NPRE 432: Lab 2

Tensile Stress-Strain

University of Illinois at Urbana-Champaign

Department of Nuclear, Plasma, and Radiological Engineering

Lab Section 2

Author

Joseph Specht

jspecht3

Professor and Teaching Assistants

James Stubbins

Silvana Tabares-Burgos

Tahmid Omi

September 25, 2024

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1 Abstract

This laboratory covered the tensile and hardness testing of eight materials: 1018CR steel, 2024 aluminum, 304 stainless steel, 1045NM steel, 1045CR steel, 7075T6 aluminum, PMMA, and brass. The tensile tests were used to generate a stress-strain curve for each material and to calculate the elastic modulus, 0.2% offset yield strength, ultimate strength, % elongation, resilience modulus, and the corrected Rockwell B Hardness values. Comparison of the aforementioned quantities showed cold rolling increased the strength, stiffness, and ultimate strength, but decreased ductility. The results for: (1) elastic modulus indicated 304 stainless steel was the stiffest material and PMMA was the least stiff material, (2) ultimate strength indicated 1045CR steel was the strongest material and PMMA was the weakest material, (3) Rockwell B Hardness indicated 304 stainless steel was the hardest metal and 2024 aluminum was the softest metal, and (4) elongation percent indicated 304 stainless steel was the most ductile material and PMMA was the least ductile material. Next, analyzing the difference between true and engineering stress-strain curves for 304 stainless steel indicated the true stress-strain will always be higher than the engineering stress-strain, but the difference between the two is most apparent after plastic deformation. For 304 stainless steel, a power law model was applied that generated power law coefficients that disagreed drastically from those accepted in literature. Finally, brass, which underwent an initial loading period and two reloading periods, had an elastic modulus that was roughly constant for the first two loading periods, but dropped dramatically for the second reloading. However, the 0.2% offset yield strength increased as the reloading occurred due to strain hardening.

2 Introduction

As humanity has erected an ever increasing number of monuments to the indomitable human spirit, the need for higher quality materials has increased. As a result, materials designed with various alloy compositions and treatment conditions have been created to suit the unique engineering challenges presented by the desire of humanity to conquer the next frontier. There are various tests and metrics by which to quantify these materials – one such test is tensile testing, the subject of this laboratory.

In this laboratory, tensile tests and hardness tests were performed on eight materials: 1018 cold rolled (CR) steel, 2024 aluminum, 304 stainless steel, 1045 normalized (NM) steel, 1045 cold rolled (CR) steel, 7075T6 aluminum, PMMA, and brass. All materials were under enough tensile force to cause catastrophic material failure. The force and strain from the tensile tests were used to generate stress-strain curves and calculate the elastic modulus, 0.2% offset yield strength, ultimate strength, % elongation, resilience modulus, and the corrected Rockwell B Hardness values. The aforementioned qualities can be used to quantify and give credence to material choice in certain scenarios. Additionally, engineering stress-stain was compared with true stress-stain and the usability of a power law relation for the true stress-strain curve was analyzed. The previously mentioned material characterization methods have proven invaluable to engineers in the past and will prove invaluable into the far future.

3 Theoretical Models

As tensile strength is one of the most important material characteristics, many theoretical models were created to quantify and describe tensile strength. The reference frame for these models stems from either a Lagrangian or Eulerian perspective, which refer to initial and instantaneous states, respectively. In tensile testing, the engineering reference frame corresponds to the Lagrangian perspective while the the true reference frame corresponds to the Eulerian perspective.

3.1 Engineering Stress and Strain

The engineering stress and strain are based on the original specimen dimensions. As stress is force per unit area, the engineering stress is defined as:

$$\sigma = \frac{P}{A_0} \tag{1}$$

where P is the axial load, a force, and A_0 is the original cross section of the specimen.

Next, engineering strain measures the difference between the instantaneous and original lengths and is defined as:

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

where L_0 is the original gauge length and L_i is the instantaneous gauge length.

3.2 True Stress and Strain

The true stress and strain are based on the instantaneous specimen dimensions. The true stress is defined as:

$$\sigma_t = \frac{P}{A_i} = \frac{P}{A_i} \cdot \frac{A_0}{A_0} = \frac{P}{A_0} \cdot \frac{A_0}{A_i} = \sigma \frac{A_0}{A_i} \tag{3}$$

Where the true stress can be represented as a function of the engineering stress.

Most metals have a high elastic modulus and undergo little dimensional change until high stress. As a result, the engineering and true stress do not differ dramatically until the plastic deformation region where they can differ quite drastically. Assuming a constant volume during plastic deformation, Eq. 3 can be rewritten in terms of the elasticity modulus. First, a constant volume can be expressed mathematically as:

$$V = A_0 L_0 = A_i L_i \tag{4}$$

therefore:

$$\frac{A_0}{A_i} = \frac{L_i}{L_0} \tag{5}$$

and considering:

$$L_i = L_0 + \Delta L \tag{6}$$

The true stress can be written as:

$$\sigma_t = \sigma \frac{L_i}{L_0} = \sigma \left(\frac{L_0 + \Delta L}{L_0} \right) = \sigma \left(\frac{L_0}{L_0} + \frac{\Delta L}{L_0} \right) = \sigma(1 + \epsilon) \tag{7}$$

Where ϵ is the elasticity modulus.

Next, the true strain is defined as:

$$\epsilon_t = \int_{L_0}^{L_i} \frac{1}{L} dL = \ln \frac{L_i}{L_0} = \ln(1 + \epsilon) \tag{8}$$

With the true stress and strain, we can determine the Ramberg-Osgood constants, which relates stress and strain in the plastic deformation regime. The most common format used is:

$$\sigma_t = K \left(\epsilon_t^P \right)^n \tag{9}$$

True stress and true plastic strain on log-log axes result in a linear relation if Eq. 9 applies to the data set.

3.3 Bridgman Necking Correction

Tension tests cause triaxial stress states in the critical location of the specimen. Modeling the triaxial stress properly requires complex models and an intricate understand of material properties. Therefore, Bridgman simplified the modeling with the following assumptions:

1. The contour of the neck can be approximated by a circular arc.

2. The cross section remains circular.

3. A von Mises criterion applies for yielding.

4. Strains are constant over the cross section of the notch.

The aforementioned assumptions represented mathematically are given as:

$$\frac{\sigma}{\bar{\sigma}} = \frac{1}{\left(1 + \frac{2R}{a}\right)\left(\ln\left(1 + \frac{a}{2R}\right)\right)} \tag{10}$$

Where $\bar{\sigma}$ is the average axial stress calculated ignoring the effect of the notch and σ is the true deviatoric axial stress at the notch.

4 Experimental Methods

This section covers the praxis used to conduct tensile testing on various materials.

4.1 Equipment and Materials

The lab manual [1] specifies to measure specimen deformation with a 25.4 mm gauge length extensometer. However, the students did not operate the extensometer properly and measured deformation by comparing the initial and final gauge lengths. The load and strain were recorded by the computerized data acquisition system.

For this laboratory, the students tested various materials via a tensile test. A list of each material used and a short description of each is given below.

1. 1045CR Steel - a cold-rolled, low-carbon steel commonly used in structural applications.
2. 1045NM Steel - a normalized, low-carbon steel commonly used in structural applications.
3. Brass - a copper-zinc alloy that is corrosion resistant.
4. PMMA - a plastic commonly used as a replacement for glass.
5. 7075T6 Aluminum - an aluminum alloy used in aircraft applications.
6. 304 Stainless Steel - the most common stainless steel.
7. 2024 Aluminum - an aluminum allow with copper as the primary alloying element.
8. 1018CR Steel, a cold-rolled, low-carbon steel used in applications that require bending.

4.2 Procedure

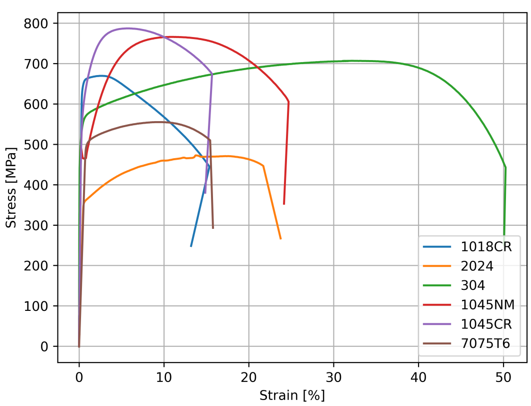
1) The students started by recording the Rockwell B hardness on the grip section of the specimen for all metallic specimens. 2) Next, the students measured the gauge and grip diameter of each specimen with

digital calipers three times. The average of these three measurements were recorded. 3) Then, the students inserted the specimens, one at a time, into the load frame and attached the extensometer. 4) Next, the students started the computer data acquisition and loaded each ductile specimen at a rate of 5 $\frac{mm}{min}$ and PMMA at a rate of 1 $\frac{mm}{min}$. The data were collected until material failure. 5) After failure, the students measured the final gauge length as to calculate the final area. 6) All pertinent data were recorded into the computer data acquisition software.

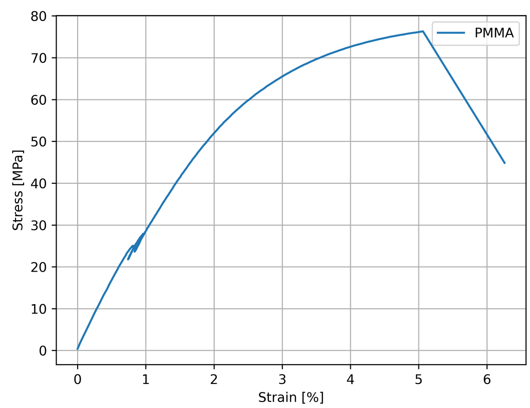
Special consideration was taken for Brass, which underwent two reloading periods to determine the effect of strain hardening. The teaching assistants mediated this trial.

5 Results

After uploading the data to the mainframe, the students processed the data using Jupyter Lab with a Python3 kernel. To perform the analysis, the students used the following python packages: csv, numpy, pandas, matplotlib, os, glob, and scipy. For data processing information, refer to Sec. 6, Analysis and Discussion of Results.



(a) Metals aside from Brass



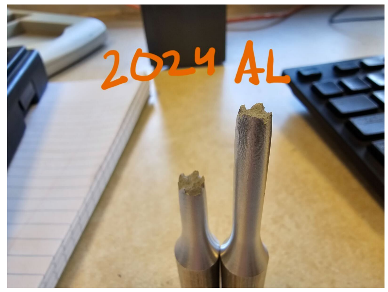
(b) PMMA

Figure 1: Engineering Stress-Strain Curves for Materials

Figure 1a shows the engineering stress-strain curves for all metals aside from brass: 1018CR steel, 2024 aluminum, 304 stainless steel, 1045NM steel, 1045CR steel, and 7075T6 aluminum. Figure 1b shows the engineering stress-strain curve for PMMA.

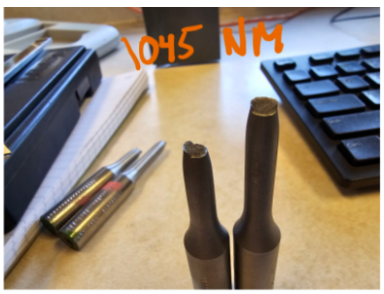
From the stress-strain testing, the students also photographed the specimen after total failure had been achieved. These photographs are shown as follows:

(a) 1018CR

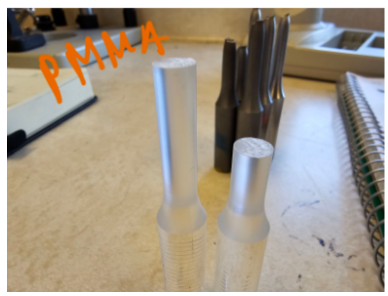


(b) 2024 Aluminum

(c) 304 Stainless Steel



(d) 1045NM Steel



(e) PMMA

(f) 1045CR Steel

(g) 7075T6 Aluminum

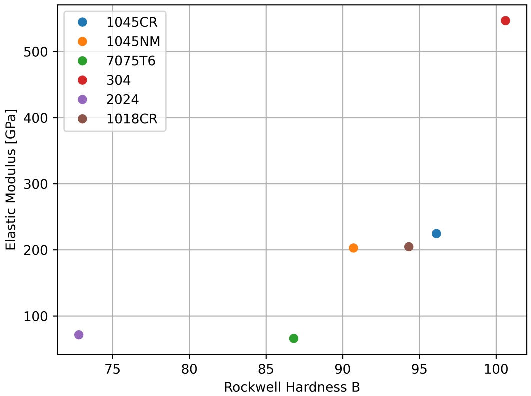
Figure 2: Total Failure for Non-Brass Metals and PMMA

Using Fig. 1, the students then calculated the: elastic modulus, 0.2% offset yield strength, ultimate tensile strength, percent elongation, and modulus of resilience. The aforementioned quantities along with the corrected Rockwell B Hardness measurement are tabulated as follows:

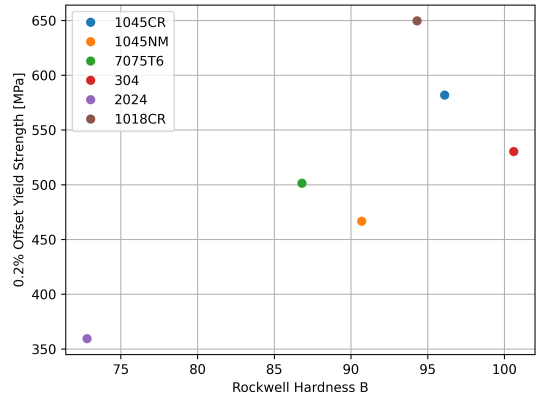
Table 1: Material Properties from Tensile Testing

	1018CR	2024	304	1045NM	PMMA	1045CR	7075T6
Elastic Mod. [GPa]	204.916	71.452	546.69	202.938	2.574	224.648	65.964
0.2% Y.S. [MPA]	649.584	359.402	530.289	466.758	60.23	581.838	501.323
Ult. Strength [MPa]	669.533	472.553	706.864	765.947	76.313	787.006	554.963
% Elongation	-36.0	-18.194	-46.25	-30.168	0.373	-23.619	-12.535
Res. Mod. [GPa]	1.03	0.904	0.257	0.537	0.705	0.753	1.905
Rockwell B Hardness	95.172	75.73	102.54	94.58	-	94.58	89.05

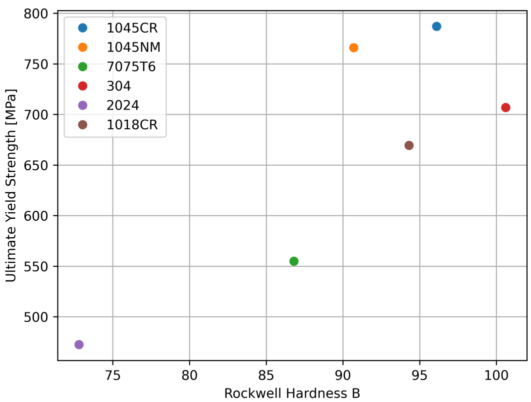
These tabulated quantities were then represented graphically as a function of Rockwell B Hardness.



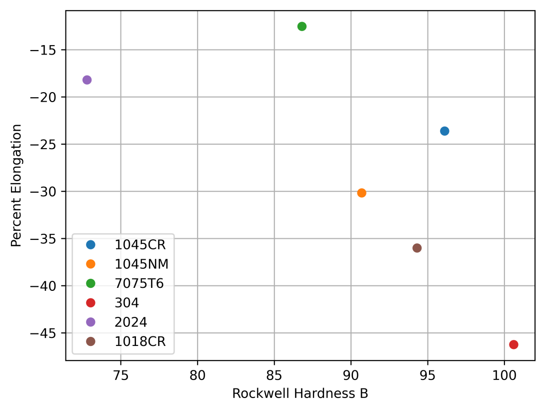
(a) Elastic Modulus



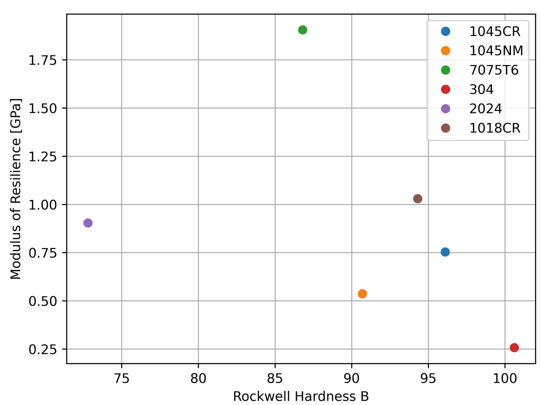
(b) 0.2% Offset Yield Strength



(c) Ultimate Yield Strength



(d) Percent Elongation



(e) Modulus of Resilience

Figure 3: Various Material Properties versus Rockwell B Hardness

Next, the students plotted the true-stress/true-strain curve for 304 stainless steel, which are given as follows:

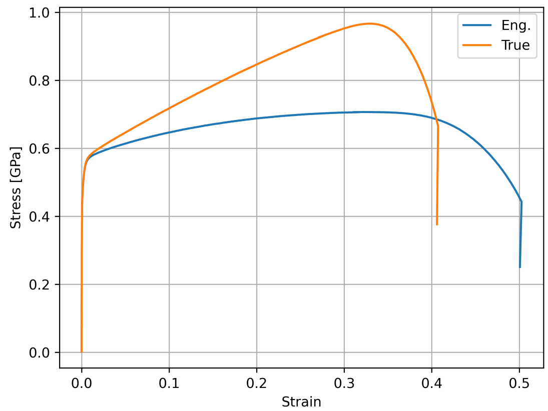
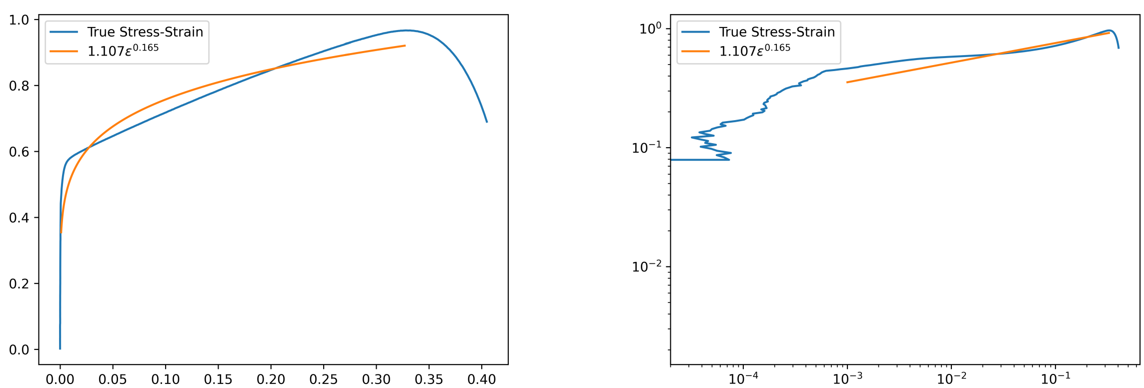


Figure 4: True and Engineering Stress-Strain Curve for 304 Stainless Steel

The students then found the Ramberg-Osgood constants for 304 stainless steel as $K = 1.107$ and $n = 0.165$. The power law estimation is given graphically as follows:



(a) Linear-Linear Scaling

(b) Log-Log Scaling

Figure 5: Ramberg-Osgood/Power Law Model for 304 Stainless Steel

Finally, the students plotted the stress-strain curve for brass and determined the elastic moduli and 0.2% offset yield strength for the initial loading and two reloading periods, which are given as follows:

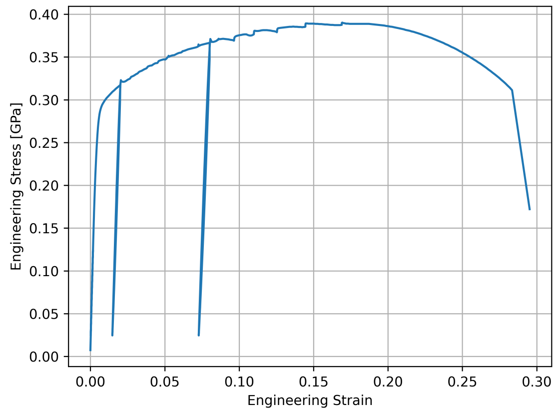


Figure 6: Brass Engineering Stress-Strain Curve

Table 2: Brass Properties After Reloading Twice

	Initial Loading	**First Reloading**	**Second Reloading**
Elastic Modulus [GPa]	54.128	55.713	46.380
0.2% Yield Offset Strength [GPa]	0.272	0.319	0.371

The students also photographed total failure of brass.

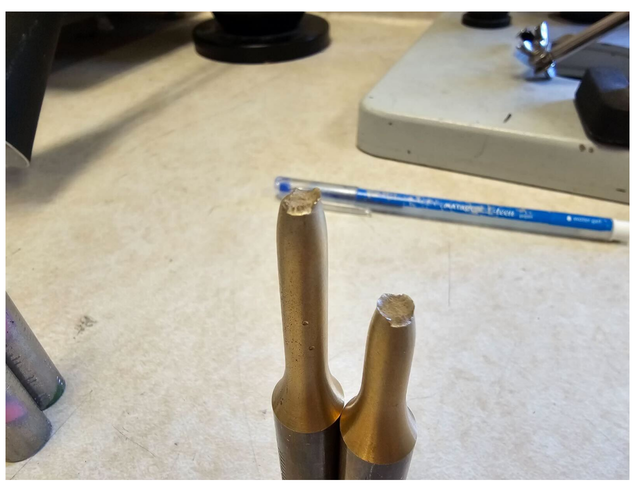


Figure 7: Total Failure for Brass

6 Analysis and Discussion of Results

This section will cover the analysis and discussion of the results obtained in Sec. 5.

6.1 Material Parameter Comparison

(PFD 1) To begin, the information in Table 1 provides insights into various material properties.

The first insight is the effect of annealing on the two 1045 steels: 1045NM and 1045CR. Interestingly, the hardness did not change between the two treatments. However, the 1045CR steel had a higher elastic modulus (224.648- compared to 202.938 GPa), 0.2% offset yield strength (581.838- compared to 466.758 GPa), resilience modulus (0.753- compared to 0.537 GPa), and a slightly higher ultimate yield strength (787.006- compared to 765.947 MPa) than the annealed 1045NM steel. The cold rolled steel seemed to be stronger, stiffer, and able to hold more load than the annealed steel. However, the strength of the cold rolling comes at the cost of lower elasticity (-23.619% compared to -30.168%). These results indicate that cold rolling steel is useful in cases where strength is needed over ductility. The comparison between the two steels indicates 0.2% offset yield strength is the material property most affected by annealing.

Moving from the 1045 steels to all materials in Table **??**, material stiffness will be compared using the elastic modulus as a metric. The material with the highest elastic modulus was 304 stainless steel with a value of 546.69 GPa, which is nearly double the second highest of 1045CR steel at 224.648 GPa. The material with the lowest elastic modulus was PMMA with only 2.574 GPa. The low elastic modulus of PMMA makes sense as PMMA deforms plastically not elastically indicating the model used does not support PMMA particularly well.

Next, material strength will be compared using ultimate strength as a metric. The material with the highest ultimate strength was 1045CR steel. 1045CR steel being the strongest material reinforces that cold rolling metals should be done when ultimate material strength is the goal. The weakest material was PMMA with an ultimate yield strength of only 76.313 MPa. PMMA being the weakest material makes sense as it is a plastic and does not deform elastically. Elastic deformation is a relatively large reservoir for energy storage, so PMMA not deforming elastically means PMMA cannot absorb as much energy before failure and have a lower total strength.

Another metric to quantify materials is hardness, which will be done using the Rockwell B Hardness scale. PMMA was discluded from the hardness measurements as any stress concentrators matter more for plastics than metals. The hardness values were also corrected according to the Lab 2 Hardness Correction Table on Canvas [2]. The hardest material was 304 stainless steel with a value of 102.54. However, most metals ranged from the lower 90's to the upper 90's indicating hardness was a relatively invariant characteristic.

The only metal that had a substantially lower hardness than the others was 2024 aluminum with a Rockwell B Hardness value of 75.73.

Ductility is a characteristic describing the ability of a material to be drawn into a wire. A more ductile material undergoes more elongation before failure, therefore, % elongation is an appropriate metric by which to compare ductility. The students were supposed to use gauge length as instructed by the manual, but the extensometer was not applied properly. Therefore, the students used initial and final gauge diameter for the calculations. The most ductile material was 304 stainless steel with a % elongation 10% higher than any other material at -46.25%. The ductility of 304 stainless steel is why it is the most commonly used stainless steel – 304 stainless steel is malleable and easy to work with. By far the least ductile material was PMMA, with a % elongation of 0.373%. The low ductility of PMMA makes sense as, generally, plastics are not regarded to be as ductile as metals.

The final parameter to compare is which material absorbed the most elastic energy. The metric by which to determine this is integrating the elastic regime of each material and validating which material has the highest value. 1045NM was eyeballed to absorb the most elastic energy as the plastic regime starts later for 1045NM steel than any other material.

6.2 Analyzing 304 Stainless Steel

Next, 304 stainless steel will be analyzed by: (1) comparing the true and engineering stress-strain curves and (2) analyzing the power-law fit.

(PFD 3) Investigating Fig. 4 shows the true stress is always higher than the engineering stress, which makes perfect sense. The engineering stress divides the force by the the initial area, but the true stress divides the force by the instantaneous area. In tension tests, the instantaneous area will always be less than or equal to the initial area because the material is being pulled apart. As the material is pulled apart, there is no mechanism by which a ductile could increase its cross-sectional area. However, the elastic deformation regions of both curves are almost the same because the instantaneous area is almost the same as the initial area. Therefore, tension tests will always show the engineering stress to be lower than the true stress, but this effect is most prominent after plastic deformation begins.

(PDF 4) Next Fig. 5 will be used to compare how well the power law models 304 stainless steel. The experimentally determined strain hardening coefficient, K, of 1.107 GPa and a strain hardening exponent, n, of 0.165. The experimentally obtained values differ substantially from the published values of a strain hardening coefficient, K, of 1.400 GPa and a strain hardening exponent, n, of 0.44 [3]. The difference in values either indicates the experimental data are inaccurate by a large margin or the power law model is not an accurate model for the true stress-strain curve.

6.3 Brass

This section will detail the stress-strain curve of brass after an initial loading phase and two reloading phases.

(PFD 5) From Fig. 6 and Table 2, the effects of strain hardening can be observed. The elastic moduli of the initial loading, first reloading, and second reloading were 54.128-, 55.713-, and 46.380 GPa respectively. The elastic modulus value for the second reloading differs from the expected trend as the specimen should have the same elastic modulus and thus a similar ductility after undergoing strain hardening. However, the elastic modulus of the second reloading is markedly lower than the elastic moduli of the initial loading and first reloading. As the ductility is proportional to the elastic modulus, we can say the brass was around the same ductility in the initial loading and the first reloading while the brass was the least ductile after the second reloading. Deviations from theory could be as simple as poor data analysis, but could also be due to easily untangled dislocation pileups being untangled in the initial loading and the first reloading with only "stubborn" dislocations pileups remaining after the second reloading.

However, the 0.2% yield offset strength agrees with the expectation of a higher 0.2% yield offset strength after more reloading occurs. The yield strength increased from 0.272- to 0.319- to 0.371 GPa over the course of the initial loading and reloadings. The increase in yield strength is due to residual strain accumulation after each deloading period.

7 Answers to Questions

Some questions were answered in Sec. 6. To avoid repetition, if a question has been previously answered, the section in which it was answered will be cited.

A verbose comparison of measured material properties can be found in Sec. 6.1. Refer to this section for any information regarding the topic.

(PDF 2) There are various issues when specifying "steel" or "aluminum" when designing structures. From Fig. 1 and Table 1, few conclusive statements can be made about trends across all steels or all aluminum alloys. The elastic modulus is less for the tested aluminum alloys compared to the tested steels and aluminum alloys have a lower ductility. However, no more definitive statements can be made. More project-specific considerations need to be made than just steel or aluminum alloy and the material properties vary so drastically from steel-to-steel and aluminum alloy-to-aluminum alloy.

A comparison of true and engineering stress-strain curves for 304 stainless steel are given in Sec. 6.2 in the paragraph beginning with (PFD 3). Similarly, a discussion about the accuracy of the power law model for 304 steel can be found in Sec. 6.2 in the paragraph beginning with (PFD 4).

An discussion of brass after a loading and two reloading phases can be found in Sec. 6.3 in the paragraph beginning with (PFD 5).

8 Conclusions

This laboratory covered the tensile and hardness testing of eight materials: 1018CR steel, 2024 aluminum, 304 stainless steel, 1045NM steel, 1045CR steel, 7075T6 aluminum, PMMA, and brass. The tensile tests were used to generate a stress-strain curve for each material and to calculate the elastic modulus, 0.2% offset yield strength, ultimate strength, % elongation, resilience modulus, and the corrected Rockwell B Hardness values. Comparison of the aforementioned quantities showed cold rolling increased the strength, stiffness, and ultimate strength, but decreased ductility. The results for: (1) elastic modulus indicated 304 stainless steel was the stiffest material and PMMA was the least stiff material, (2) ultimate strength indicated 1045CR steel was the strongest material and PMMA was the weakest material, (3) Rockwell B Hardness indicated 304 stainless steel was the hardest metal and 2024 aluminum was the softest metal, and (4) elongation percent indicated 304 stainless steel was the most ductile material and PMMA was the least ductile material. Next, analyzing the difference between true and engineering stress-strain curves for 304 stainless steel indicated the true stress-strain will always be higher than the engineering stress-strain, but the difference between the two is most apparent after plastic deformation. For 304 stainless steel, a power law model was applied that generated power law coefficients that disagreed drastically from those accepted in literature. Finally, brass, which underwent an initial loading period and two reloading periods, had an elastic modulus that was roughly constant for the first two loading periods, but dropped dramatically for the second reloading. However, the 0.2% offset yield strength increased as the reloading occurred due to strain hardening.

9 References

[1] NPRE 432, Tensile Stress-Strain.

[2] NPRE 432 Canvas, Lab 2 Hardness Correction Table.

[3] Callister, William D. *Fundamentals of Materials Science and Engineering: An interactive Etext.* New York, Wiley, 2000.