ratio for Grey 20 Cast Iron are characteristic of a brittle material, and are calculated to be:

$$\%EL = 2.00 \ \%$$
$$\%RA = 3.44 \ \%$$
$$\nu = 0.87$$

The error between the calculated values and accepted values of the tensile properties were mixed for the different properties of Grey 20 Cast Iron. The difference in calculated values vs. accepted values for some tensile properties were: 58.14 GPa vs. 82 GPa (29.09% error) for the modulus of elasticity, 151.94 MPa vs. 65 MPa (133.75% error) for the yield strength, 181.92 MPa vs. 152 MPa (19.68% error) for ultimate tensile strength, and 2.00% vs. 7% (71.43% error) for the percent elongation.

Table 6: Grey 20 Cast Iron Tensile Properties

Quantity	**Symbol**	**Value**
Modulus of Elasticity	E	58.14 GPa
Proportional Limit	σ_p	111.20 MPa
Yield Strength	σ_y	151.94 MPa
Ultimate Tensile Strength	σ_u	181.92 MPa
Fracture Strength	σ_f	181.92 MPa
Strain Hardening Ratio	σ_u/σ_y	1.25
Modulus of Resilience	U_r	1.307 $\frac{kJ}{m^3}$
Modulus of Toughness	U_t	1.24 $\frac{MJ}{m^3}$
Strain Hardening Exponent	n	0.2441
Strength Coefficient	H	569.77 MPa
Elongation	$\%EL$	2.00%
Reduction in Area	$\%RA$	3.44%
Poisson's Ratio	ν	0.87

3.4 AA 6061 Heat Treated Aluminum

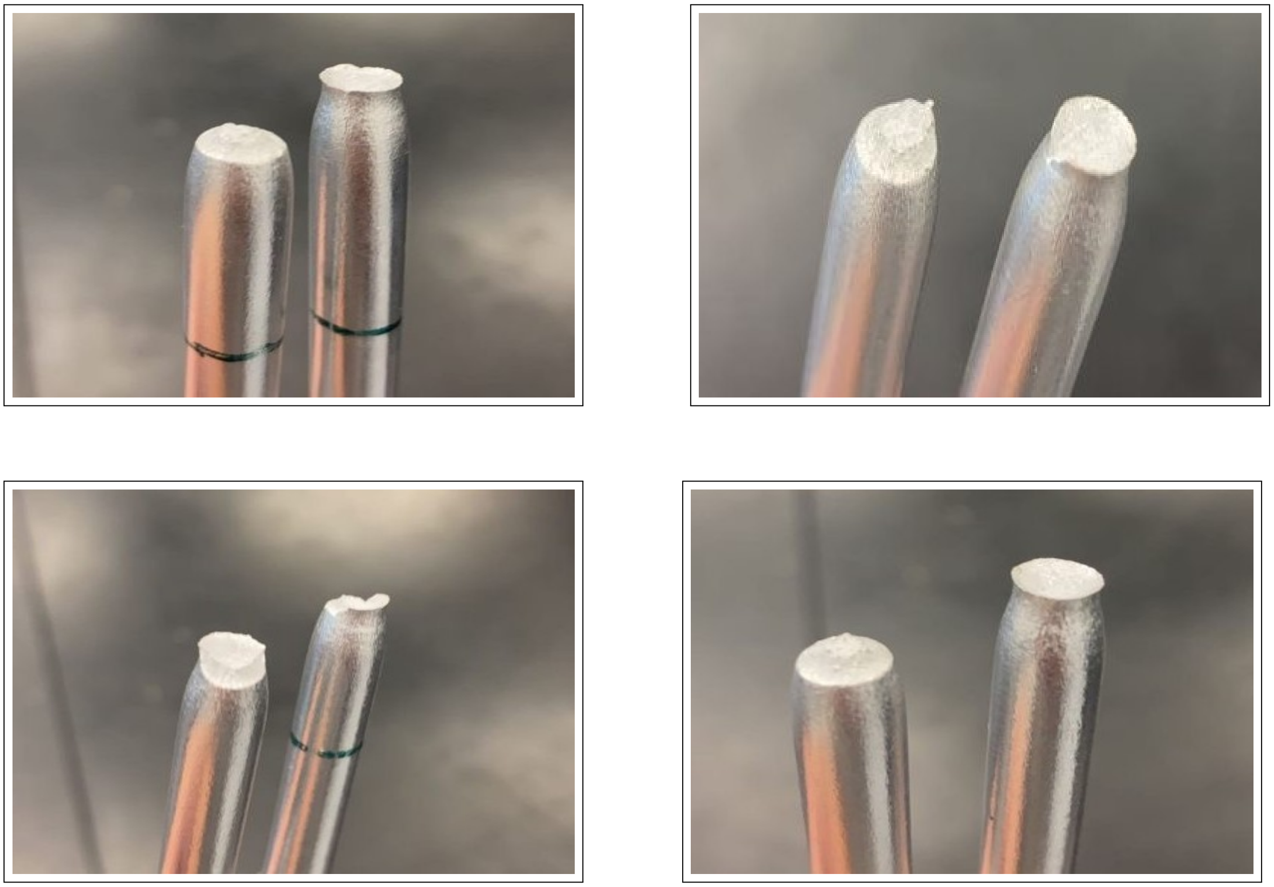

Figure 21: AA 6061 with heat treatments of 0 hrs (top left), 2 hrs (top right), 4 hrs (bottom left), and 6 hrs (bottom right) after fracture.

Four AA 6061 Aluminum specimens with differing heat treatment lengths of 0, 2, 4, and 6 hours were tested. The measured values for the lengths and diameters of the specimens are listed in Table 7.

Table 7: AA 6061 Heat Treated Aluminum Measurements

Quantity	**Symbol**	**0 HR**	**2 HR**	**4 HR**	**6 HR**
Initial Length	L_0	50.0 mm	50.0 mm	50.0 mm	50.0 mm
Initial Diameter	D_0	8.65 mm	8.65 mm	8.65 mm	8.65 mm
Final Length	L_f	57.7 mm	59.8 mm	58.6 mm	55.3 mm
Final Diameter	D_f	7.60 mm	7.10 mm	8.00 mm	8.00 mm

For each tensile test, Equations (1) and (2) were used to find the engineering stress-strain curve for each heat treatment, shown in Figure 22. Comparing the plots, as the aluminum alloy is heat treated for a longer period of time, the ultimate tensile stress decreases, while the strain at fracture increases. The only specimen that this does not hold true for is the 6-hour heat treated aluminum, which has a greater ultimate tensile strength than the shorter heat treatments. The values for the ultimate tensile stress, fracture stress, and modulus of toughness are listed in Table 8.

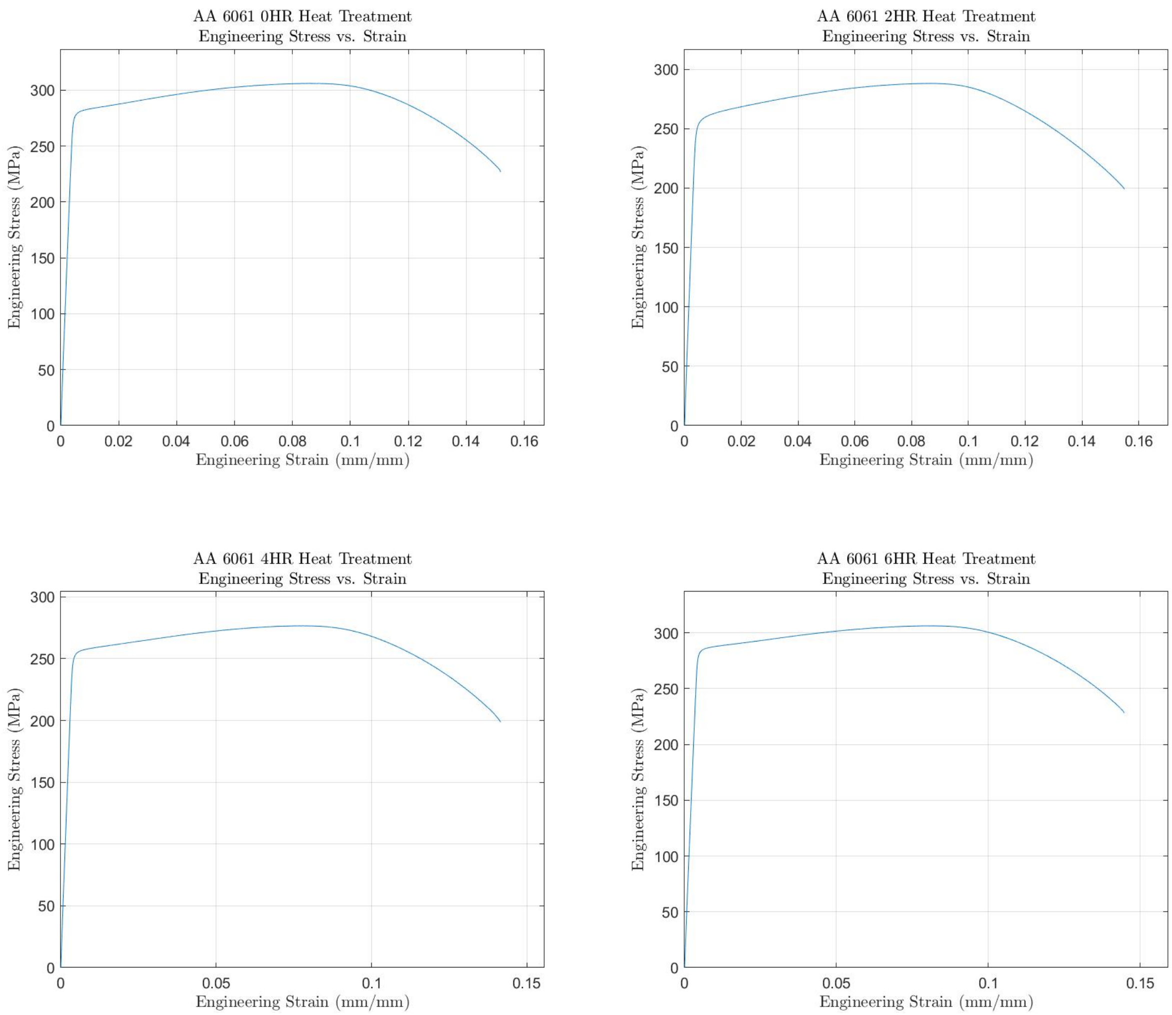

Figure 22: Engineering stress-strain curve for different heat treatments of AA 6061 Aluminum Alloy

Focusing on the elastic regions of the engineering stress-strain curves, it was found that the modulus of elasticity for the different heat treatments are nearly the same, shown in Figure 23. However, there is a difference between the yield stresses of the materials. Similar to the evolution of the ultimate tensile stress, the yield stress decreases with a longer duration of heat treatment, except for the case of the 6 hour heat treatment, which has a greater yield stress than the 4 hour and 2 hour heat treatments. The values for the modulus of elasticity, proportional limit, yield stress, and modulus of resilience are listed in Table 8.

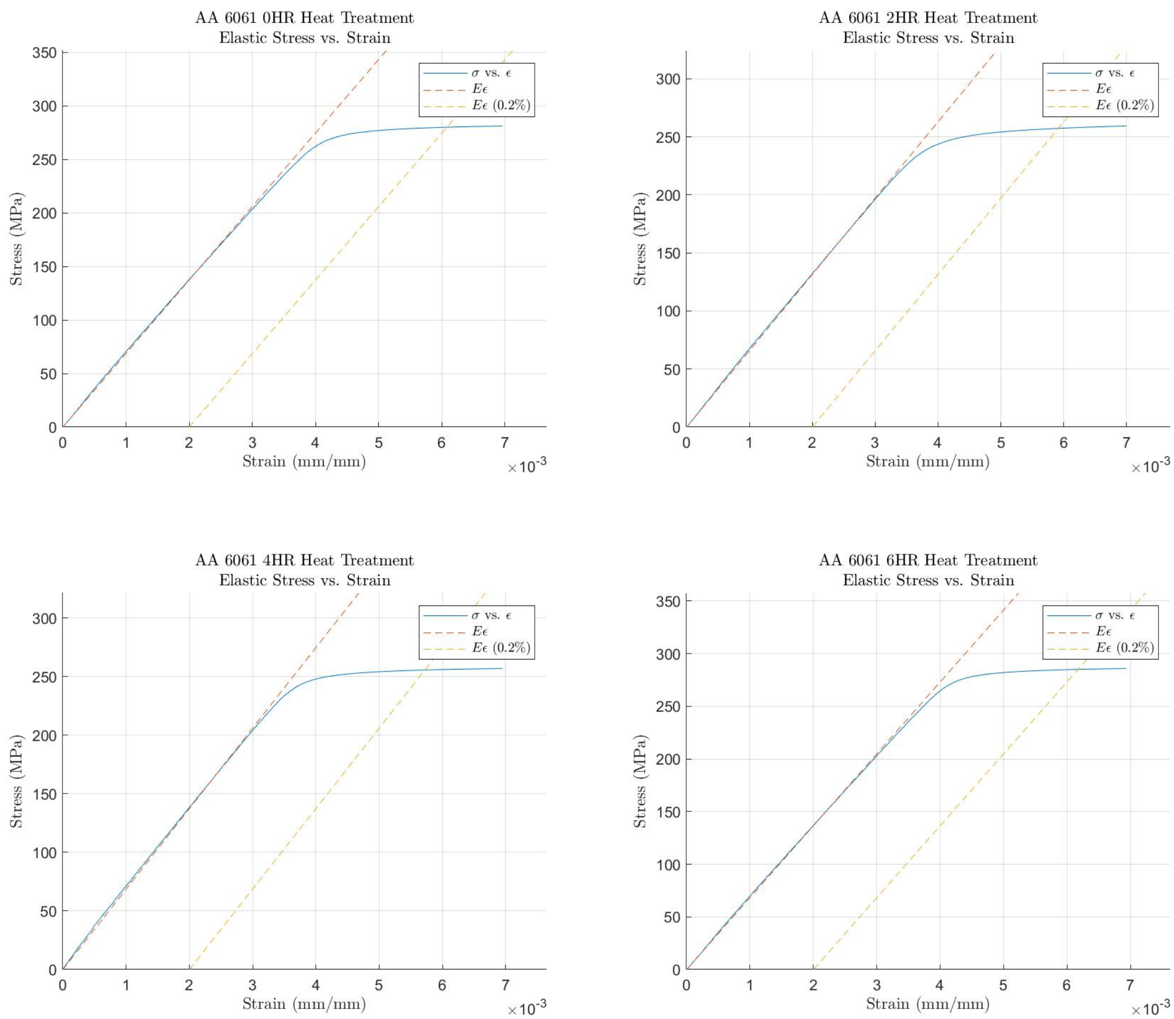

Figure 23: Elastic region of the stress-strain curve for different heat treatments of AA 6061 Aluminum Alloy

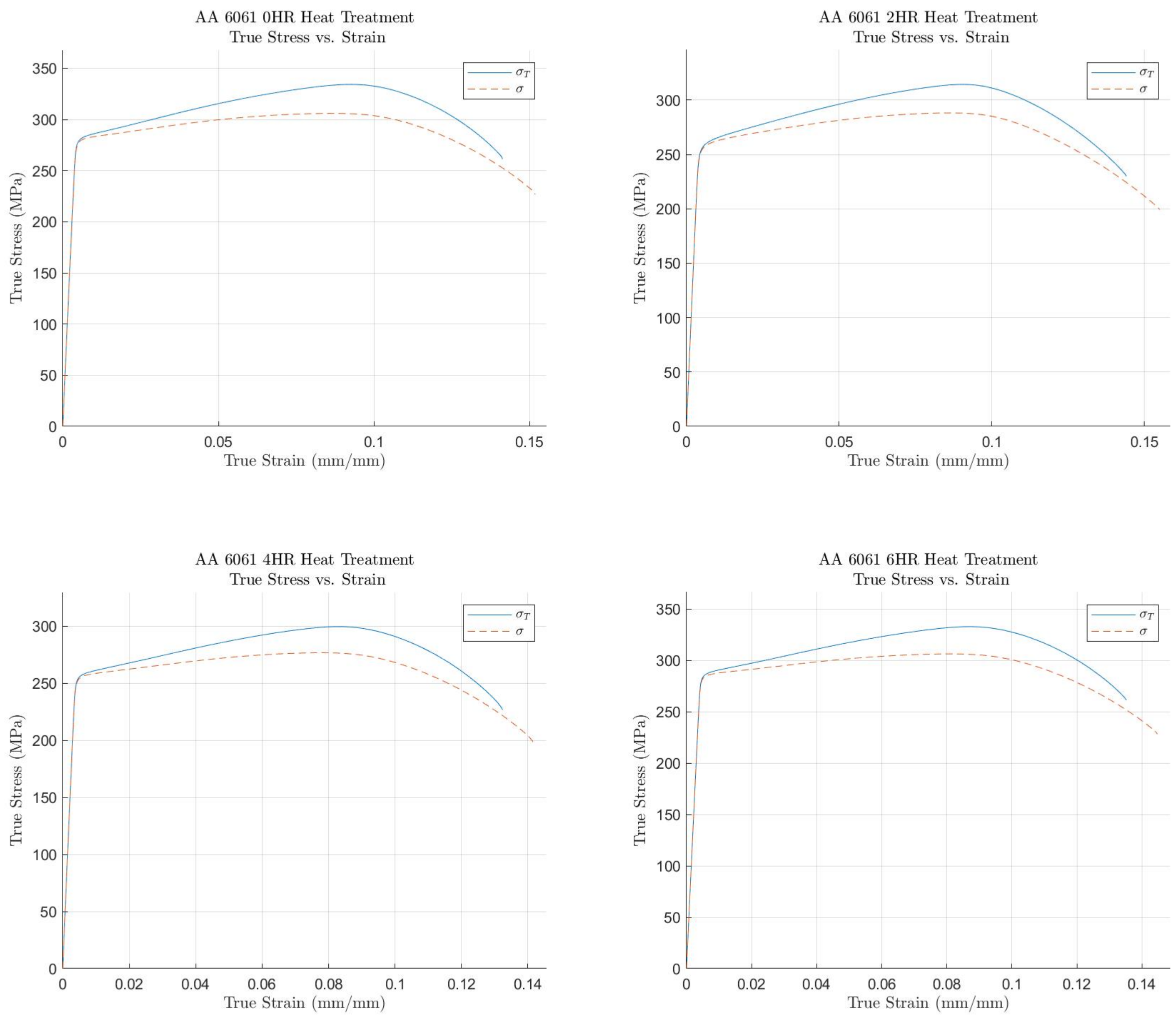

Figure 24: True stress-strain curve for different heat treatments of AA 6061 Aluminum Alloy

The true stress-strain curves for the AA6061 Heat Treated Aluminum specimens were found by using Equations (6) and (7), shown in Figure 24.

Focusing on the plastic region of the true stress-strain curve, and plotting in logarithmic form, shown in Figure 25, the values of the strain hardening exponent and strength coefficient can be found. From the results, listed in Table 8, there is small, but decreasing deviation in the values of the strain hardening exponent, which is expected as heat treatment recovers cold-worked grains to their original state.

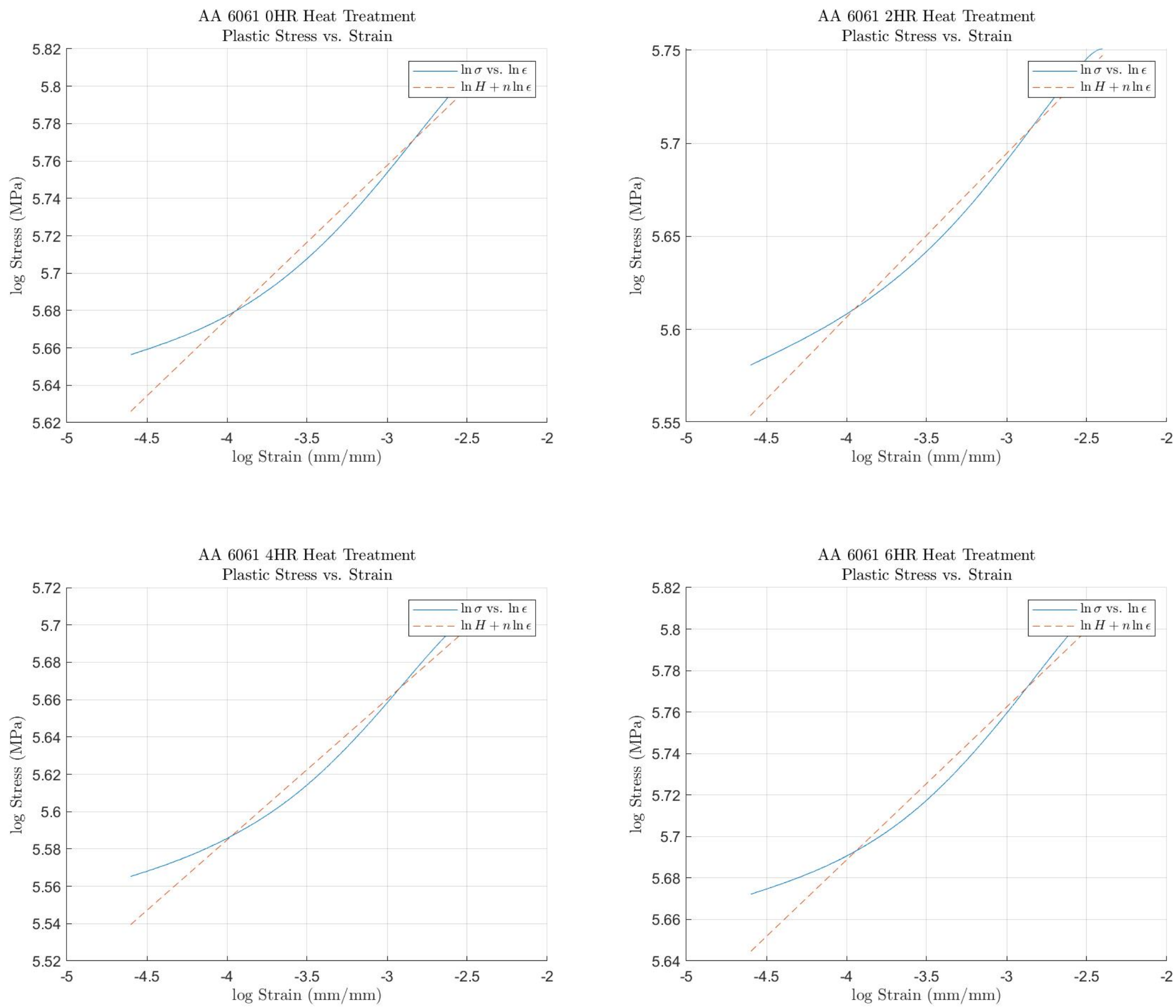

Figure 25: LogLog true stress-strain curve for different heat treatments of AA 6061 Aluminum Alloy

The percent elongation and reduction of area of the different heat treated aluminum alloys, listed in Table 8, show that an increase in the duration of heat treatment corresponds to an increase in ductility and toughness, and decrease in ultimate tensile strength, except for the case of the 6-hour heat treatment. The elasticity of the alloy had insignificant change with respect to the duration of the heat treatment.

Comparing the calculated values for AA6061 0 HR Heat Treated Aluminum and their accepted values, there is small variation between the two. The difference in calculated values vs. accepted values for some tensile properties were: 68.67 GPa vs. 68.90 GPa (0.34% error) for the modulus of elasticity, 280.00 MPa vs. 276 MPa (1.45% error) for the yield strength, 305.98 MPa vs. 310 MPa (1.30% error) for ultimate tensile strength, and 15.40% vs. 15% (2.67% error) for the percent elongation.

Table 8: AA 6061 Heat Treated Aluminum Tensile Properties

Quantity	**Symbol**	**0 HR**	**2 HR**	**4 HR**	**6 HR**	**Units**
Elasticity	E	68.67	65.72	68.68	68.28	GPa
Proportional Limit	σ_p	137.43	131.55	138.05	136.48	MPa
Yield Strength	σ_y	280.00	257.18	255.53	284.99	MPa
Tensile Strength	σ_u	305.98	288.17	276.61	306.23	MPa
Fracture Strength	σ_f	226.80	199.23	198.53	228.15	MPa
Hardening Ratio	σ_u/σ_y	1.09	1.12	1.08	1.07	-
Resilience	U_r	2.039	1.957	1.860	2.087	kJ/m^3
Toughness	U_t	44.48	42.24	37.65	42.80	MJ/m^3
Strain Hardening	n	0.08	0.09	0.08	0.07	-
Strength Coefficient	H	405.17	387.06	360.09	396.92	MPa
Elongation	$\%EL$	15.40	19.60	17.20	10.60	%
Reduction in Area	$\%RA$	22.80	32.63	14.46	14.46	%
Poisson's Ratio	ν	0.79	0.91	0.44	0.71	-

4 Conclusion

In conclusion, the physical tensile properties for each material found from the tensile tests were similar to the accepted values of those tensile properties. Of the materials tested, the most ductile was A36 Hot Rolled Steel, with a percent elongation of 33.20%, and the most brittle was Grey 20 Cast Iron, with a percent elongation of 2.00%. The material with the highest ultimate tensile strength was 1018 Cold Rolled Steel at 658.91 MPa, and the lowest was Grey 20 Cast Iron at 181.92 MPa. The toughest material was A36 Hot Rolled Steel with a modulus of toughness of 126.43 MJ/m^3, and the material with the lowest modulus of toughness was Grey 20 Cast Iron at 1.24 MJ/m^3.

Comparing the different heat treatments of AA6061 Aluminum Alloy, a longer heat treatment generally corresponded with a greater percent elongation and ductility, but a lower ultimate tensile strength and toughness. The duration of the heat treatment had little to no effect on the elasticity of the material.

References

[1] D. D. Campbell, "Lab2 - tension (sp19)," 2019.

[2] ——, "Lecture 5: Tensile test," 2021.

[3] R. C. Hibbeler, *Mechanics of Materials*, N. Dias, Ed. Pearson, 2015, vol. 10.

[4] J. William D. Callister and D. G. Rethwisch, *Material Science and Engineering: An Introduction*, D. Sayre, Ed. Wiley, July 2014, vol. 9.

[5] D. D. Campbell, "Tension experimental procedure," 2021.

Appendix A - Raw Data

Table A-1: Initial Length Measurements

Initial Lengths (mm)						
Material	**1**	**2**	**3**	**4**	**5**	**Avg**
1018 Steel	50.0	50.0	50.0	50.0	50.0	50.0
A36 Steel	50.0	50.0	50.0	50.0	50.0	50.0
Cast Iron	50.0	50.0	50.0	50.0	50.0	50.0
AA6061 0HR	50.0	50.0	50.0	50.0	50.0	50.0
AA6061 2HR	50.0	50.0	50.0	50.0	50.0	50.0
AA6061 4HR	50.0	50.0	50.0	50.0	50.0	50.0
AA6061 6HR	50.0	50.0	50.0	50.0	50.0	50.0

Table A-2: Initial Diameter Measurements

Initial Diameters (mm)						
Material	**1**	**2**	**3**	**4**	**5**	**Avg**
1018 Steel	8.65	8.65	8.65	8.65	8.65	8.65
A36 Steel	8.65	8.65	8.65	8.65	8.65	8.65
Cast Iron	8.65	8.65	8.65	8.65	8.65	8.65
AA6061 0HR	8.65	8.65	8.65	8.65	8.65	8.65
AA6061 2HR	8.65	8.65	8.65	8.65	8.65	8.65
AA6061 4HR	8.65	8.65	8.65	8.65	8.65	8.65
AA6061 6HR	8.65	8.65	8.65	8.65	8.65	8.65

Table A-3: Final Length Measurements

Final Lengths (mm)						
Material	**1**	**2**	**3**	**4**	**5**	**Avg**
1018 Steel	55.7	55.7	57.2	55.0	55.5	55.8
A36 Steel	64.8	64.0	63.5	65.0	64.9	64.4
Cast Iron	50.9	50.7	50.8	50.5	50.0	50.6
AA6061 0HR	58.8	58.3	58.5	58.6	58.4	58.5
AA6061 2HR	58.3	58.0	58.1	58.3	58.2	58.2
AA6061 4HR	58.0	57.9	58.0	58.1	58.0	58.0
AA6061 6HR	57.8	57.5	57.6	57.8	57.8	57.7

Table A-4: Final Diameter Measurements

Final Diameters (mm)						
Material	**1**	**2**	**3**	**4**	**5**	**Avg**
1018 Steel	5.70	6.00	6.00	5.70	5.58	5.80
A36 Steel	5.40	5.48	5.10	5.40	5.42	5.34
Cast Iron	8.60	8.60	8.30	8.50	8.50	8.50
AA6061 0HR	7.50	7.40	7.50	7.90	7.70	7.60
AA6061 2HR	7.00	7.30	7.10	7.00	7.20	7.12
AA6061 4HR	8.00	7.50	7.80	7.90	8.00	7.84
AA6061 6HR	8.02	8.01	8.03	8.01	8.02	8.02

Appendix B - Matlab Code

The following pages in this appendix contain the Matlab code used for all of the calculations in this report. The code beings on the next page.

```matlab
% Name: Jonathan Tyler Boylan
% Date: 10/21/2021
% EML3012C
% Tension Lab MATLAB

clear
clc
close all
format compact

it = "Interpreter";
lx = "Latex";

% Change figure visibility
set(0,'DefaultFigureVisible','off')

% Tensile Properties Save File
tensile_file = fopen('tensile_properties.txt','w');

% Save Figures to jpg?
savefig = true;

% Specimen names
specimen_names = [
    "1018 Cold Rolled Steel",...
    "A36 Hot Rolled Steel",...
    "Grey 20 Cast Iron",...
    "AA 6061 0HR Heat Treatment",...
    "AA 6061 2HR Heat Treatment",...
    "AA 6061 4HR Heat Treatment",...
    "AA 6061 6HR Heat Treatment"
    ];

% Specimen data files
file_names = [
    "1018_STEEL",...
    "A36_STEEL",...
    "CAST_IRON",...
    "AA_6061_0HR",...
    "AA_6061_2HR",...
    "AA_6061_4HR",...
    "AA_6061_6HR"
    ];

% Measured Data
lengths_0 = [50,50,50,50,50,50,50]; % mm
diameters_0 = [8.65,8.65,8.65,8.65,8.65,8.65,8.65].*1e-3; % m

lengths_f = [56.4 66.6 51 57.7 59.8 58.6 55.3]; % mm
diameters_f = [5.8 5.3 8.5 7.6 7.1 8.0 8.0]*1e-3; % m

% Number of Points after Fracture (to be removed)
```

```
PAF = [2 1 1 1 1 2 1];

% Plastic Region Start
plastic_strain = [0.01 0.023 0.004 0.01 0.01 0.01 0.01];

for i = 1:length(file_names)

    % Get initial measurements
    L0 = lengths_0(i);
    D0 = diameters_0(i);

    % Calculate initial area
    A0 = pi/4*D0^2; % m^2

    % Get specimen tensile data
    data = readtable(file_names(i));

    % Get Load and Strain data
    load = data.Load_kN'; % kN
    strain = data.Strain_mm'; % mm

    % Remove points after fracture (PAF)
    load = load(1:end-PAF(i));
    strain = strain(1:end-PAF(i));

    % Adjust so first point is at (0,0)
    load = load - load(1);
    strain = strain - strain(1);

    % Plot raw data
    figs(1) = figure();
    figf(1) = "RAW";
    scatter(strain,load,'x')
    grid on
    title([specimen_names(i) " Raw Data"],it,lx)
    ylim([0 max(load)*1.10])
    xlim([0 strain(end)*1.10])
    xlabel("$\Delta L$ (mm)",it,lx)
    ylabel("Load (kN)",it,lx)

    % Find Engineering Stress and Strain
    stress_eng = load./A0.*1e-3; % MPa
    strain_eng = strain./L0; % mm/mm

    % Plot Engineering Stress vs. Strain
    figs(2) = figure();
    figf(2) = "ENGSS";
    plot(strain_eng,stress_eng);
    grid on
    title([specimen_names(i) "Engineering Stress vs. Strain"],it,lx)
    ylim([0 max(stress_eng)*1.10])
    xlim([0 strain_eng(end)*1.10])
    xlabel("Engineering Strain (mm/mm)",it,lx)
    ylabel("Engineering Stress (MPa)",it,lx)
```

```
    % Calculate True Stress and Strain
    stress_true = stress_eng.*(1 + strain_eng);
    strain_true = log(1 + strain_eng);

    % Plot True Stress and Strain
    figs(3) = figure();
    figf(3) = "TRUESS";
    hold on
    plot(strain_true,stress_true);
    plot(strain_eng,stress_eng,'--')
    grid on
    title([specimen_names(i) " True Stress vs. Strain"],it,lx)
    ylim([0 max(stress_true)*1.10])
    xlim([0 strain_true(end)*1.10])
    xlabel("True Strain (mm/mm)",it,lx)
    ylabel("True Stress (MPa)",it,lx)
    legend(["$\sigma_T$" "$\sigma$"],it,lx)


    % Calculate Tensile Properties

    % Modulus of Elasticity & Proportional Limit

    % Get Region of Proportionality
    region = 0.002;
    strain_region = strain_eng(strain_eng < region);
    stress_region = stress_eng(1:length(strain_region));

    Proportional_Limit = max(stress_region);

    % Smooth Data in Region
    strain_region = smoothdata(strain_region);
    stress_region = smoothdata(stress_region);

    Elasticity = mean(diff(stress_region)./
diff(strain_region))*1e-3; % GPa

    % Plot Elasticity on Engineering Stress vs. Strain
    region = 0.007;
    strain_region = strain_eng(strain_eng < region);
    stress_region = stress_eng(1:length(strain_region));

    figs(4) = figure();
    figf(4) = "ELASTIC";
    hold on
    plot(strain_region,stress_region)
    plot(strain_region,Elasticity.*strain_region.*1e3,'--');
    grid on
    title([specimen_names(i) "Elastic Stress vs. Strain"],it,lx)
    ylim([0 max(stress_region)*1.25])
    xlim([0 strain_region(end)*1.1])
    xlabel("Strain (mm/mm)",it,lx)
    ylabel("Stress (MPa)",it,lx)
```

```
    % Yield Strength
    offset = 0.002;
    strain_region = strain_region(strain_region < stress_region./
Elasticity.*1e-3 + offset);
    stress_region = stress_region(1:length(strain_region));
    plot(strain_region + offset,Elasticity.*strain_region.*1e3,'--');

    legend(["$\sigma$ vs. $\epsilon$" "$E\epsilon$" "$E\epsilon$ (0.2\
%)"],it,lx)

    Yield_Strength = stress_region(end);

    % Ultimate Tensile Strength
    Tensile_Strength = max(stress_eng);

    % Engineering Fracture Strength
    Fracture_Strength = stress_eng(end);

    % Percent Elongation (Data)
    Percent_Elongation_D = strain_eng(end)*100;

    % Percent Elongation (Measured)
    Percent_Elongation_M = (lengths_f(i) - L0)/L0*100;

    % Reduction in Area (Measured)
    Af = pi/4*diameters_f(i)^2;
    Area_Reduction = (A0 - Af)/A0 * 100;

    % Poisson's Ratio
    epsilon_x = diameters_f(i)/D0 - 1;
    epsilon_z = Percent_Elongation_M/100;
    Poissons_Ratio = -epsilon_x/epsilon_z;

    % Resilience
    Resilience = .5*Yield_Strength/Elasticity;

    % Tensile Toughness
    brittle = strain_eng(end) < 0.05;
    if brittle
        Toughness = (2/3)*Tensile_Strength*strain_eng(end);
    else
        Toughness = (Tensile_Strength +
 Yield_Strength)*strain_eng(end)/2;
    end

    % Get LogLog Plastic Region
    region = plastic_strain(i);
    region2 = strain_true(stress_true == max(stress_true));
    strain_region = strain_true(strain_true > region & strain_true <
 region2);
    stress_region = stress_true(strain_true > region & strain_true <
 region2);
```

```
    % Fit line to Log plot
    p = polyfit(log(strain_region),log(stress_region),1);

    % Strain Hardening Exponent (slope)
    Strain_Hardening = p(1);

    % Strength Coefficient (bias)
    lnH = p(2);
    Strength_Coefficient = exp(lnH);

    % Plot Plastic Region
    figs(5) = figure();
    figf(5) = "PLOG";
    hold on
    plot(log(strain_region),log(stress_region))
    plot(log(strain_region),log(strain_region).*Strain_Hardening +
 lnH, '--')
    grid on
    title([specimen_names(i) "Plastic Stress vs. Strain"],it,lx)
    xlabel("log Strain (mm/mm)",it,lx)
    ylabel("log Stress (MPa)",it,lx)
    legend(["$\ln\sigma$ vs. $\ln\epsilon$" "$\ln k + n \ln \epsilon
$"],it,lx)

    strain_region = strain_true(strain_true > region);
    stress_region = Strength_Coefficient.*strain_true(strain_true >
 region).^Strain_Hardening;

    % Plot Hardening over True
    figs(6) = figure();
    figf(6) = "HARD";
    hold on
    plot(strain_true, stress_true)
    plot(strain_region, stress_region)
    grid on
    title([specimen_names(i) "Strain Hardening on True Stress vs.
 Strain"],it,lx)
    ylim([0 max(stress_region)*1.25])
    xlim([0 strain_region(end)*1.1])
    xlabel("Strain (mm/mm)",it,lx)
    ylabel("Stress (MPa)",it,lx)
    legend(["$\sigma$ vs. $\epsilon$" "$k\epsilon^n$"],it,lx)


    % Print Tensile Properties
    pd = 35;
    fprintf(tensile_file, "Tensile Properties of %s\n",
 specimen_names(i)); % header
    fprintf(tensile_file,"%s\n",pad("-",pd + 10,'-'));
    fprintf(tensile_file,"%s Value\n",pad("Property",pd));
    fprintf(tensile_file,"%s\n",pad("-",pd + 10,'-'));
    fprintf(tensile_file,"%s %.2f GPa\n", pad("Modulus of Elasticity
 (E)",pd), Elasticity);
```

```
    fprintf(tensile_file,"%s %.2f MPa\n", pad("Proportional Limit
 (#_p)",pd),Proportional_Limit);
    fprintf(tensile_file,"%s %.2f MPa\n", pad("Yield Strength
 (#_y)",pd), Yield_Strength);
    fprintf(tensile_file,"%s %.2f MPa\n", pad("Tensile Strength
 (T.S)",pd), Tensile_Strength);
    fprintf(tensile_file,"%s %.2f MPa\n", pad("Fracture Strength
 (#_f)",pd), Fracture_Strength);
    fprintf(tensile_file,"%s %.2f %%\n", pad("Elongation [Data]
 (%EL)",pd), Percent_Elongation_D);
    fprintf(tensile_file,"%s %.2f \n", pad("Elongation [Measured]
 (%EL)",pd), Percent_Elongation_M);
    fprintf(tensile_file,"%s %.2f %%\n", pad("Reduction in Area
 (%RA)",pd), Area_Reduction);
    fprintf(tensile_file,"%s %.2f \n", pad("Poisson's Ratio (#)",pd),
 Poissons_Ratio);
    fprintf(tensile_file,"%s %.3f kJ/m^3\n", pad("Modulus of
 Resilience (U_r)",pd), Resilience);
    fprintf(tensile_file,"%s %.2f MJ/m^3\n", pad("Modulus of Toughness
 (U_t)",pd), Toughness);
    fprintf(tensile_file,"%s %.4f\n", pad("Strain Hardening Exponent
 (n)",pd), Strain_Hardening);
    fprintf(tensile_file,"%s %.2f\n", pad("Strength Coefficient
 (H)",pd), Strength_Coefficient);
    fprintf(tensile_file,'\n\n'); % end


    % Save Figures
    if savefig
        for j = 1:length(figs)

 saveas(figs(j),strcat("Figures/",file_names(i),"_",figf(j),".jpg"))
        end
    end
end

tensile_file = fclose(tensile_file);
```

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Appendix C - Matlab Code Output File

The following pages in this appendix contain the output from the Matlab code in Appendix B. The text begins on the next page.

Tensile Properties of 1018 Cold Rolled Steel

Property	Value	Standard Value	Error
Modulus of Elasticity (E)	184.05 GPa	200.00 GPa	7.98 %
Proportional Limit (σ_p)	368.50 MPa		
Yield Strength (σ_y)	634.32 MPa	370.00 GPa	71.44 %
Tensile Strength (σ_u)	658.91 MPa	440.00 GPa	49.75 %
Fracture Strength (σ_f)	420.75 MPa		
Elongation [Data] (%EL)	12.08 %		
Elongation [Measured] (%EL)	12.80 %	15.00 %	14.67 %
Reduction in Area (%RA)	55.04 %		
Poisson's Ratio (ν)	2.57	0.29	787.61 %
Modulus of Resilience (U_r)	1.723 kJ/m^3		
Modulus of Toughness (U_t)	78.11 MJ/m^3		
Strain Hardening Exponent (n)	0.03	0.23	87.52 %
Strength Coefficient (H)	750.36		

Tensile Properties of A36 Hot Rolled Steel

Property	Value	Standard Value	Error
Modulus of Elasticity (E)	199.58 GPa	200.00 GPa	0.21 %
Proportional Limit (σ_p)	414.09 MPa		
Yield Strength (σ_y)	353.30 MPa	250.00 GPa	41.32 %
Tensile Strength (σ_u)	502.82 MPa	475.00 GPa	5.86 %
Fracture Strength (σ_f)	361.87 MPa		
Elongation [Data] (%EL)	29.53 %		
Elongation [Measured] (%EL)	33.20 %	23.00 %	44.35 %
Reduction in Area (%RA)	62.46 %		
Poisson's Ratio (ν)	1.17	0.26	348.66 %
Modulus of Resilience (U_r)	0.885 kJ/m^3		
Modulus of Toughness (U_t)	126.42 MJ/m^3		
Strain Hardening Exponent (n)	0.22	0.23	5.37 %
Strength Coefficient (H)	884.24		

Tensile Properties of Grey 20 Cast Iron

Property	Value	Standard Value	Error
Modulus of Elasticity (E)	58.14 GPa	82.00 GPa	29.09 %
Proportional Limit (σ_p)	111.20 MPa		
Yield Strength (σ_y)	151.94 MPa	65.00 GPa	133.75 %
Tensile Strength (σ_u)	181.92 MPa	152.00 GPa	19.68 %
Fracture Strength (σ_f)	181.92 MPa		
Elongation [Data] (%EL)	1.02 %		

```
Elongation [Measured] (%EL)    2.00 %          7.00  %          71.43 %
Reduction in Area (%RA)        3.44 %
Poisson's Ratio (ν)            0.87            0.29             198.98 %
Modulus of Resilience (U_r)    1.307 kJ/m^3
Modulus of Toughness (U_t)     1.24 MJ/m^3
Strain Hardening Exponent (n)  0.24            0.23             6.11 %
Strength Coefficient (H)       569.77


Tensile Properties of AA 6061 0HR Heat Treatment
-------------------------------------------------------------------------
--
Property                       Value           Standard Value     Error
-------------------------------------------------------------------------
--
Modulus of Elasticity (E)      68.67 GPa       68.90 GPa        0.34 %
Proportional Limit (σ_p)       137.43 MPa
Yield Strength (σ_y)           280.00 MPa      276.00 GPa       1.45 %
Tensile Strength (σ_u)         305.98 MPa      310.00 GPa       1.30 %
Fracture Strength (σ_f)        226.80 MPa
Elongation [Data] (%EL)        15.18 %
Elongation [Measured] (%EL)    15.40 %         15.00  %         2.67 %
Reduction in Area (%RA)        22.80 %
Poisson's Ratio (ν)            0.79            0.33             138.86 %
Modulus of Resilience (U_r)    2.039 kJ/m^3
Modulus of Toughness (U_t)     44.48 MJ/m^3
Strain Hardening Exponent (n)  0.08            0.23             64.25 %
Strength Coefficient (H)       405.17


Tensile Properties of AA 6061 2HR Heat Treatment
-------------------------------------------------------------------------
--
Property                       Value           Standard Value     Error
-------------------------------------------------------------------------
--
Modulus of Elasticity (E)      65.72 GPa       68.90 GPa        4.62 %
Proportional Limit (σ_p)       131.55 MPa
Yield Strength (σ_y)           257.18 MPa      276.00 GPa       6.82 %
Tensile Strength (σ_u)         288.17 MPa      310.00 GPa       7.04 %
Fracture Strength (σ_f)        199.23 MPa
Elongation [Data] (%EL)        15.49 %
Elongation [Measured] (%EL)    19.60 %         15.00  %         30.67 %
Reduction in Area (%RA)        32.63 %
Poisson's Ratio (ν)            0.91            0.33             177.04 %
Modulus of Resilience (U_r)    1.957 kJ/m^3
Modulus of Toughness (U_t)     42.24 MJ/m^3
Strain Hardening Exponent (n)  0.09            0.23             61.74 %
Strength Coefficient (H)       387.06


Tensile Properties of AA 6061 4HR Heat Treatment
-------------------------------------------------------------------------
--
```

Property	Value	Standard Value	Error
Modulus of Elasticity (E)	68.68 GPa	68.90 GPa	0.32 %
Proportional Limit (σ_p)	138.05 MPa		
Yield Strength (σ_y)	255.53 MPa	276.00 GPa	7.42 %
Tensile Strength (σ_u)	276.61 MPa	310.00 GPa	10.77 %
Fracture Strength (σ_f)	198.53 MPa		
Elongation [Data] (%EL)	14.15 %		
Elongation [Measured] (%EL)	17.20 %	15.00 %	14.67 %
Reduction in Area (%RA)	14.46 %		
Poisson's Ratio (ν)	0.44	0.33	32.39 %
Modulus of Resilience (U_r)	1.860 kJ/m^3		
Modulus of Toughness (U_t)	37.65 MJ/m^3		
Strain Hardening Exponent (n)	0.08	0.23	67.23 %
Strength Coefficient (H)	360.09		

Tensile Properties of AA 6061 6HR Heat Treatment

Property	Value	Standard Value	Error
Modulus of Elasticity (E)	68.28 GPa	68.90 GPa	0.90 %
Proportional Limit (σ_p)	136.48 MPa		
Yield Strength (σ_y)	284.99 MPa	276.00 GPa	3.26 %
Tensile Strength (σ_u)	306.23 MPa	310.00 GPa	1.22 %
Fracture Strength (σ_f)	228.15 MPa		
Elongation [Data] (%EL)	14.48 %		
Elongation [Measured] (%EL)	10.60 %	15.00 %	29.33 %
Reduction in Area (%RA)	14.46 %		
Poisson's Ratio (ν)	0.71	0.33	114.82 %
Modulus of Resilience (U_r)	2.087 kJ/m^3		
Modulus of Toughness (U_t)	42.80 MJ/m^3		
Strain Hardening Exponent (n)	0.07	0.23	67.93 %
Strength Coefficient (H)	396.92		

Appendix D - Additional Plots

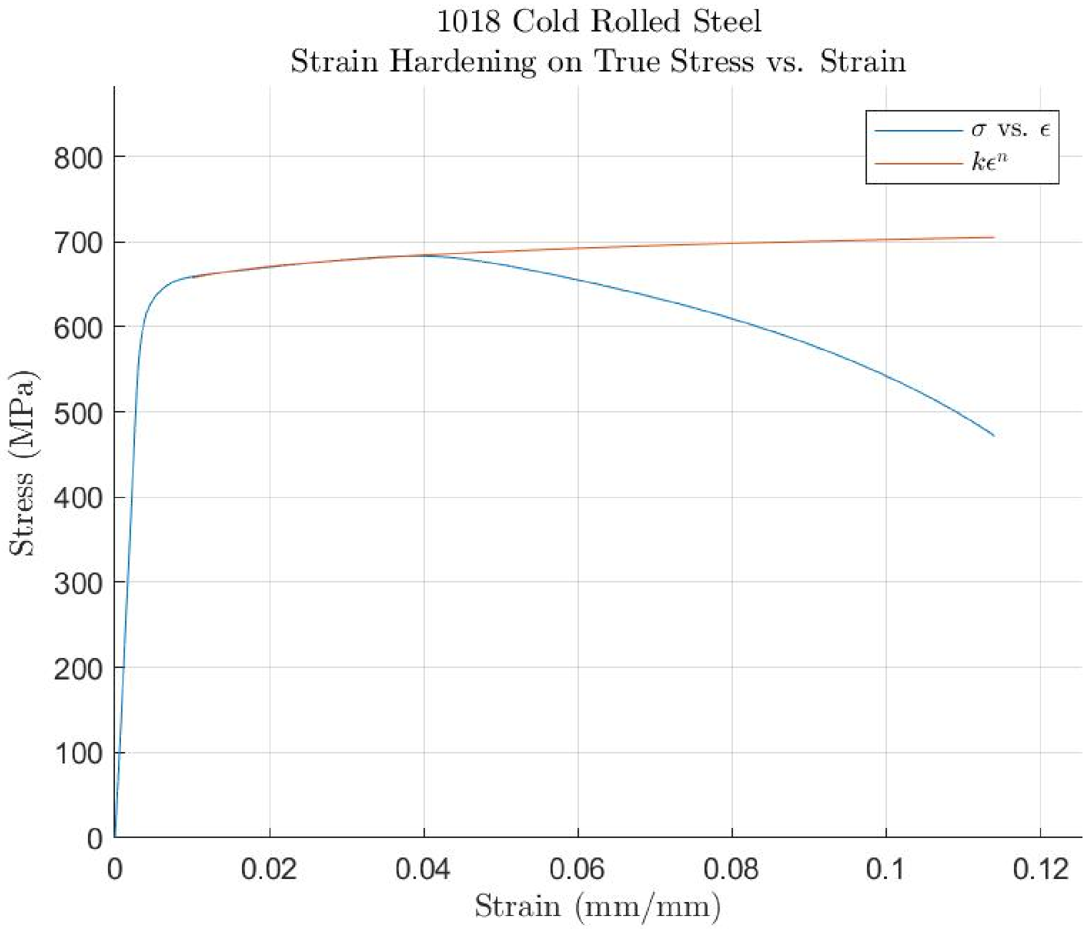

Figure D-1: True stress-strain curve for 1018 Cold Rolled Steel with strain hardening correction.

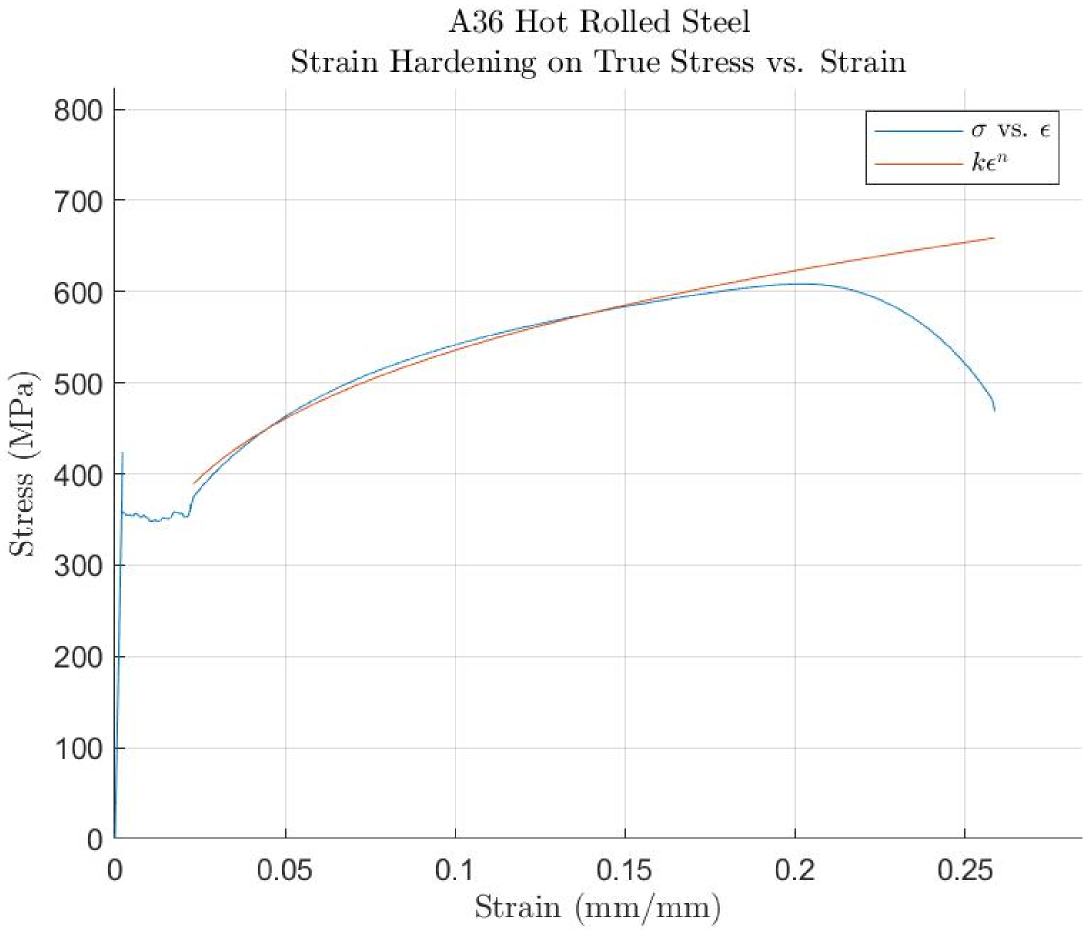

Figure D-2: True stress-strain curve for A36 Hot Rolled Steel with strain hardening correction.

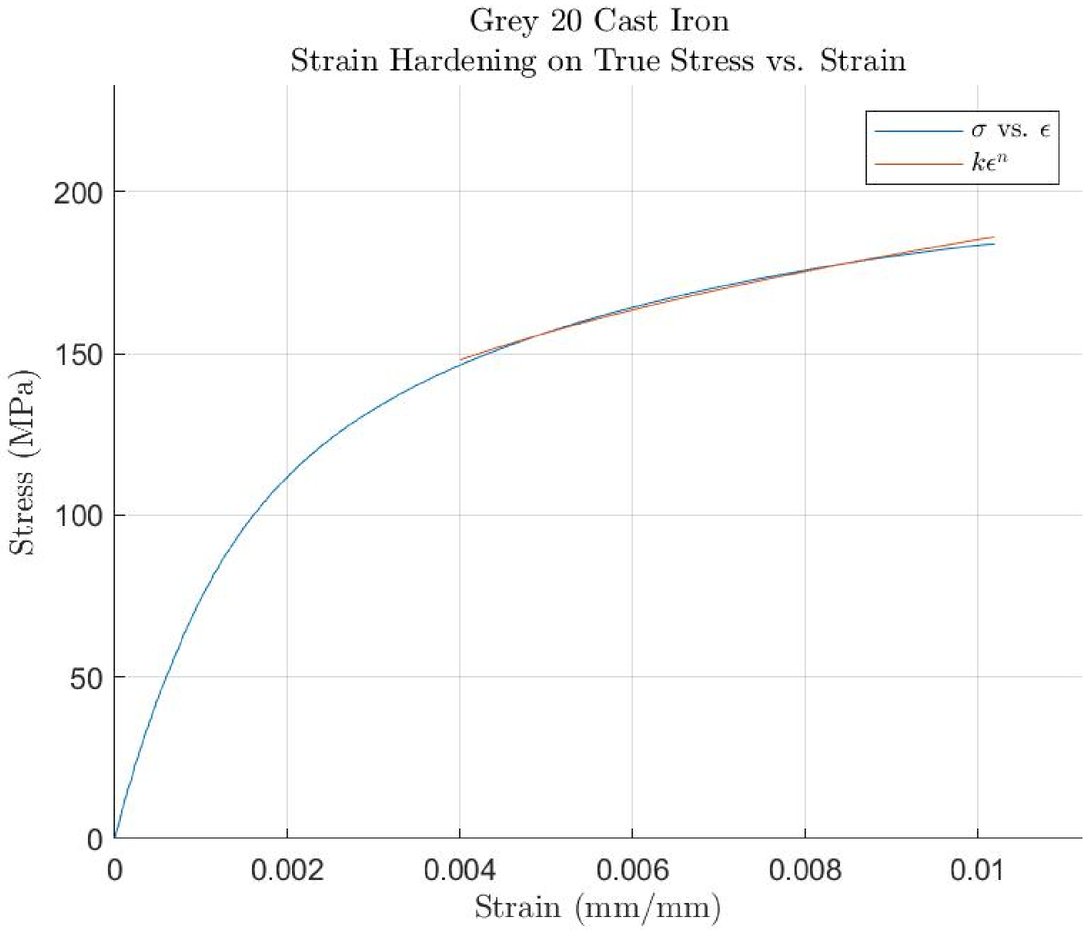

Figure D-3: True stress-strain curve for Grey 20 Cast Iron with strain hardening correction.

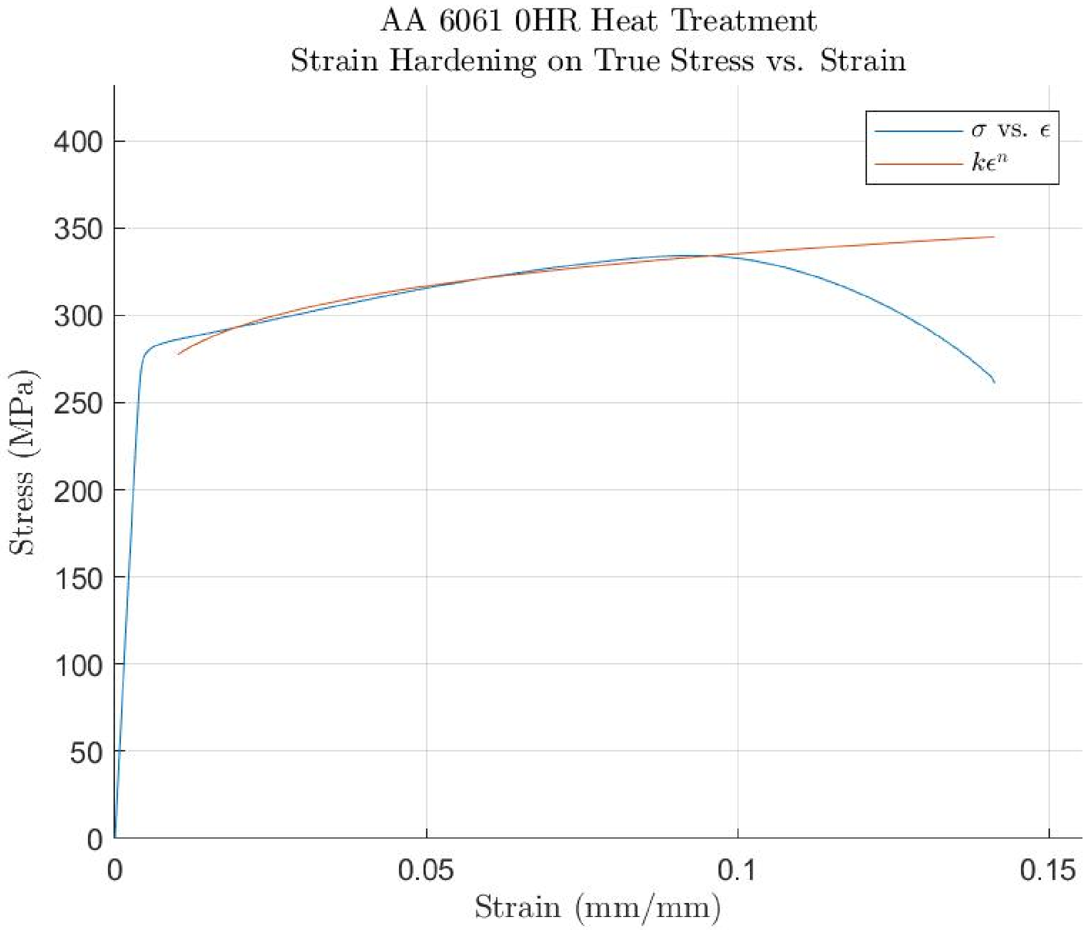

Figure D-4: True stress-strain curve for 6061 Heat Treated Aluminum Alloy (0HR) with strain hardening correction.

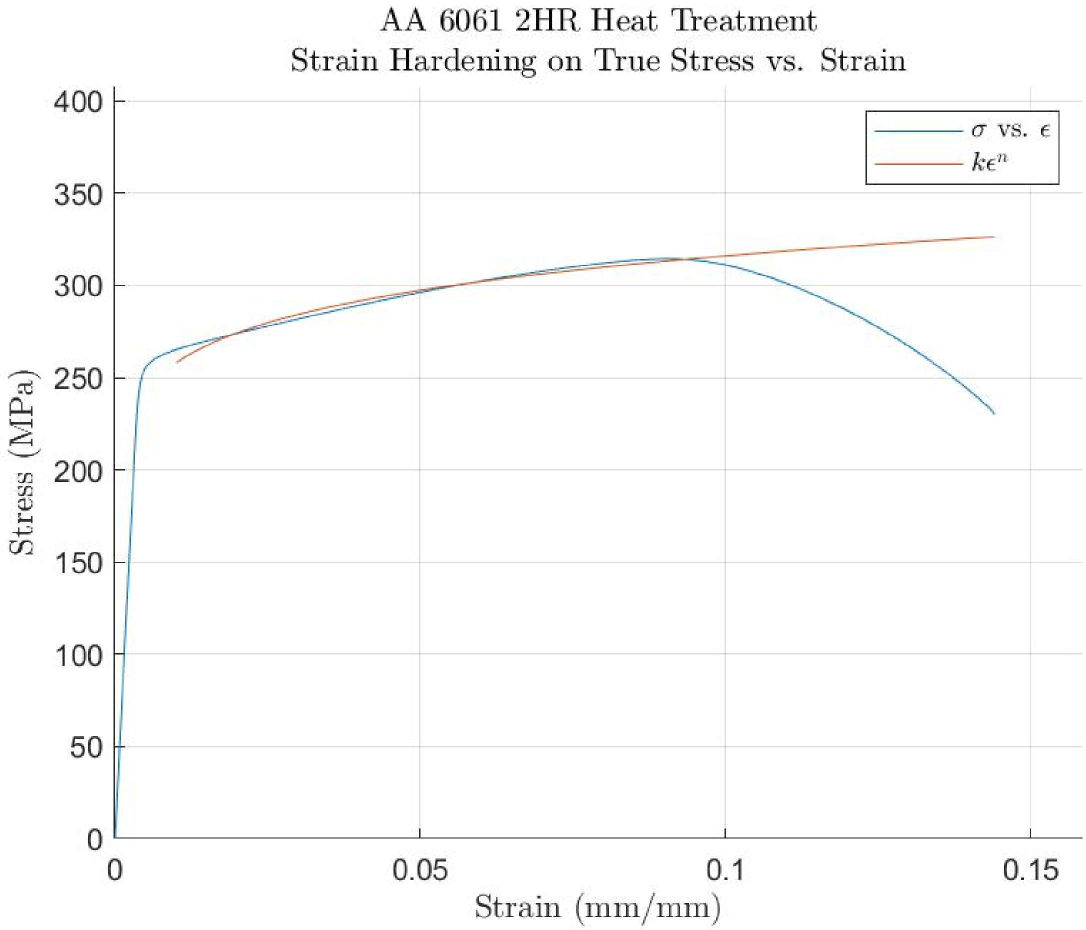

Figure D-5: True stress-strain curve for 6061 Heat Treated Aluminum Alloy (2HR) with strain hardening correction.

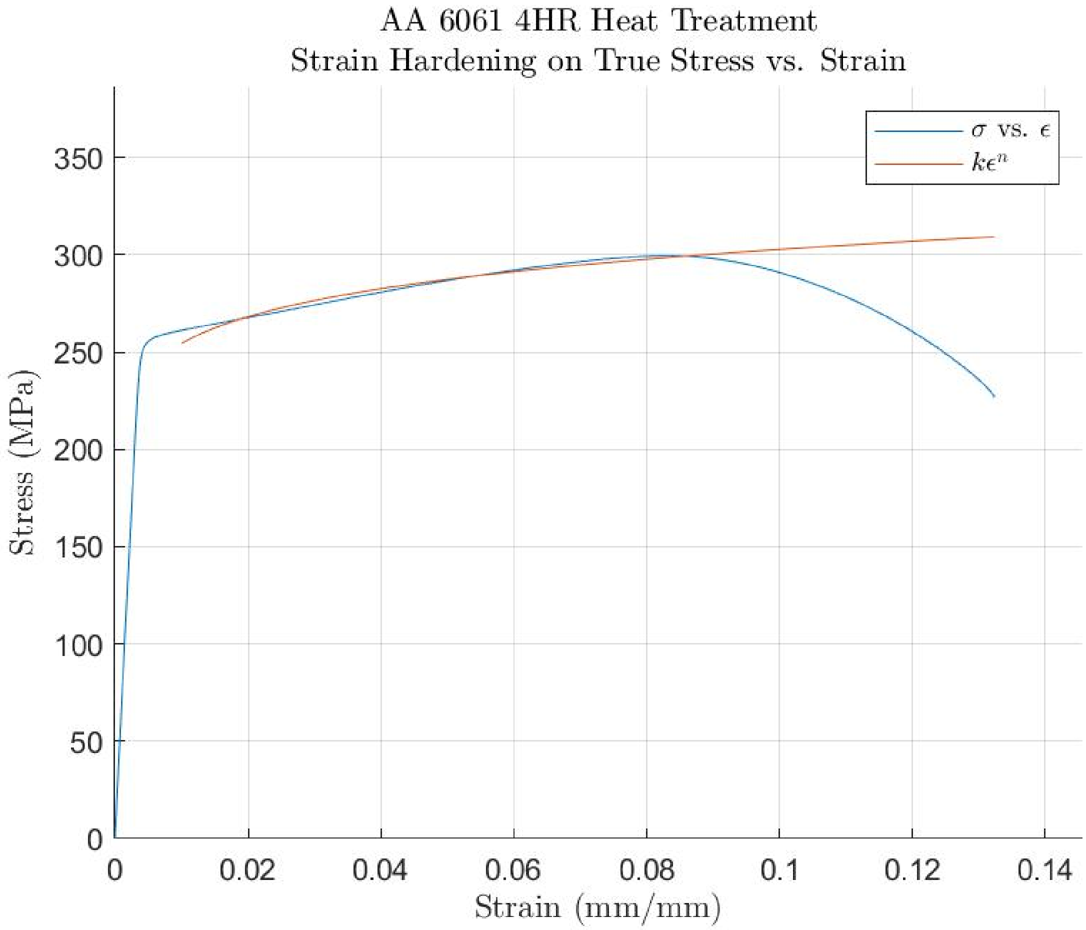

Figure D-6: True stress-strain curve for 6061 Heat Treated Aluminum Alloy (4HR) with strain hardening correction.

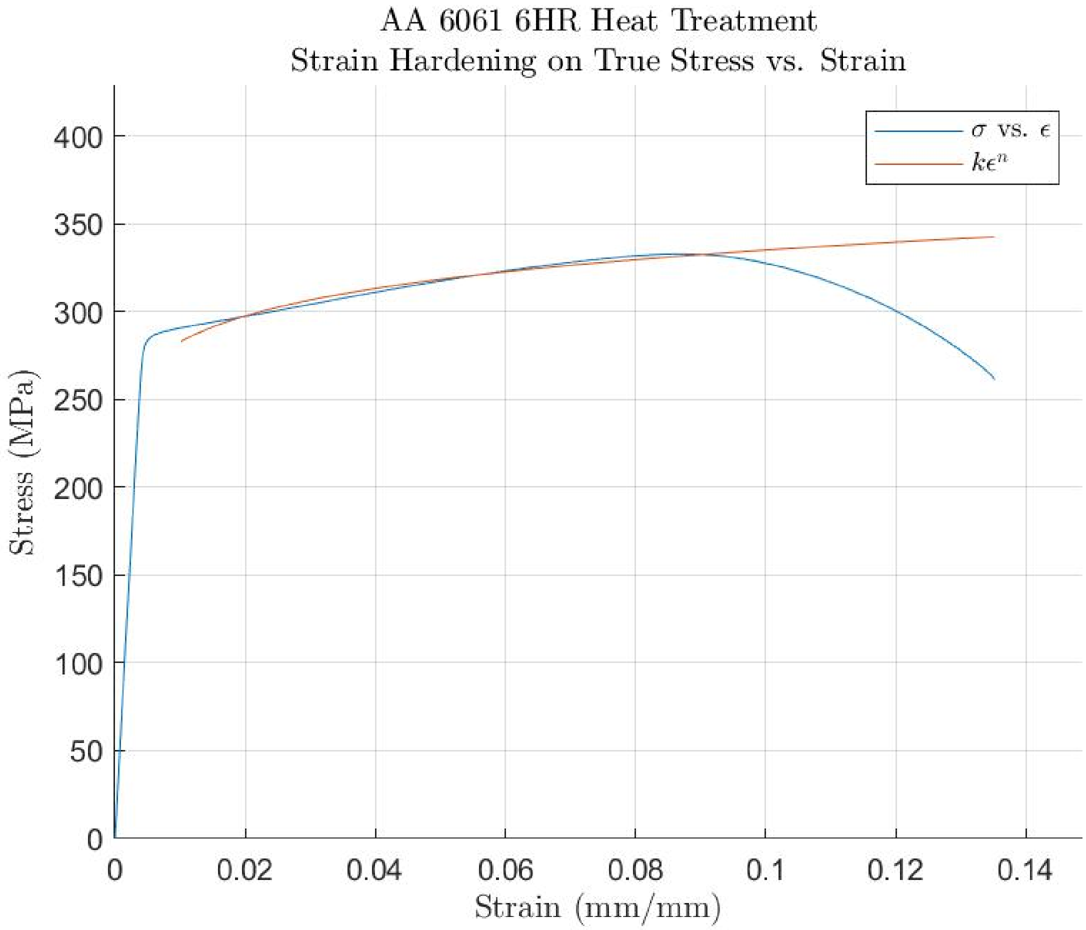

Figure D-7: True stress-strain curve for 6061 Heat Treated Aluminum Alloy (6HR) with strain hardening correction.