MONOTONIC TENSILE LOADING AND FRACTURE TOUGHNESS

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Introduction:

When working with new materials, it is important to know their mechanical properties. Engineers must know how a specific material will behave under different conditions. Some properties to know include the fracture toughness, elastic modulus, ultimate failure strength and other properties to avoid potentially catastrophic failures. Performing mechanical tests will help you pick the right material for your application.

The purpose of the lab performed was to measure and determine mechanical properties of different materials. Two tests were performed: a tensile test and a Charpy test. The monotonic loading test, or the tensile test, is used to measure several properties: yield strength, elastic modulus, ultimate tensile strength, and strain at fracture, to name a few. The Charpy test is used to measure the fracture toughness using impact loading.

Through performing the tensile test, our goal was to determine material properties using a stress-strain curve. We used this curve to determine these properties for 6061 Aluminum and AISI 1045 steel. We compared the results using engineering stress and strain with the results using true stress and strain. True stress and strain use the instantaneous area and length as it changes while engineering stress and strain only uses the initial measurements. From analysis of the stress-strain output from the experiment, we were able to determine several properties. The first portion of the test shows the elastic modulus. This is a linear relationship between stress and strain before permanent deformation occurs. After this region, the material starts to yield and the bond between atoms start to break. The material starts to enter the region of plastic deformation and will not return to its original length after the load is released. Within the plastic deformation phase, we can measure the strength at fracture as well as the ultimate strength, which is the highest force per initial area achieved before fracture [1].

In performing the Charpy test, we used our knowledge of the conservation of energy to measure the energy needed to break a material at a point of imperfection. The specimens are notched in the middle to create an artificial "defect," or a place for the sample to break. We compared results for heat-treated, quenched, and non heat-treated AISI 1045 steel samples. We also observed the difference in the cross section along the breaking plane.

These results from our test allow us to compare the stress-strain relationship in two different kinds of metals and the difference in toughness between heat treated and non heat treated steel. We did experience a break that did not fit in the normal measurement for the Charpy test this makes our data off a bit. This is will be laid out in the discussion. Our data was limited to a small number of tests. If this material were to be used for engineering purposes, more iterations of the same tests should be performed.

Theory:

In our lab we examined how different material properties can be calculated through mechanical testing. In this lab, we examined material properties exhibited in AISI 1045 steel and 6061 aluminium alloy. To find these material properties, we will use the monotonic tensile loading test and Charpy test.

The first test we implemented was the Charpy test which measures the impact energy a material can absorb before the point of fracture. The test uses a swinging pendulum to fracture a notched sample. This pendulum utilizes the conservation of energy principle to calculate fracture energy. Taking the difference of potential energy of the pendulum before and after impact allows us to find fracture energy. Results from the Charpy test allow us to find the energy to fracture that material, the toughness of the material and also whether a material is brittle or ductile. In this test we expect that brittle materials such as heat treated steel will have a smooth and crystalline appearance at the break, while ductile materials will have a rough and contorted surface at break [2]. We also expect to see a direct relationship of a material's hardness and that materials fracture energy.

The second test we used was the monotonic tensile loading test. After performing this test, we will be able to calculate an engineering stress using (eq.1) where P is the force applied A_0 initial cross section area. To find engineering strain, we use (eq.2) where Δl is the change in length and l_0 is the original length [2].

$$\sigma = \frac{P}{A_0}, \quad \varepsilon = \frac{\Delta l}{l_0} \tag{1),(2}$$

An important thing to note is that as we increase our load closer to fracture point, we see that an increase of length occurs as the area decreases. This phenomena is known as necking and it presents issues in ductile materials as the assumption of constant area and length no longer apply. To correct for this issue we can plot using the true strain and true stress results which are given by the following equations where *A* is the current cross-sectional area of the sample and *l* is the current length of the sample

$$\tilde{\sigma} = \frac{P}{A} \qquad \tilde{\varepsilon} = \int_{l_0}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) \tag{3),(4}$$

The engineering and true stress-strain curves should be almost identical in areas such as the elastic region and most of the plastic region. But as we approach the point of fracture, we will see that there is a significant departure from the two curves due to necking. Also, due to the limitations of our lab we are unable to measure the area of our sample at each strain, so we will use the relationship between true stress and strain and engineering stress and strain in order to calculate the value.

Once the test is complete we will be able to identify many different material properties such as the elastic modulus, which is defined as the linear relationship between stress and strain in the elastic region. We can also find points such as the yield stress which denotes the departure of elastic behavior to the area of plastic deformation. We are also able to identify the fracture and ultimate tensile strength on a stress vs. strain curve. It is important to note that ultimate tensile strength will not appear on a true strain and stress curve. Other properties obtained in the lab include the percent reduction in area(eq.5), the power law relationship(eq.6) and the toughness of the material (eq.7).

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right)\times 100 \quad , \quad \tilde{\sigma} = K\tilde{\varepsilon}^n \tag{5),(6}$$

$$u_f = \int_0^{\tilde{\varepsilon}_f} \tilde{\sigma} d\tilde{\varepsilon} = \int_0^{\varepsilon_Y} E\varepsilon d\varepsilon + \int_{\varepsilon_Y}^{\tilde{\varepsilon}_f} K\tilde{\varepsilon}^n d\tilde{\varepsilon} = \frac{S_Y \varepsilon_Y}{2} + \frac{K\left(\varepsilon_f^{n+1} - \varepsilon_Y^{n+1}\right)}{n+1} \tag{7}$$

Experimental Procedures:

In Charpy impact tests, we used the Sonntag universal impact machine. The samples used for testing were all AISI 1045 steel. There were five heat treated, five non-heat treated, and one heat treated but not tempered. The first step of the Charpy test was to put the sample at the center of the specimen supports and orient the notch face away from the hammer. Next, we smoothly released the hammer and let it touch the sample for checking the notch alignment. If the sample was not aligned, we raised the hammer to the latched position and repositioned the samples. We then raised the hammer to the initial position and released the hammer to test the impact energy of the sample. After that, we locked the hammer back into position and recorded the impact energy. Finally, we took the fractured sample to a microscope and identified the fracture behavior [3].

In monotonic tensile loading test, a high-load capacity INSTRON machine was used for testing the samples' stress and strain. The samples tested were 6061 Al alloy and AISI 1045 steel. To start the test, we measured and recorded the dimensions of each sample. Next, we opened the INSTRON software in the control system and set up a file for recording data. Then, we inputted the dimensions of the sample and the loading speed into the software. At the same time, the sample was loaded into the fixture by tightening the grips on both end of the sample. After that, we started the test and the interface showed the plot of the sample's strain and stress curve. For first, third, and fifth tests, we let the machine run until the sample fractured. However, during second, fourth, and sixth tests, an extensometer was clamped to center part of the sample and we stopped the test after the sample extend to a prescribed distance. Finally, we saved the data from the test, removed the sample from the fixture, and pressed the "return" button on the INSTRON control panel for next test.

Results:

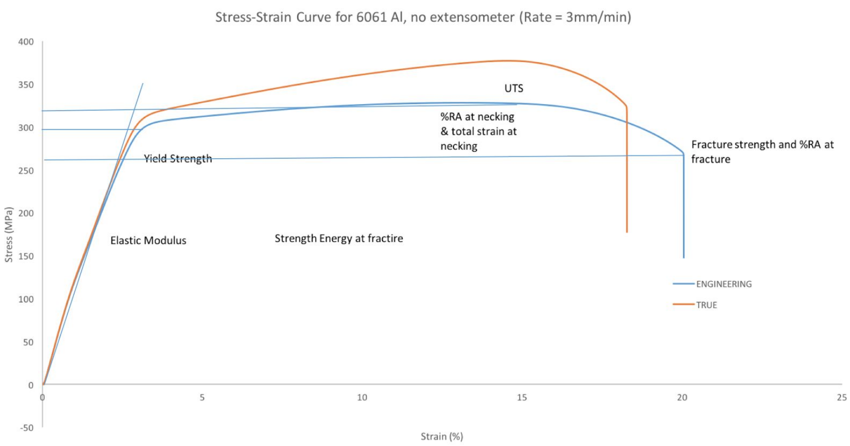
The mechanical properties of 6061 aluminum and AISI 1045 steel were found through performing monotonic loading tests. Since the elastic modulus is to be linear, it was found by finding the slope between two data points. The yield strength and fracture point were determined graphically by observing where the stress became nonlinear and before it started to decrease rapidly. The ultimate tensile strength was found by using the MAX command in Microsoft Excel. Finally, the percent reduction in area and the strain energy at fracture were found by using equations 5, 6, and 7, respectively.

Material (elongation rate)	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Fracture Point		Total Strain at necking [1]	Strain Energy at Fracture (MPa)	Percent Reduction in Area	
				Strain (%)	Stress			Fracture	Necking

					(MPa)				
6061 Al Alloy (3mm/min)	76.7	300.1	328.5	20.0	269.1	0.123	39.16	16.7	0.25
6061 Al alloy (6mm/min)	69.4	316.5	330.1	19.9	272.2	0.132	37.5	16.6	0.58
AISI 1045 Steel (6mm/min)	117.1	415.95	672.7	30	550.0				

Table 1. Mechanical properties of 6061 Al alloy and AISI 1045 steel extracted from monotonic loading tests

By comparing AISI 1045 Steel and 6061 Aluminum alloy both at the same elongation rate, we see that steel's yield strength is larger than aluminum's by 31.4% and that steel's ultimate tensile strength is about twice as large as that of aluminum.



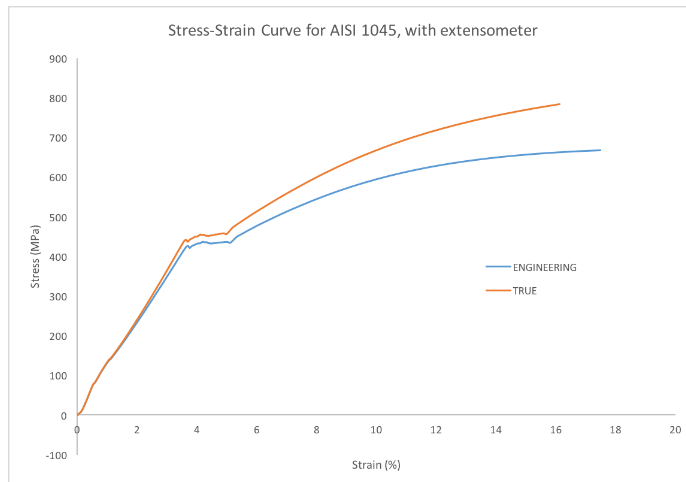


Figure 1. Stress-Strain for 6061 Al alloy

Figure 2. Stress-Strain for AISI 1045 Steel

Test	Sample	Charpy Number	Notes	Test parameter	Average of clean tests	Standard deviation
a	1045 HT	27		100 foot pounds		
b	1045 HT	26		100 foot pounds		
c	1045 HT	24		100 foot pounds		
d	1045 HT	29		100 foot pounds		
e	1045 HT	26		100 foot pounds	26.4	1.624807681
f	1045 NHT	25.5	sample did not fracture completely	100 foot pounds		
g	1045 NHT	10		100 foot pounds		
h	1045 NHT	6.5		100 foot pounds		
i	1045 NHT	8.5		100 foot pounds		
j	1045 NHT	5		100 foot pounds	7.5	7.398648525
k	1045 HT NO TEMPER	3.5		100 foot pounds		

Table 2. Data results from performing Charpy tests

From performing the Charpy tests, we can see that AISI 1045 has a 137.8% higher average energy impact when heat treated than when not heat treated. A gaussian curve is produced in MATLAB using the normpdf function. One data point (test f) was thrown out due to the specimen not fracturing after impact.

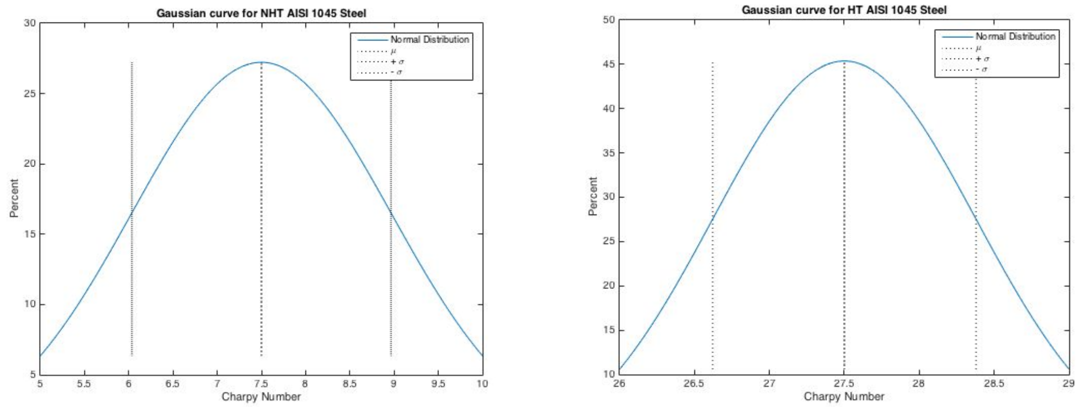


Figure 3. Gaussian Distributions for non-heat treated and heat treated 1045 steel

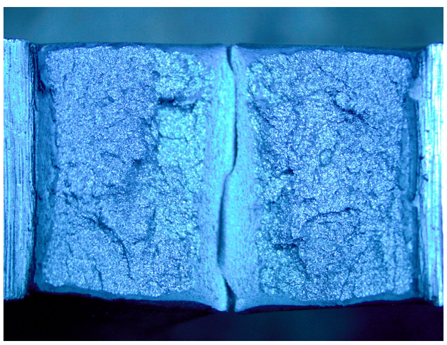


Figure 4. NHT sample, no fracture sample

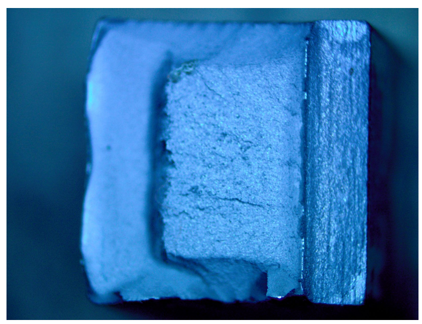


Figure 5. HT sample

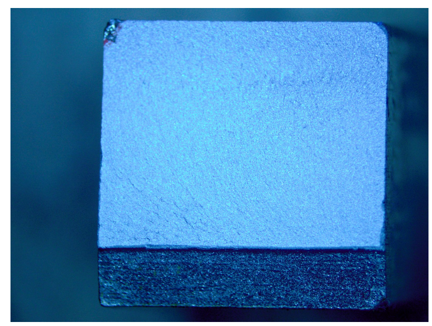


Figure 6. Non Tempered

Discussion:

Our results from the tensile tests follow the behavior expected of 6061 Al alloy and 1045 steel. When comparing the engineering stress-strain response with the true stress-strain response, we can see that the two responses are similar for the material's elastic region, but then begin to deviate around the material's yield point. The data from the tensile tests also shows that the yield strength and ultimate strength of the 1045 steel are higher (approximately 31.4%) than that of the 6061 Al alloy. Furthermore, the steeper slope of the elastic region of the 1045 steel suggests a higher Young's modulus. The results from the Charpy impact test show that the heat treated samples had a higher (approximately 137.8%) average impact energy required for fracture. We also observe that the untreated samples have rougher fracture surfaces than the heat treated samples.

The deviation in engineering and true stress-strain responses from the tensile tests is expected, because the true stress-strain response accounts for the reduction in cross sectional area sustained during plastic deformation, which results in a higher stress for a given strain. In the material's elastic region, the cross sectional area does not change significantly during tensile loading, which is why the two responses are the same in this region. If we compare the stress-strain responses for 6061 Al alloy and AISI 1045 steel, we note that the steel has a higher yield strength, ultimate strength, and Young's modulus. This is due to the presence of interstitial carbon atoms in the steel sample, as well as the higher density of the steel. It is also worth noting that changing the rate of elongation does not result in discernable differences in the stress-strain responses. Additionally, the stress-strain response for the steel has a double yield point, while the aluminum does not. This is because small carbon atoms fill in dislocations in the steel during yielding, resulting in a temporary increase in yield stress.

Heat treating samples increases the amount of martensite present in a sample, which leads to an increase in the hardness and brittleness of the sample. The higher impact energy required to fracture the heat treated samples shows that heat treating a sample increases its fracture toughness. We can observe the effect of heat treating on brittleness by studying the cross sections of our samples after testing. The untreated samples have rougher surfaces, which is characteristic of a ductile failure. On the other hand, the heat treated samples have very smooth cross sections, suggesting a brittle failure.

One major possible source of error in the lab came from operator variation when performing impact tests. Due to the fact that group members took turns aligning the sample and releasing the pendulum, not all samples may have been tested in the same manner. Additionally, each sample of a given material could differ from the others (especially for heat treated samples) because of the random nature of defect formation, or because the samples were prepared by multiple people. This human error was likely responsible for the abnormal behavior observed in one of our non-heat treated samples. One final qualification on our results is that the formula we used for true stress is only valid up to the point of necking.

Conclusion:

In this lab we analyzed the stress-strain response for samples of 6061 Al alloy and AISI 1045 steel undergoing a tensile test. We also examined the effect of heat treating on the fracture toughness and brittleness of AISI 1045 steel. Through the course of this investigation, we found that 1045 steel has a higher yield stress, ultimate stress, and Young's modulus than the 6061 Al alloy. We also found that the engineering stress-strain response for both materials deviated from the true stress-strain response after the yield point. The results of our Charpy testing showed that heat treating a sample increases its toughness, but reduces its ductility. Overall, this lab demonstrated the importance of testing materials to determine their properties when trying to select an appropriate material or treatment for a given application.

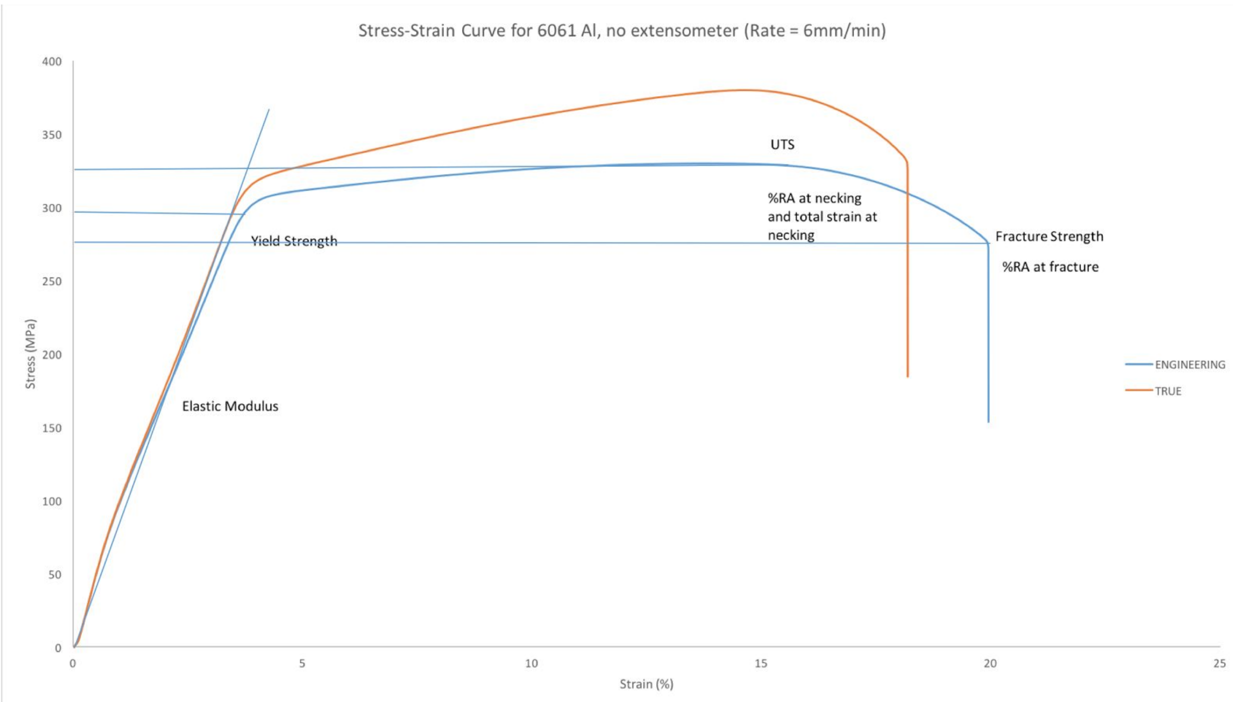
Appendix A: References

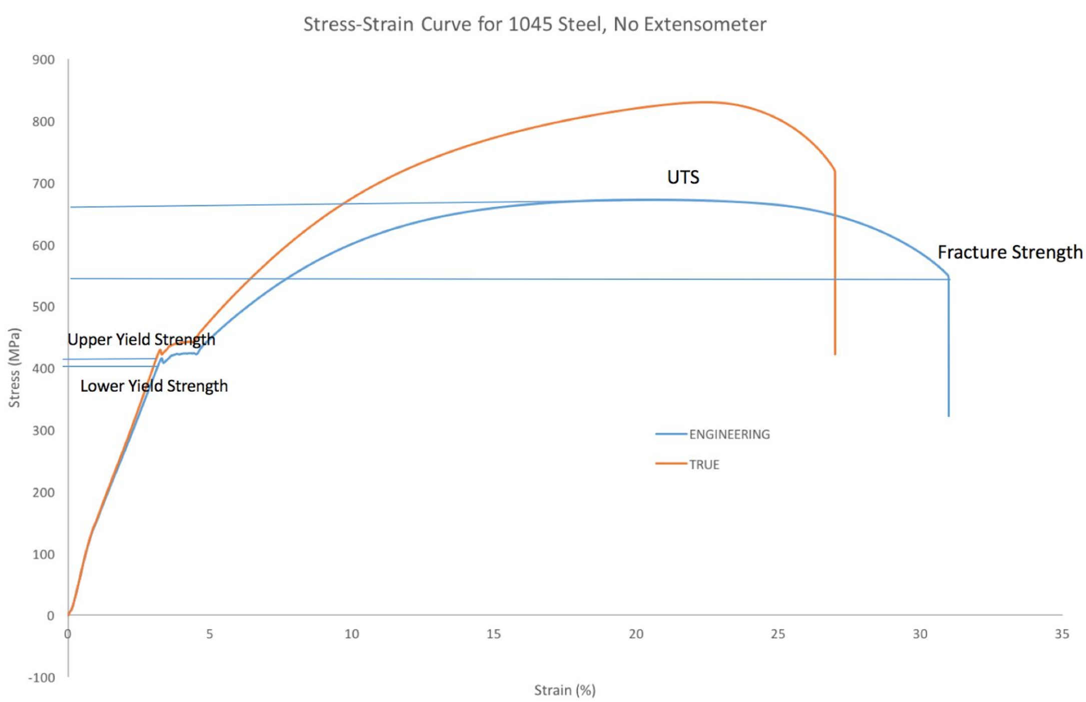
[1] N. E. Dowling, Mechanical Behavior of Materials, 4th edn (Pearson, 2012).

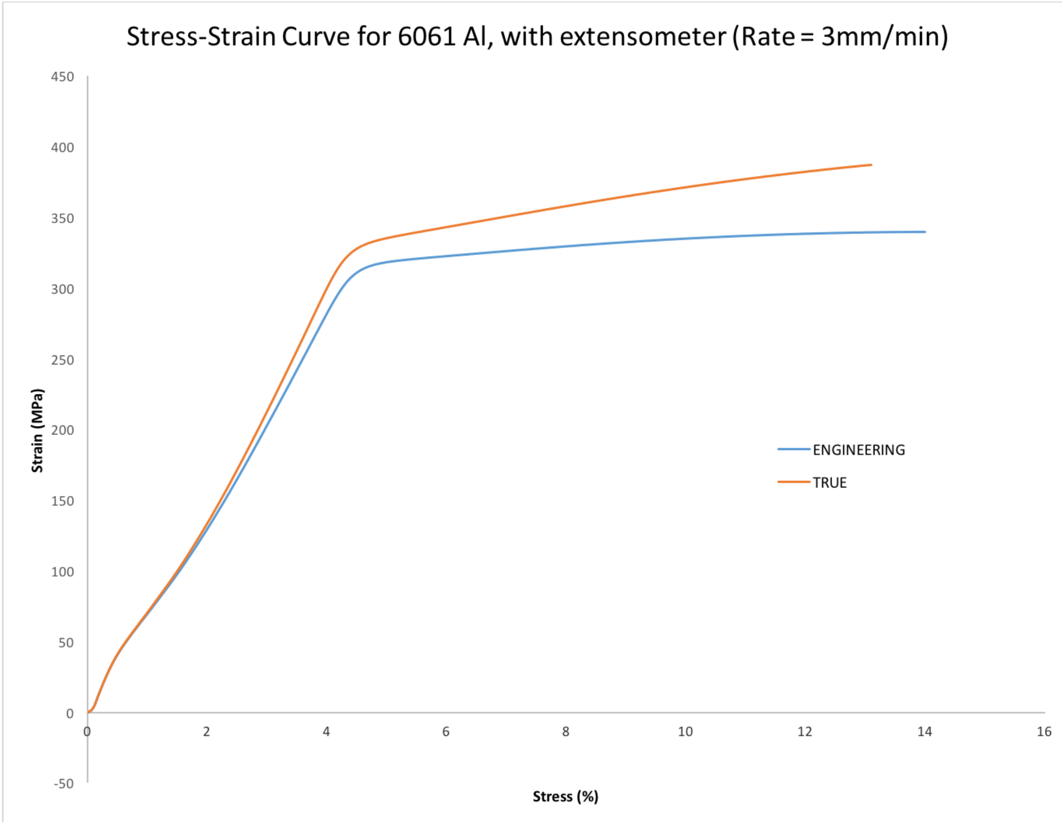
[2] W. D. Callister, Materials Science and Engineering, an Introduction, 7th edn (John Wiley and Sons, 2007).

[3] K Komvopoulos, Mechanical Testing of Engineering Materials, 1st edn (University Readers, 2011).

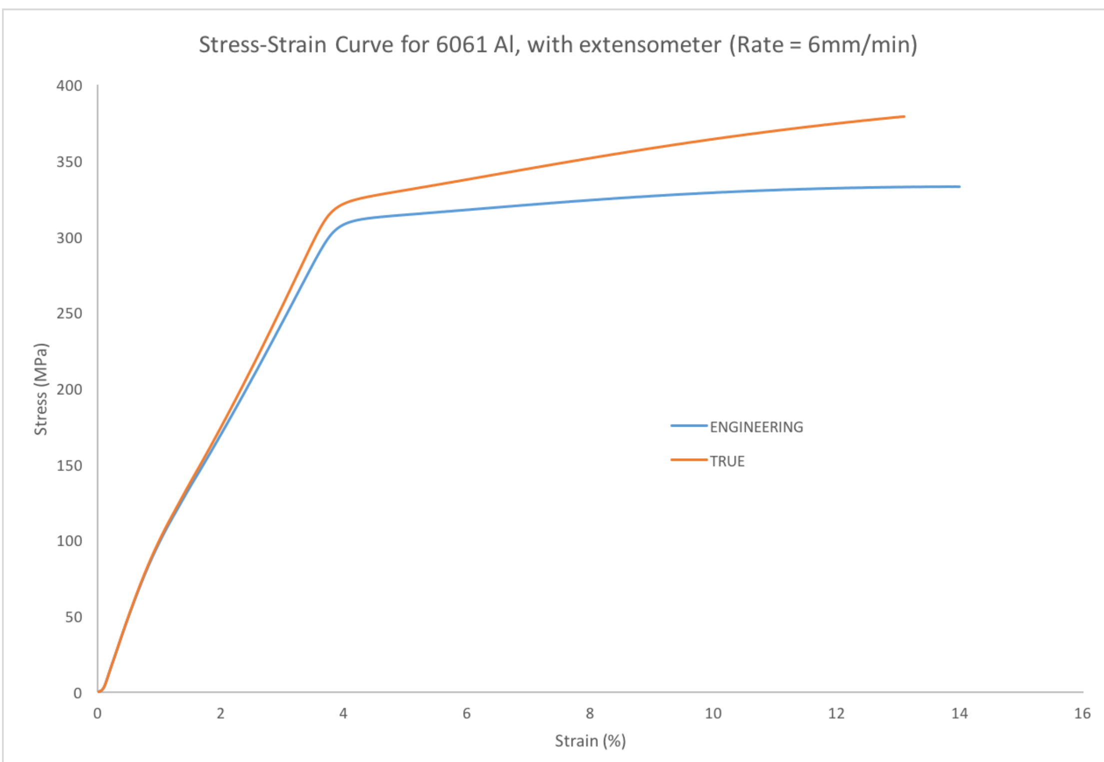
Appendix B: Stress Strain Curves for Remaining Samples







Stress-Strain Curve for 6061 Al, with extensometer (Rate = 3mm/min)
Strain (MPa)
Stress (%)
ENGINEERING
TRUE
450
400
350
300
250
200
150
100
50
0
-50
0
2
4
6
8
10
12
14
16



Stress-Strain Curve for 6061 Al, with extensometer (Rate = 6mm/min)
Stress (MPa)
Strain (%)
ENGINEERING
TRUE
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16

"I, Sonja Davison, confirm that Darren Kong wrote Theory of the lab report. ______________"

"I, Darren Kong, confirm that Jordan Francis wrote Discussion and Conclusion of the lab report. ______________"

"I, Jordan Francis, confirm that Jinyu Ni wrote Experimental Procedure of the lab report. ______________"

"I, Jinyu Ni, confirm that AdolfoTec wrote Results of

the lab report. ______________"

"I, Adolfo Tec, confirm that Sonja Davison wrote Abstract and Intro of the lab report. Adolfo Tec"