# An Analysis and Comparison of Material Properties comof Engineering Materials

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## ABSTRACT

In this paper, the material properties of common engineering materials were measured using tension tests, compression tests, and hardness tests. All tests were conducted on material specimens of gray cast iron, 1018 steel cold rolled, 1045 steel normalized, and 7075 aluminum alloy. Additionally, tension tests and hardness tests only were conducted on 1045 steel cold rolled and 304 stainless steel. Hardness tests only were conducted on rectangular samples of 4340 steel and 7075 aluminum alloy. Tension tests and compression tests only were conducted on PMMA.

Tension and compression tests were conducted using an Instron Model 4400. After the tests, engineering stress-strain graphs were constructed for each of the tension and compression tests, and elastic modulus, yield strength, ultimate strength, and failure strength were calculated for each test. Cold rolling was found to increase strength considerably, with 1045 cold rolled having 23.87% higher yield strength and 0.03% lower ultimate strength than 1045 normalized; consequently, normalizing had a positive effect on ductility, the normalized 1045 steel had 48.1% reduction of area (%RA) and 27.11% elongation (%EL) while the cold rolled 1045 steel had only 50.1%RA and 4.64%EL; the normalized steel also had more significant necking before fracture than the cold rolled steel. %RA and %EL were not always consistent with each other, and both metrics were inconsistent with some materials. When comparing true stress and strain with engineering strain for

1045 steel, true stress was higher than engineering stress in tension and lower than engineering stress in compression due to the changing cross-sectional area.

Hardness tests were conducted with all test specimens using a Wilson Model 523 Rockwell hardness tester and HRB numbers were recorded. Additionally, HRB numbers, HRC numbers, and Brinell hardness numbers were recorded for 4340 steel and 7075 aluminum alloy. Brinell hardness tests were conducted using a Wilson Model J Brinell hardness tester. For 4340 steel and 7075 aluminum alloy, the Rockwell hardness numbers were converted to Brinell hardness numbers and compared with the Brinell hardness numbers obtained by the test.

PMMA could not be hardness tested because it is too brittle, and could sustain cracking under the hardness tester.

# 1. INTRODUCTION

### 1.1 Engineering Materials

Nine materials were tested in this study

- ASTM Grade 40 Gray Cast Iron (UNS F12801) is a type of cast iron which contains graphitic microstructures. The graphite composition gives the iron its gray color. Gray cast iron is commonly used in engine blocks and brake rotors. This is due to the material’s ability to withstand thermal cycling without strain. Gray cast iron also has good lubrication due to graphite flakes; however, its graphite flakes also cause gray cast iron to be very brittle. The flakes act as crack propagation sites [6]. Specimens of gray cast iron were hardness tested, tension tested, and compression tested.

- SAE/AISI 1018 Steel (UNS G10180) is a mild carbon steel characterized by a balanced chemical composition and flexible applications. The steel is easily welded and machined. 1018 Steel is one of the cheapest steels, allowing it to be used in a wide range of settings including manufacturing, mining, and construction [7]. The 1018 steel used in our tests had a cold-rolled process, which increased strength at the cost of ductility. Specimens of 1018 steel were hardness tested, tension tested, and compression tested.
- SAE/AISI 1045 Steel (UNS G10450) is a medium carbon steel. It has a carbon content of between 0.42 and 0.50 percent. Some uses for 1045 steel include gears, shafts, axles, and other machine parts [1]. Its versatility, high strength characteristics, and low cost have led 1045 steel to be one of the most used grades of steel in the world. [8] There were two different steel treatments of 1045 used in this study. Specimens that underwent normalizing heat treatment were tested in both tension and compression, while cold-rolled specimens were tested in tension only. All specimens were hardness tested accordingly.
- SAE/AISI 4340 Steel (UNS G43400) is a medium carbon low alloy steel characterized by high strength and toughness. Machining is more difficult, and should be done in the normalized or annealed condition, due to its high strength. Welding 4340 is exceedingly difficult and not recommended because the heat involved can will affect the material properties within the welded area. Because of these limitations, 4340 steel is only used in situations which require high strength; some applications include aircraft

landing gear and transmission gears and shafts. [9] Specimens of 4340 steel were hardness tested.

- 7075-T6 Aluminum Alloy (UNS A97075) is an alloy of aluminum first developed in secret by Sumitomo Metal Industries in Japan for use in Japanese fighter aircraft in World War II [10]. Today, it is primarily used in aerospace applications like aircraft fuselages, as well as gears and shafts. It is used in high strength situations. Its primary alloying element is zinc [11]. 7075 has several tempers, which have differing mechanical properties. The temper used was 7075-T6. Specimens of 7075-T6 aluminum alloy was hardness tested, tension tested, and compression tested.
- SAE 304 Stainless Steel (UNS S30400) is the most used stainless steel. Its weldability, machinability, corrosion resistance, and temperature resistance allow 304 to be a very versatile option for piping, fasteners, commercial appliances, and consumer products. [12] Specimens of 304 stainless steel were hardness tested and tension tested only.
- Polymethyl methacrylate (PMMA) is a transparent polymer commonly known as acrylic or plexiglass. PMMA is commonly used as a substitute for glass that must withstand higher impact forces due to its higher elasticity; for example, PMMA is used in combination with polycarbonate in bulletproof glass [13]. While more elastic than glass, it has a lower tensile strength and similar impact resistance to tempered glass. PMMA has better optical clarity and less thermal conductivity than glass [14]; for this reason, PMMA is often used in

displays. Specimens of PMMA were tested in tension and compression. We did not test PMMA specimens for hardness.

### 1.2 Normalized Steel Heat Treatment

“Normalizing is a heat treatment process that is used to make a metal more ductile and tough after it has been subjected to thermal or mechanical hardening processes. Normalizing involves heating a material to an elevated temperature and then allowing it to cool back to room temperature by exposing it to room temperature air after it is heated. This heating and slow cooling alters the microstructure of the metal which in turn reduces its hardness and increases its ductility.” [4]

### 1.3 Cold Rolling

Cold rolling is a process of cold working in which metal is pushed through rollers below its recrystallization. By pushing the metal through rollers, the crystalline structure is deformed, and strain hardening takes place, increasing a material’s strength at the expense of ductility. Cold rolling finds its purpose in components which require high precision and strength, but do not expect to see deformation. Many metals can be cold rolled, such as titanium, aluminum, and alloys; however, most cold rolling is done with steel [15].

### 1.4 Engineering Strain

Engineering strain is a measure of the deformation of the test material. It is essentially the length of axial stretch experienced by a loaded specimen divided by the total unloaded length of the specimen. It can be obtained by the following formula:

$$\varepsilon = \frac{\Delta L}{L} \tag{1}$$

Where $\varepsilon$ is engineering strain, $\Delta L$ is the change in length, and $L$ is the original length. Engineering strain is a unitless value but is commonly shown with units of mm/mm. Engineering strain is used more commonly for stress strain testing because it is more useful for evaluating the maximum static load that can be applied.

### 1.5 Engineering Stress

Engineering stress is a measure of the force applied on a sample relative to its cross sectional area. It differs from true stress because true stress takes into account the change in cross-sectional area during a test. When necking occurs in tension tests, the engineering strain will measure lower than the true strain because the decrease in area causes the engineering strain to decrease. Engineering stress is given by the formula:

$$\sigma = \frac{F}{A_0} \tag{2}$$

where $\sigma$ is the engineering stress, $F$ is the applied force, and $A_0$ is the original cross-sectional area. Engineering stress is used more commonly for stress strain testing because it is more useful for evaluating the maximum static load that can be applied.

### 1.6 Young's Modulus / Elastic Modulus - Hooke's Law

Young's modulus, or the elastic modulus, is a measure of a material's stiffness and its ability to resist deformation. It is the elastic stress divided by the elastic strain, given by this equation:

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

This equation describes the relationship between stress and strain in the elastic region only, according to Hooke's Law. The elastic region refers to the area of the stress strain curve in which the specimen, if unloaded, will return to its original length with minimal deformation.

### 1.7 Percent Elongation

Percent elongation (%EL) is a method of quantifying the ductility of a material. A greater percent elongation indicates a greater degree of plastic necking in the sample before fracture. Since brittle materials will experience failure points that fracture the material early before necking can occur to a significant degree, they will have a smaller %EL.

Percent elongation is a measure of the change in length from the original specimen length and the length right before fracture. It can be calculated from the following formula:

$$\%EL = \frac{\mathrm{L} - \mathrm{L}_0}{\mathrm{L}_0} \cdot 100\% \tag{4}$$

Where $L$ is the final length of the specimen gage, and $L_0$ is the original length of the specimen gage.

### 1.8 Percent Area Reduction

Percent area reduction (%RA) is another method of quantifying the ductility of a material. A greater %RA indicates a greater degree of plastic necking in the sample before fracture, since necking causes a smaller cross-sectional area. Since brittle materials will experience failure points that fracture the material early before necking can occur to a significant degree, they will have a smaller %RA. %RA is less useful for brittle materials, since they will have a near zero decrease in area.

%RA is a measure of the change in cross-sectional area from the original specimen length and the length right before fracture. It can be calculated from the following formula:

$$\%RA = \frac{\mathrm{A} - \mathrm{A}_0}{\mathrm{A}_0} \cdot 100\% \tag{5}$$

### 1.9 Percent Error

Percent error is a method for evaluating the accuracy of results. It is a way of comparing properties obtained from the experiment, and expected properties established in literature. It is obtained by the following formula:

$$\delta = \left| \frac{v_O - v_E}{v_E} \right| \cdot 100\% \tag{6}$$

Where δ is the percent error, $v_O$ is the observed value, and $v_E$ is the expected value.

### 1.10 Mechanical Testing

Tension and compression tests are common for determining material properties; they are used for analyzing stress-strain relationships, which can be further analyzed to determine strength, elasticity, and ductility. In tension tests, a specimen, typically of round dog bone geometry, is secured in two clamps in the load cell. The load frame applies uniaxial tension, typically until failure. In compression tests, a cylindrical specimen is used, and a rod puts the specimen in uniaxial compression. The specimen may or may not be tested until failure. Applied force is recorded by the machine and strain is recorded by an attached extensometer.

### 1.11 Hardness Testing

Hardness tests are measures of the force required to penetrate a material. The two tests evaluated in this study are the Rockwell hardness test and the Brinell hardness test.

Rockwell hardness tests come in many different scales, designed to test different materials. The most common scales are the “B” and “C” scales, and their measurements are given by HRB and HRC numbers, which are arbitrary dimensionless numbers. The HRB scale test is done by indenting the sample with a 1/16 inch ball indenter. The HRC scale test is done by indenting the sample with a “Brale indenter”, a conical diamond with a incidence angle of 120 degrees. [17] The tests are done with the following steps: (1) The indenter applies a minor load of 98 N, and the displacement is measured. (2) The indenter applies a major load, which is 980 N and 1470 N for HRB and HRC scales, respectively. (3) The indenter dwells at this major load for a short duration, allowing plastic deformation to take place on the test sample. (4) The indenter unloads to the minor load, and the displacement is measured. (5) The initial displacement is subtracted from the final displacement, in order to measure the amount of plastic deformation incurred by the major load. (6) The Rockwell hardness number is calculated by the machine and shown on the display.

Because the hardness tests performed on the tension and compression test specimens were done on the side of the grip, the test surface was not flat, but curved. In order to account for the curvature of the test surface, we must add a hardness correction value to the hardness number. Correction factors for common cylindrical diameters are listed in tables which are available on the internet. [18] A sample calculation of the hardness correction can be found in the appendix.

Our Rockwell hardness tests were conducted with a Wilson Model 523 Rockwell Hardness Tester. All materials except PMMA underwent Rockwell-B tests, and rectangular specimens of 7075-T6 aluminum alloy and AISI 4340 steel underwent additional Rockwell-C tests.

The Brinell hardness scale is a single continuous scale that can represent all harnesses. The Brinell hardness test is conducted by applying a ten millimeter ball into the test specimen with known force, and measuring the diameter of the resulting indentation.

Our Brinell hardness tests were conducted using a Wilson Model J Brinell Hardness Tester, and our indentation size was measured using a digital microscope which could automatically lock-on to the indentations and provide a diameter reading. Brinell hardness tests were conducted only on rectangular specimens of 7075-T6 aluminum alloy and AISI 4340 steel.

**1.12 True Stress and Strain**

True stress is a measure of stress that accounts for the reduction in area caused by necking. If it is assumed that volume is held constant and is proportional to strain, then we find that:

$$\sigma_t = \sigma(1 + \varepsilon) \tag{7}$$

Where $\sigma_t$ is true stress, $\sigma$ is engineering stress, and $\varepsilon$ is engineering strain. By including engineering strain, we approximate the instantaneous cross-sectional area by assuming a cylinder with constant volume. However, once necking begins, we can *not* approximate the specimen as a cylinder, since the cross sectional varies on the vertical axis; Therefore, equation 7 is only accurate before necking occurs.

True strain is a measure of strain that accounts for the elongation of the material as it deforms. It is given by the following equation:

$$\varepsilon_t = ln(1 + \varepsilon) \tag{8}$$

where $\varepsilon_t$ is true strain and $\varepsilon$ is engineering strain.

**1.13 Stress – Strain Behavior**

The load frame cannot directly measure elastic modulus or ultimate strength. In order to obtain these properties, one must calculate the engineering stress and engineering strain for each data point. One can then construct a plot of all the points and create a stress strain plot. From this plot, we can clearly see: (a) the elastic region, denoted by a portion of the graph in which data points form a linear trend; (b) the plastic region, a nonlinear region that immediately follows the elastic region—in most materials, the plastic region has a negative curvature trend; (c) the yield point, which occurs at the boundary between the elastic and plastic regions; (d) the ultimate strength, the point in the plastic region with the highest recorded stress; and (e) the failure strength, which is the engineering stress of the point on the graph with highest strain, excluding any extraneous data points.

In the elastic region, if the material is unloaded, all the strain can be recovered elastically; the specimen will return to its original length with minimal deformation.

In the plastic region, if the material is unloaded, some of the material's strain can be recovered elastically, but the remaining plastic strain is permanent and cannot be recovered; consequently, the specimen will return to a zero-stress state with some permanent deformation. The path that the material takes to its zero-stress state will be a linear path with slope equal to the elastic modulus of the material. The amount of permanent strain on the material in the plastic region is given by the equation

$$\varepsilon_{\text{permanant}} = \varepsilon - \frac{\sigma}{E} \tag{9}$$

where $\varepsilon_{\text{permanant}}$ is the permanent strain on the material, $\varepsilon$ is the maximum engineering strain experienced by the material before unloading, $\sigma$ is the maximum engineering stress experienced by the material before unloading, and $E$ is the elastic modulus.

The yield point of the material, as stated, is the boundary between the elastic and plastic regions. In some materials, the yield point is obvious as it occurs at local maximum on the graph, where the material loses strength as it yields. In other materials, the yield point is less pronounced, as a curve exists between the elastic and plastic regions. In these cases, it is necessary to use the 0.2% offset yield method. As shown in figure 5, the 0.2% offset method involves constructing a line which has the same slope as the elastic modulus that intercepts the x-axis (engineering strain axis) at 0.2% strain. The intersection of this offset line with a linear interpolation of the data is the calculated yield point.

# 2. PROCEDURE

## 2.1 Testing Devices

The machine used for tension and compression tests is an Instron model 4400 Load Frame, along with an extensometer.

The load frame operated by driving two screws located in the columns with an electric motor. The screws are attached on each side to the crosshead, which is in turn attached to the load cell. During tests, the load frame records data about the force applied and the vertical displacement.

The extensometer is a small device clipped to the specimen at the gage. There is a detent on the extensometer allowing the experimenter to place both prongs at a specified distance apart. The extensometer measures the strain of the sample, and the data is sent to the computer. [16]

## 2.2 Specimens

The specimens tested in tension were round dog-bone geometry specimens. Figure 6 shows the nominal dimensions of the specimens used in the tension test. Specimens of gray cast iron, 1018 cold-rolled steel, 1045 cold-rolled steel, 1045 normalized steel, 304 stainless steel, 7075 aluminum alloy, and PMMA were tested in tension. All tension specimens except PMMA were also hardness tested.

The specimens used for compression were solid cylinder specimens. Specimens of gray cast iron, 1018 cold-rolled steel, 1045 normalized steel, 7075 aluminum, and PMMA were tested in compression. These specimens had a nominal diameter of 12.7 mm and nominal length of 38.1 mm, except for PMMA, which had a nominal diameter of 19.1 and a nominal length of 63.5. All compression specimens except PMMA were also hardness tested.

The specimens used for hardness testing were rectangular specimens of 7075 aluminum and 4340 steel were hardness tested only. These specimens were tested in both Rockwell hardness tests and a Brinell hardness test.

## 2.3 Experimental Preparations

Before each test, we used a digital caliper to measure each specimen's diameter, which allowed its cross-sectional area to be calculated. Each specimen, except PMMA specimens, were tested using a Wilson model 523 Rockwell hardness tester, and an HRB number was recorded. The specimen was then loaded into the testing machine. In tension tests, the specimen was secured with one end in each clamp. The clamps, or grips, were then tightened. In this position, we placed an extensometer on two points on the specimen, as shown in figure 1. In compression tests, the specimen was placed in a safety box with polycarbonate paneling, which acted as a safety measure against fragmentation. The specimen was centered under a metal rod which moved freely vertically but could be pushed down by the crosshead. The crosshead was then moved down to provide a slight force on the metal rod, which held the specimen in place, as shown in figure 2. An extensometer was also attached to all compression samples except PMMA, since the extensometer could be damaged by the failure of PMMA. Before starting the test, the force and displacement were zeroed on the computer.

### 2.4 Testing Procedure

Upon starting the test, the computer automatically controlled the raising or lowering of the load frame until either failure or manual stopping. In tension tests, all specimens were tested until failure. After the specimens failed, we removed the specimens from the grips, and the fracture surfaces were analyzed. The diameter of the specimen very close to the point of fracture was measured with the digital calipers. Three measurements of this diameter were recorded, and the average recorded in the computer for each test.

In compression tests, only PMMA was tested until failure. To avoid potentially damaging the extensometer, we were instructed to stop the compression tests of 1018 steel and 7075 aluminum to avoid exceeding a 75 kN and 65 kN load, respectively. Tests for cast iron and 1045 steel did not have to be stopped since the force required exceeded the loading limit of the load frame before the extensometer was at risk of damage. After the test, the crosshead was jogged up and the specimen removed. The final diameter and length were then recorded using the digital calipers. Three measurements of the diameter and length were made, and averages of each were recorded in the computer. To aid identification of bucking and barreling, an incandescent lamp was placed at a low angle, and the specimen slowly rolled longitudinally until shadows of the cylinder surface could be identified. By observing the shadows, the shape of the cylinder walls could be characterized. Buckling was recorded in any specimens which showed a concave surface at any point on the cylinder wall. Barreling was recorded in any specimens which showed a convex surface at some angles but did not show a concave surface at any angle. This shadow test was not conducted on PMMA since its buckling behavior was visually apparent during testing.

In compression tests, rectangular samples of 7075 aluminum alloy and 4340 steel were tested in Rockwell-B, Rockwell-C, and Brinell hardness tests. In Rockwell tests, the specimen was placed in the anvil, and a tightening wheel rotated until a display on the machine indicated sufficient tightening, and the wheel locked in place. Once the Rockwell hardness value was displayed, the wheel was loosened, and the specimen removed. Since the specimens had been reused many times, a clean spot on the specimen which had not been tested before had to be found and the test conducted at that location. In the Brinell hardness test, the specimens were placed in the anvil, and the tightening wheel was tightened until the specimen made contact with the testing cone. The lever on the right side of the machine was then pulled until it stopped and held for twenty seconds. The handle was then returned to its original position and the material removed from the anvil. The specimen was then measured with a digital microscope, which could automatically lock onto the indent made by the hardness tester. The diameter of the indentation was recorded and a Brinell hardness number recorded.

# 3. RESULTS

### 3.1 Tension Test

The results of the tension test are shown in table 1, and a summary of results for both tension and compression tests are shown in Table 3.

The gray cast iron exhibited a brittle failure, with a nearly flat fracture surface, and minimal necking; it showed the lowest ductility, with a %EL of 0.93% and %RA of 0.28%, indicative of its brittle nature. AISI 1018 cold-rolled steel exhibited low ductility, with a %EL of 0.92% and a significant %RA of 50.13%. A cup and cone fracture surface was observed for this material, and some necking. AISI 1045 cold-rolled steel indicated similar ductility to 1018, with a %EL of 4.64% and %RA of 50.1%, along with a cup and cone fracture surface, and some necking. AISI 1045 normalized steel was significantly more ductile than its cold rolled counterpart, achieving a %EL of 27.11% and %RA of 48.1%. 1045 also had a cup and cone fracture surface and significant necking. 7075-T6 aluminum alloy had a %EL of 17.22% and %RA of 51.0%, reflecting high ductility. This material also had a cup and cone fracture surface and significant necking. SAE 304 stainless steel was the most ductile material tested, with a %EL of 52.38% and %RA of 76.71%; it also had a cup and cone fracture surface and significant necking. PMMA exhibited a low

%EL of 8.04% and %RA of 8.04, indicating brittle behavior, but not as brittle as cast iron. Qualitatively, PMMA also had a brittle fracture like cast iron, and a nearly flat fracture surface with no visible necking.

Material properties for the tests were derived from stress strain diagrams. A sample calculation of engineering stress can be found in the appendix. An overlay of stress strain curves from all tested metals can be seen in Figure 28

For Gray Cast Iron (UNS F12801), the maximum load reached was 14.92 kN. The Young's modulus was 140.98 GPa. Cast iron did not exhibit a clear yield point during the test. The stress-strain curve for gray cast iron can be seen in Figure 7.

For AISI 1018 Steel, Cold Rolled (UNS G10180), the yield load was 26.78 kN, and the yield stress was 573.07 MPa. The maximum load was 27.56 kN. The Young's modulus was 213.4 GPa. The stress-strain curve for AISI 1018 steel can be seen in Figure 8, and the elastic region of the stress-strain curve can be seen in Figure 9.

For AISI 1045 Steel, Cold Rolled (UNS G10450), the yield load was 22.81 kN, and the yield stress was 462.6 MPa. The maximum load was 32.59 kN. The Young's modulus was 176.61 GPa. The stress-strain curve for AISI 1045 cold-rolled steel can be seen in Figure 10, and the elastic region of the stress-strain curve can be seen in Figure 11.

For AISI 1045 Steel, Normalized (UNS G10450), the yield load was 18.56 kN, and the yield stress was 489.5 MPa. The maximum load reached was 30.62 kN. The Young's modulus was 207.93 GPa. The stress-strain curve for AISI 1045 normalized steel can be seen in Figure 13, and the elastic region of the stress-strain curve can be seen in Figure 14.

For 7075-T6 Aluminum Alloy (UNS A97075), the yield load was 20.36 kN, and the yield stress was 470.08 MPa. The maximum load was 22.55 kN. The Young's modulus was 74.58 GPa. The stress-strain curve for 7075-T6 aluminum alloy can be seen in Figure 15, and the elastic region of the stress-strain curve can be seen in Figure 16.

For SAE 304 Stainless Steel (UNS S30400), the yield load was 19.01 kN, and the yield stress was 470.08 MPa. The maximum load reached was 27.45 kN. The Young's modulus was 189.64 GPa. The stress-strain curve for SAE 304 stainless steel can be seen in Figure 17, and the elastic region of the stress-strain curve can be seen in Figure 18.

For PMMA, the maximum load was 4.03 kN. The Young's modulus was 2.73 GPa. PMMA did not exhibit a clear yield point during the test. The stress-strain curve for PMMA can be seen in Figure 19.

### 3.2 Compression Test

The results of the compression test are shown in Table 2, and a summary of results for both tension and compression tests are shown in Table 3.

For Gray Cast Iron (UNS F12801), the yield load was 72.77 kN, and the yield strength was 549.92 MPa. The maximum load reached was 100 kN, at which point the test was stopped due to the load limit of the testing frame being reached. The Young's modulus was 140.98 GPa, and the ultimate strength was 758 MPa. The stress-strain curve for gray cast iron can be seen in Figure 20, and the elastic region of the stress-strain curve can be seen in Figure 21.

For AISI 1018 Steel, Cold Rolled (UNS G10180), the yield load was 71.73 kN, and the yield strength was 569.8 MPa. The maximum load was 75.77 kN. The test was stopped upon reaching the instructed load limit of 75 kN to prevent damage to the extensometer. The Young's modulus was 213.4 GPa, and the ultimate strength was 692.2 MPa. The specimen showed signs of buckling during post-test analysis. The stress-strain curve for AISI 1018 steel can be seen in Figure 22, and the elastic region of the stress-strain curve can be seen in Figure 23.

For AISI 1045 Steel, Normalized (UNS G10450), the yield load was 57.78 kN, and the yield strength was 462.6 MPa. The maximum load reached was 100 kN. The test was stopped due to the load limit of the testing frame being reached. The Young's modulus was 207.93 GPa, and the ultimate strength was 800.72 MPa. The specimen showed signs of buckling during post-test analysis. The stress-strain curve for AISI 1045 normalized steel can be seen in Figure 24, and the elastic region of the stress-strain curve can be seen in Figure 25.

For 7075-T6 Aluminum Alloy (UNS A97075), the yield load was 61.62 kN, and the yield strength was 489.5 MPa. The maximum load was 65.45 kN. The test was stopped upon reaching the instructed load limit of 65 kN to prevent damage to the extensometer. The specimen showed signs of buckling during post-test analysis. The Young's modulus was 74.58 GPa, and the ultimate strength was 519.94 MPa. The stress-strain curve for 7075-T6 aluminum alloy can be seen in Figure 26.

For PMMA, the yield load was 20.22 kN, and the yield strength was 70.14 MPa. The maximum load was 38.59 kN. The test was stopped when the PMMA specimen shattered. The Young's modulus was 2.73 GPa, and the ultimate strength was 133.84 MPa. The specimen buckled substantially before failure, and the buckling was visually apparent. The stress-strain curve for PMMA can be seen in Figure 27.

### 3.3 Hardness Test

The data for the comparative hardness tests which involved rectangular specimens can be found in table 4, and the hardness data for the compression specimens can be found in table 3. The data in table 4 were obtained by averaging data from individual hardness tests conducted by the entire lab section.

For 4340 Steel, the average Brinell hardness number was 694.7 $kgf/mm^2$, measured using a 10 mm ball indenter and a 3000 kg load. The average Rockwell B hardness number was 122.26 HRB, and the average Rockwell C hardness number was 61.98 HRC. The Brinell hardness number converted from the Rockwell C hardness value was 658 $kgf/mm^2$. The Rockwell B hardness value could not be converted to a Brinell hardness value, since it was out of the range of the Rockwell-B scale.

For 7075 Aluminum Alloy (7075 Al), the average Brinell hardness number was 186.7 $kgf/mm^2$. The average Rockwell B hardness number was 95.5 HRB, and the average Rockwell C hardness number was 14.56 HRC. The Brinell hardness number converted from the Rockwell C hardness value was 195.5 kgf/mm², while the converted value from the Rockwell B hardness was 214.1 kgf/mm².

For Gray Cast Iron (UNS F12801), the Rockwell B hardness number (corrected for curvature) was 100.0 HRB, and the converted Brinell hardness number was 240 HB. For AISI 1018 Steel, Cold Rolled (UNS G10180), the Rockwell B hardness number was 94.5 HRB, and the converted Brinell hardness number was 205.5 HB. AISI 1045 Steel, Normalized (UNS G10450) had the same Rockwell B hardness number as 1018 steel, at 94.5 HRB, and the converted Brinell hardness number was also 205.5 HB. For 7075-T6 Aluminum Alloy (UNS A97075), the Rockwell B hardness number was 88.0 HRB, and the converted Brinell hardness number was 175 HB. PMMA was not tested for hardness.

# 4. DISCUSSION

### 4.1 Ductility Comparison

The most ductile material that was tested in tension was SAE 304 Stainless Steel, which had the both the highest %EL and highest %RA, at 52.38% and 76.71%, respectively. The most brittle material tested in tension was cast iron which had the second lowest %EL and lowest %RA of 0.92 and 0.28, respectively. The %EL for cast iron was narrowly superseded by cold rolled AISI 1018 steel, which had a %EL of 0.92; notably, however, 1018 cold rolled had a much higher %RA than cast iron, at 50.13%; therefore, cast iron is judged as the most brittle.

Cast iron and PMMA both had brittle fractures, with a very flat fracture surface and minimal necking before fracture. Both materials experienced little change in shape before failure. Despite 1018 cold rolled having the lowest %EL, it experienced significant necking before failing and thus is not as brittle as PMMA or cast iron.

Between %EL and %RA, %RA seemed to be the better indicator of ductility; since %EL indicated 1018 cold rolled as the most ductile while discounting PMMA, which, although had a higher %EL, had a much more brittle fracture surface and no necking, unlike 1018. %EL and %RA were also not consistent with each other; for example, normalized 1045 steel had a much higher %EL than its cold-rolled counterpart, but had a slightly lower %RA. Because of these factors, the best way of judging ductility is a combination of %EL, %RA, and observation of the fracture surface.

Cold rolling seemed to have a negative effect on ductility, with the cold rolled 1045 steel having significantly less elongation than the normalized 1045 steel. The cold rolled steel had a 82.88% reduction in the percent elongation compared to the normalized steel.

### 4.2 Stress-Strain Comparison

The yield strengths of the materials were relatively consistent between tension and compression. Cast iron and PMMA cannot not be compared due to a lack of yielding, but all other materials had percent differences below 5%. 7075 aluminum had the greatest percent difference, at 4.07%. Notably, 1045 normalized had a nearly identical yield strength in tension and compression.

Elastic modulus was also reasonably consistent between tension and compression. The greatest difference in elastic modulus was for gray cast iron, with a 15.34% difference and PMMA, with a 17.32% difference. The brittle materials appear to have the greatest inconsistency in elastic modulus.

Nearly all of the compression tests had to be stopped before the specimens reached their real ultimate strength, due to having to stop the test before potentially damaging the extensometer, or reaching the load frame's maximum force. For this reason, the ultimate strength for metals cannot be compared between tension and compression. PMMA is the only material for which ultimate strength can be compared, since it was tested until failure in compression. PMMA had an ultimate strength of 79.38 MPa and 133.84 MPa in tension and compression, respectively. Because they are quite different from each other, we can conclude that the ultimate strength for PMMA is not consistent between tension and compression. Fig 29 and 12

**4.3 True and Engineering Stress Strain Curves**

The comparison between true and engineering stress and strain for 1045 cold rolled steel in tension can be found in figure 12, and 1045 normalized steel in compression can be found in figure 29. In tension, the absolute value of the true stress is greater than the absolute value of the engineering stress. The reason for this is because as the specimen is put under tension, the cross-sectional area decreases, so the true stress increases. In compression, the opposite is true; because the cross-sectional area increases, the absolute value of the true stress is less than the engineering stress.

The engineering stress-strain curve is more useful to engineers because it identifies the point at which the material starts necking, which the true stress-strain curve does not. The true stress and strain are also more difficult to measure, since the instantaneous area must be measured during the test.

### 4.4 PMMA

PMMA behaved very differently in tension and compression. While very brittle and shattering quickly in tension, it withstood compressive force for a very long time and sustained a large amount of deformation before shattering, indicating more ductile behavior in compression. Furthermore, PMMA appeared to yield in compression, while it did not yield in tension. While not as pronounced as the normalized 1045, PMMA's stress strain curves had significant negative curvature while leaving the elastic region in compression. It could also be true that all of the materials would have behaved more ductile in compression, as the other tests were stopped before reaching significant plastic deformation.

PMMA was the only material that was not hardness tested. The reason for this is due to PMMA's low strength and brittleness. PMMA has very little plastic deformation before failure. Because hardness tests measure the amount of plastic deformation to quantify hardness, it would be difficult to put measurable plastic deformation on PMMA without breaking the specimen.

## 5. CONCLUSIONS

From the material tests, analysis of the data from those tests, and observations made before, during and after the tests, we conclude that:

1. SAE 304 stainless steel is the most ductile material that was tested. It had significant necking, a percent reduction in area of 76.71% and a percent elongation of 52.38%.
2. Cast iron is the most brittle material that was tested. It had no visible plastic deformation, a percent reduction in area of 0.28% and a percent elongation of 0.93%.
3. Neither %EL or %RA provide a complete look at ductility. They must be used in combination with analysis of the fracture surface to determine and compare ductility.
4. A cup and cone fracture surface indicates a ductile fracture while a flat fracture surface indicates a brittle fracture.
5. Cold rolling increases strength of a material at the cost of ductility for AISI 1045 steel. While the cold rolled 1045 steel had a 23.87% higher yield strength, it also had a 82.88% lower area reduction.
6. PMMA and cast iron behave differently under compression and under tension. Both materials yield under compression, while they do not yield under tension. Both materials are more ductile under compression than under tension.

7. The ultimate strength for PMMA is inconsistent between tension and compression. It had a percent difference of $50.28\%$ between tension and compression.
8. Engineering stress is lower for materials in tension and higher for materials in compression, due to the changing cross-sectional area.

## 6. ACKNOWLEDGEMENTS

Materials and equipment used to perform this experiment were provided by the Mechanical Testing Instructional Laboratory (MTIL) at the University of Illinois at Urbana-Champaign.

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APPENDICES

## A.1 Tables and Figures

**Table 1: Results from Tension Test Including Measured Dimensions, Percent Elongation, Reduction in Area, Young's (Elastic) Modulus, Yield Strength, Ultimate Strength, and Mechanical Behavior for Tested Materials**

| Measurement or property | | | Material | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Quantity | Symbol | Units | Gray Cast iron | AISI 1018 Steel, Cold Rolled | AISI 1045 Steel, Cold rolled | AISI 1045 Steel, Normal-ized | 7075-T6 Aluminum Alloy | SAE 304 Stainless Steel | PMMA |
| | Initial data | | | | | | | | |
| Diameter | $d_0$ | mm | 7.08 | 7.12 | 7.12 | 7.19 | 7.13 | 7.17 | 8.17 |
| Cross-sectional area | $A_0$ | $mm^2$ | 39.41 | 39.88 | 39.81 | 40.60 | 39.93 | 40.41 | 62.09 |
| | Strength | | | | | | | | |
| Yield load | $P_y$ | kN | 12.07 | 26.78 | 22.81 | 18.56 | 20.36 | 19.01 | 2.62 |
| Max. load | $P_{max}$ | kN | 14.92 | 27.56 | 32.59 | 30.62 | 22.55 | 27.45 | 4.03 |
| Shape changes during deformation | — | — | No Change | Necking | Necking | Necking | Necking | Necking | No Change |
| Description of fracture surface | — | — | Cup & Cone | Cup & Cone | Cup & Cone | Cup & Cone | Cup & Cone | Cup & Cone | Flat |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Hardness | | | | | | |
| Rockwell hardness | HRB | — | 102.3 | 93.5 | 93.5 | 88.6 | 86.7 | 101.3 | |
| | | | Ductility | | | | | | |
| Gage length | $l_0$ | mm | 25.4 | | | | | | |
| Percent elongation | %EL | — | 0.93 | 0.92 | 4.64 | 27.11 | 17.22 | 52.38 | 8.04 |
| Final diameter | $d_f$ | mm | 7.09 | 5.03 | 0 | 5.18 | 4.99 | 3.46 | 8.01 |
| Final area | $A_f$ | $mm^2$ | 39.5 | 19.88 | 0 | 21.07 | 19.56 | 9.41 | 50.35 |
| Percent reduction of area | %RA | — | 0.28 | 50.13 | 50.1 | 48.1 | 51.0 | 76.71 | 3.88 |
| | | | Mechanical properties derived from stress–strain diagram | | | | | | |
| Young's modulus | E | GPa | 140.98 | 213.4 | 176.61 | 207.93 | 74.58 | 189.64 | 2.73 |
| Yield strength | $\sigma_y$ | MPa | | 569.8 | 573.07 | 462.6 | 489.5 | 470.08 | |
| Ultimate strength | $\sigma_u$ | MPa | 758 | 692.2 | 800.44 | 800.72 | 519.94 | 668.61 | 133.84 |
| Mechanical behavior (description) | — | — | Not Very Ductile | Less ductile | Less ductile | Ductile | Ductile | Very Ductile | Brittle |

**Table 2: Results from Compression Test Including Measured Dimensions, Young's (Elastic) Modulus, Yield Strength, Ultimate Strength, and Hardness Numbers for Tested Materials**

| Measurement or property | | | Material | | | | |
|---|---|---|---|---|---|---|---|
| Quantity | Symbol | Units | Cast iron | 1018 CR Steel | 1045 NM Steel | 7075 Alum | PMMA |
| | Initial data | | | | | | |
| Diameter | d0 | mm | 12.98 | 12.66 | 12.61 | 12.66 | 19.16 |
| Cross-sectional area | $A_0$ | $mm^2$ | 132.3242 | 125.88 | 124.89 | 125.88 | 288.32 |
| Gage length | I0 | mm | 39.95 | 40.03 | 39.98 | 39.98 | 65.05 |
| | Strength | | | | | | |
| Yield load | Py | kN | 72.77 | 71.73 | 57.78 | 61.62 | 20.22 |
| Max. load | $P_{max}$ | kN | 100 | 75.77 | 100 | 65.45 | 38.59 |
| Reason for stopping test | — | — | Load limit of the load frame reached | Instructed to stop the test at 75 kN | Load limit of the load frame reached | Instructed to stop the test at 65 kN | Blew up |
| Description of fracture surface and final shape | — | — | Not Stated | Buckling | Buckling | Significant Buckling | Shattered |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Hardness-Rockwell B (1/16'' ball, 100 $kg_f$) | | | | | | |
| Average observed hardness readings (uncorrected for curvature) | HRB | — | 98.4 | 92.6 | 92.4 | 85.8 | |
| Correction for curvature* | HRB | — | 1.58 | 1.87 | 1.88 | 2.21 | |
| Rockwell hardness | HRB | — | 100.0 | 94.5 | 94.5 | 88.0 | |
| Brinell hardness (converted) | HB | $kg_f/mm^2$ | 240 | 205.5 | 205.5 | 175 | |

**Table 3, Summary of Results for Tension, Compression, and Hardness Tests for Materials which were Tested in Tension and Compression**

| Mechanical property | | | Material | | | | |
|---|---|---|---|---|---|---|---|
| Quantity | Symbol | Units | Cast iron | 1018 steel | 1045 N Steel | 7075 Al | PMMA |
| | ensile properties (from Tensile Test .ab) | | | | | | |
| Young's modulus | E | GPa | 120.28 | 184.16 | 207.02 | 65.93 | 3.26 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Yield strength | $\sigma_y$ | MPa | | 574.4 | 462.7 | 509.9 | |
| Ultimate strength | $\sigma_u$ | MPa | 378.98 | 601.92 | 800.72 | 564.78 | 79.38 |
| Percent elongation | %EL | — | 0.93 | 0.92 | 4.64 | 17.22 | 8.04 |
| Shape changes during deformation | — | — | None | Necking | Necking | Necking | None |
| Nature of fracture surface | — | — | Flat | Cup & Cone | Cup & Cone | Cup & Cone | Flat |
| Rockwell (corrected for curvature) | HRB | | 103.5 | 95.5 | 98.5 | 89.0 | |
| Brinell (converted) | HB | | 264 | 214.1 | 230.8 | 177.8 | |
| | Compression properties | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Young's modulus | E | GPa | 140.98 | 213.4 | 207.93 | 74.58 | 2.73 |
| Yield strength | □ y | MPa | 549.92 | 569.8 | 462.6 | 489.5 | 70.14 |
| Ultimate strength | □ u | MPa | 758 | 692.2 | 800.72 | 519.94 | 133.84 |
| Shape changes during deformation | — | — | Unknown | Buckling | Buckling | Buckling | Considerable Buckling |
| Nature of fracture surface | — | — | Unknown | Did not fracture | Did not fracture | Did not fracture | Small pieces everywhere |
| Rockwell (corrected for curvature) | HRB | | 100.0 | 94.5 | 94.5 | 88.0 | |
| Brinell (converted) | HB | | 240 | 205.5 | 205.5 | 175 | |
| Brinell—SI force units | $p = 9.81 m/s^2 \times$ HB | MPa | | | | | |

**Table 4, Comparative Hardness Data (Lab Section Average)**

| Measurement or property | | | Material | |
|---|---|---|---|---|
| Quantity | Symbol | Units | 4340 Steel | 7075 Al |
| Hardness—Brinell (ball diameter D = 10 mm; indenter load = 3000 kg) | | | | |
| Brinell hardness number | HB | kgf /mm$^2$ | 694.7 | 186.7 |
| Hardness—Rockwell B and C | | | | |
| Rockwell B hardness number | HRB | — | 122.26 | 95.5 |
| Rockwell C hardness number | HRC | — | 61.98 | 14.56 |
| Brinell hardness (converted from Rockwell B or C hardness) | | | | |
| Converted Brinell hardness number | HB | kgf /mm$^2$ | From C: 658<br>B is out of range | From C: 195.5<br>From B: 214.1 |

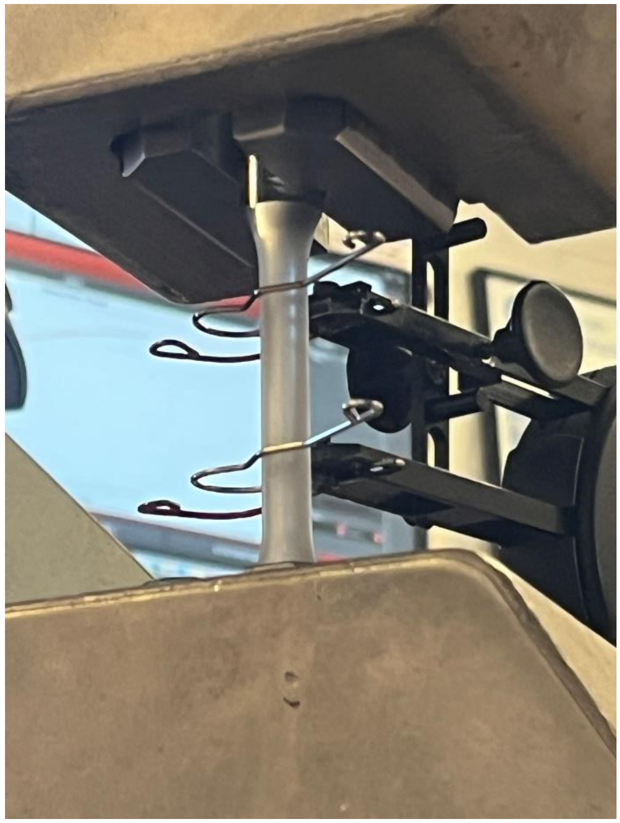

**Figure 1, Example of Tension Test Specimen In Load Cell Showing Extensometer Placement on Gage**

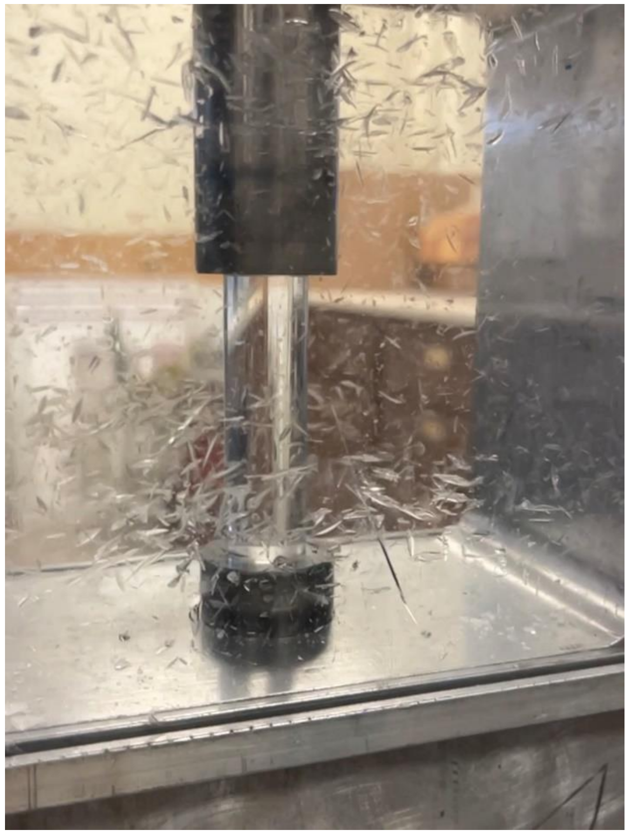

**Figure 2: Example of Compression Test Specimen Placed in Load Cell Before Test Without Extensometer**

**Figure 3, 1045 Steel Tensile Stress Strain Plot**

**Figure 4, Elastic Region of 1045 Steel Tensile Stress Strain Plot**

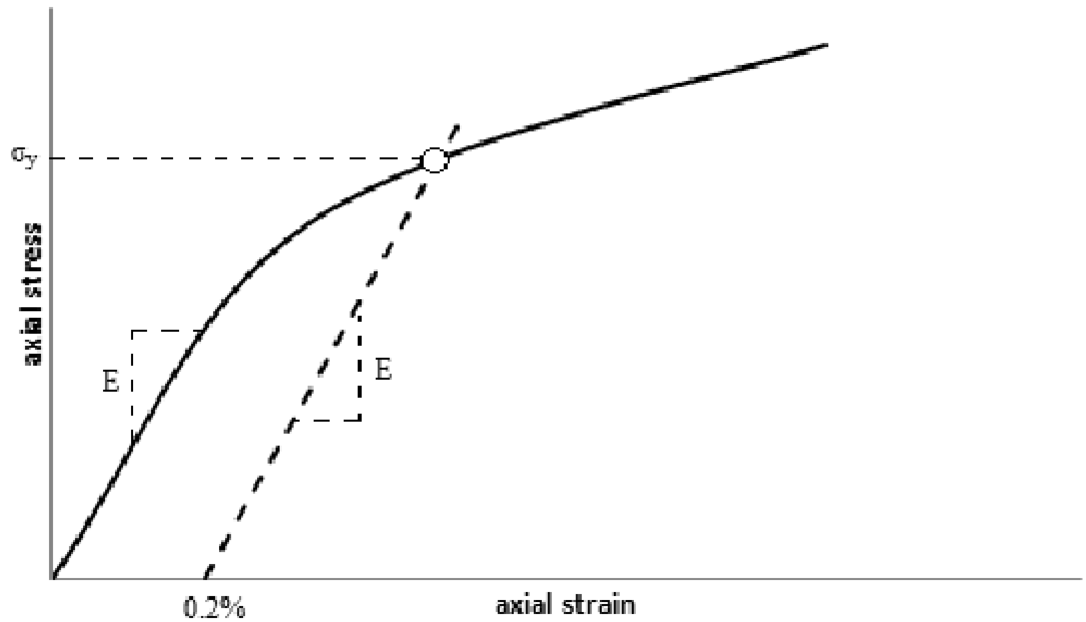


**Figure 5, Example of Using 0.2% Offset Rule for Calculating the Yield Point of a Material with a Continuous Curve between Elastic and Plastic Regions**

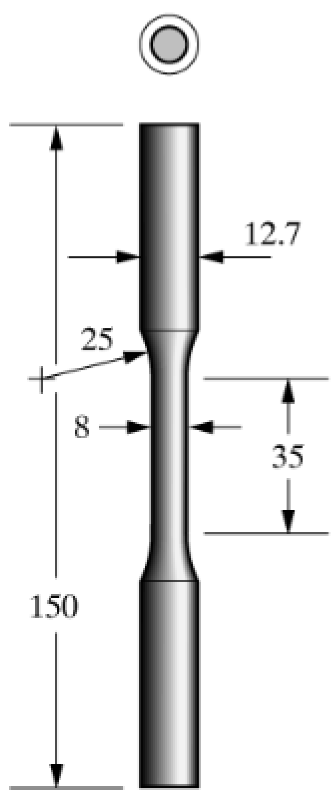


**Figure 6, Nominal Tension Specimen Dimensions (mm).**

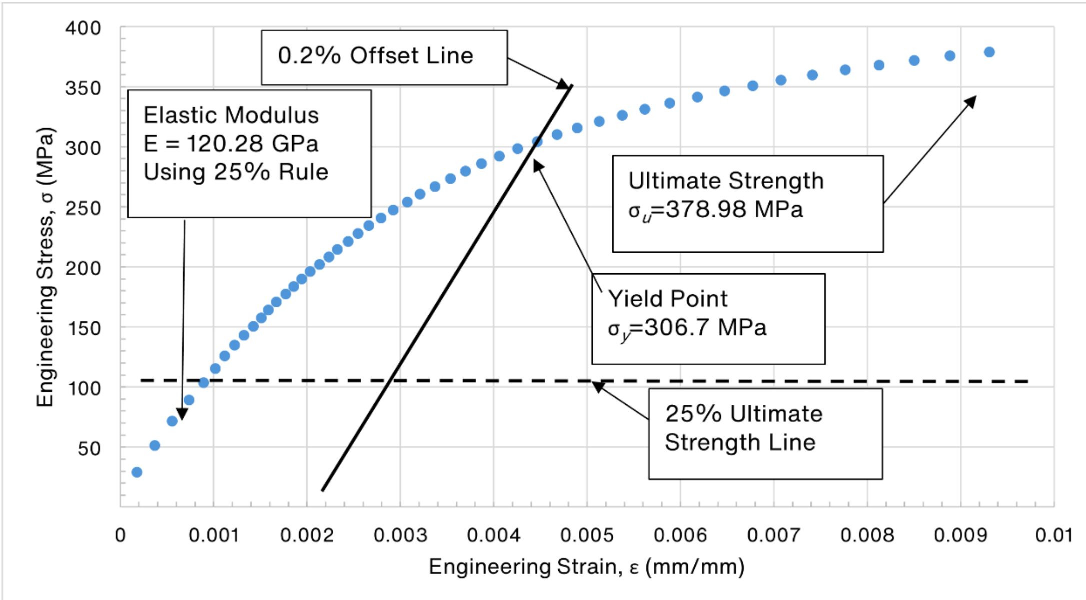


**Figure 7: Engineering Stress and Strain Diagram for Grade 40 Gray Cast Iron (UNS F12801) in Tension**

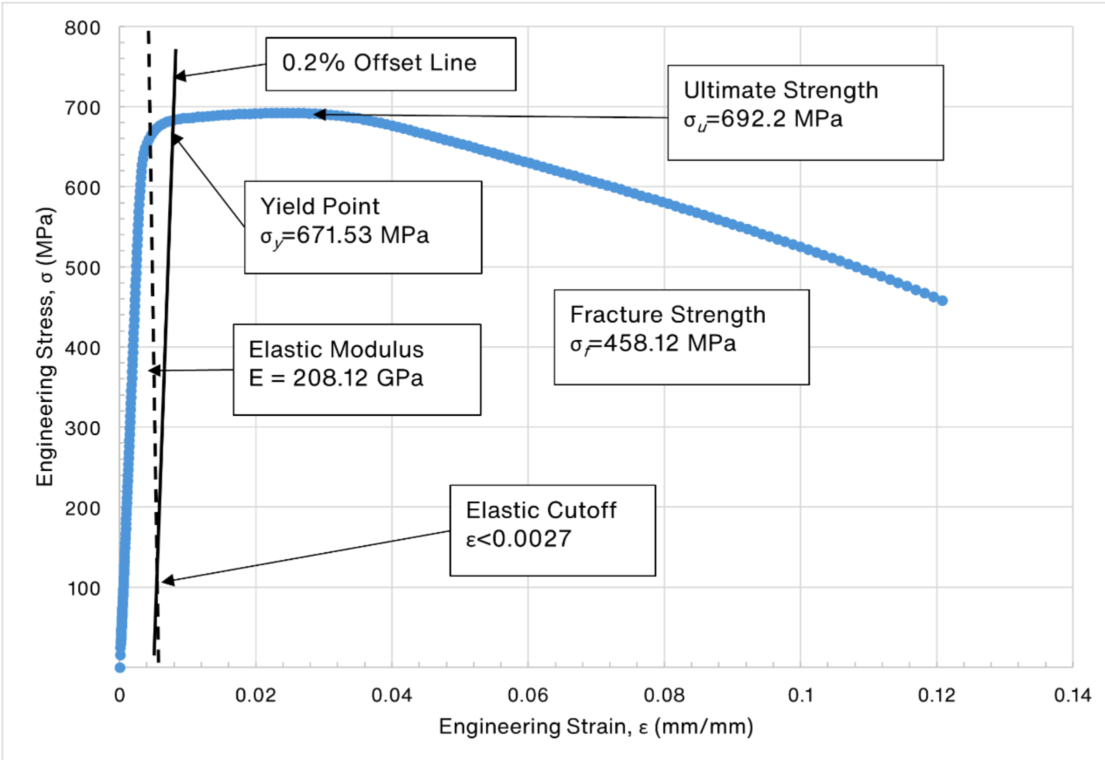


**Figure 8: Engineering Stress and Strain Diagram for Cold Rolled AISI 1018 Steel (UNS G10180) in Tension**

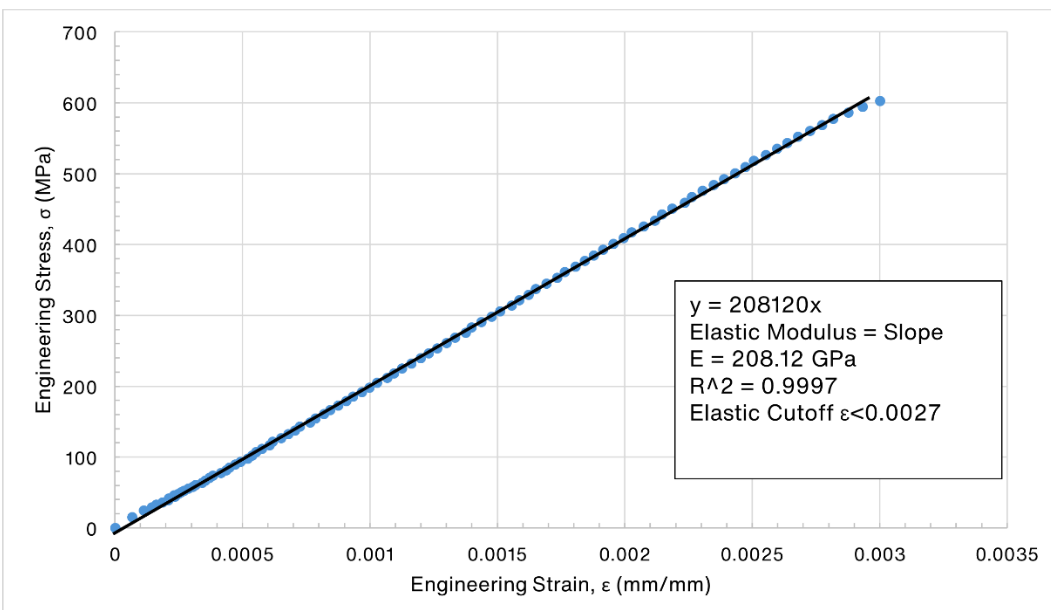


**Figure 9: Elastic Region of Engineering Stress and Strain Diagram for Cold Rolled AISI 1018 Steel (UNS G10180) in Tension**

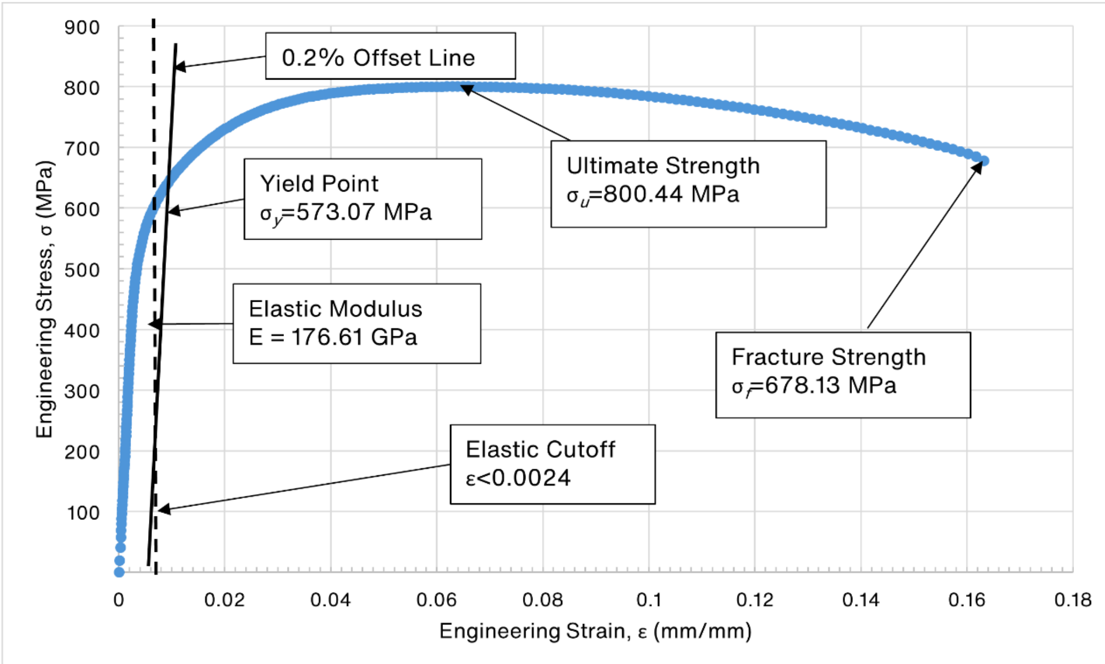


**Figure 10: Engineering Stress and Strain Diagram for Cold Rolled AISI 1045 Steel (UNS G10450) in Tension**

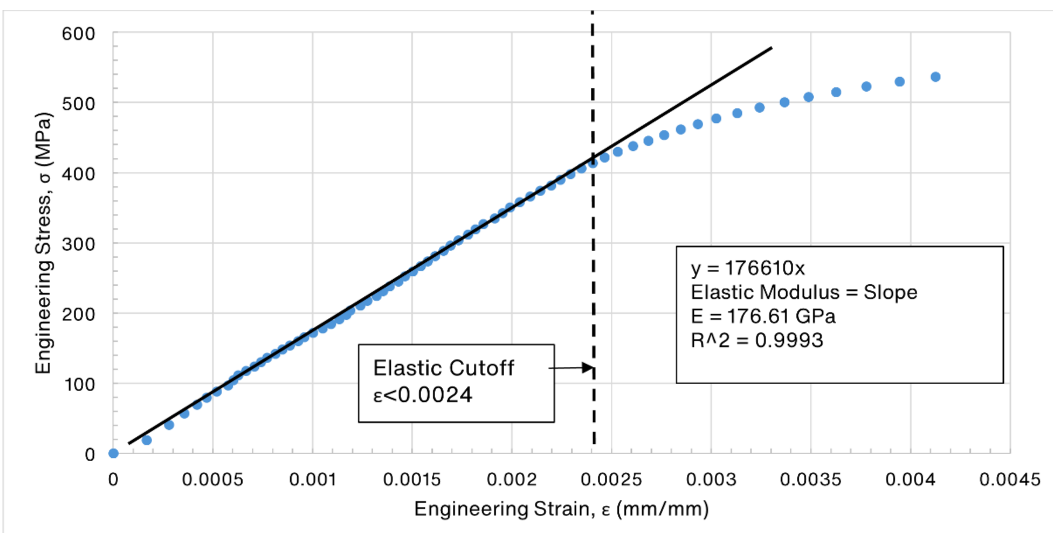


**Figure 11: Elastic Region of Engineering Stress and Strain Diagram for Cold Rolled AISI 1045 Steel (UNS G10450) in Tension**

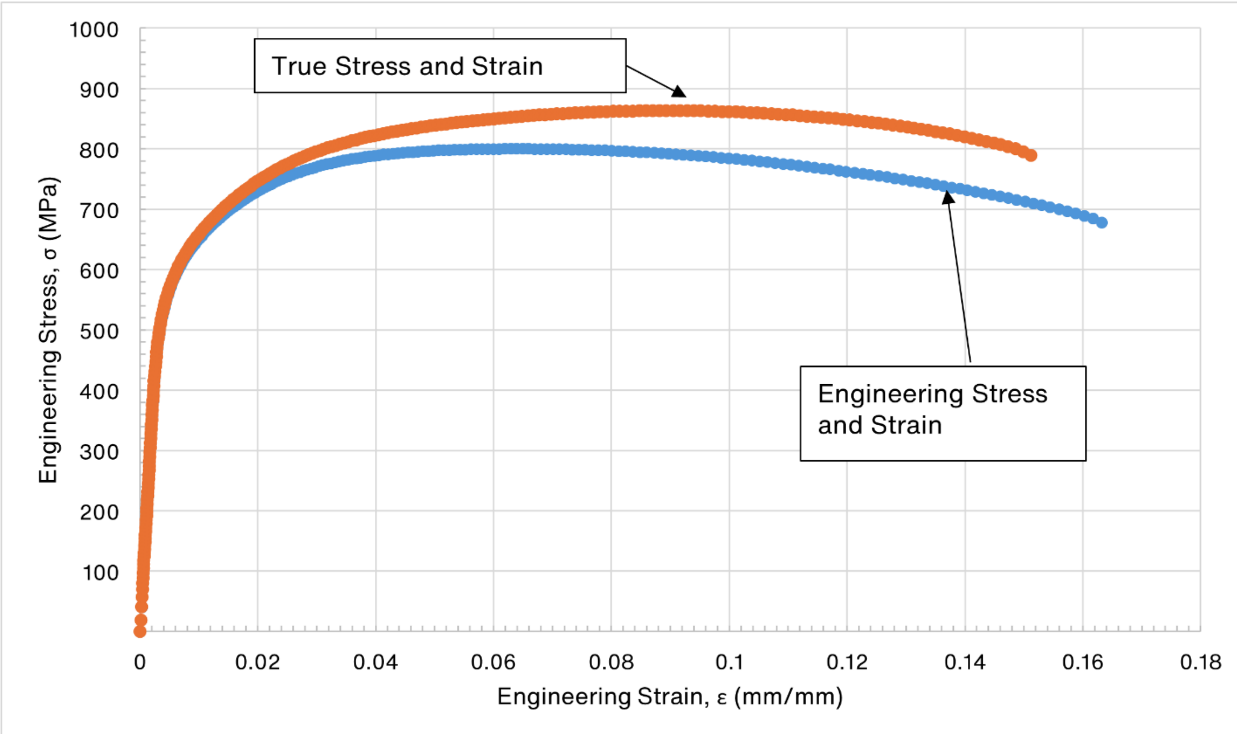


**Figure 12: Diagram of Engineering Stress and Strain Compared with True Stress and Strain for Cold Rolled AISI 1045 Steel (UNS G10450) in Tension**

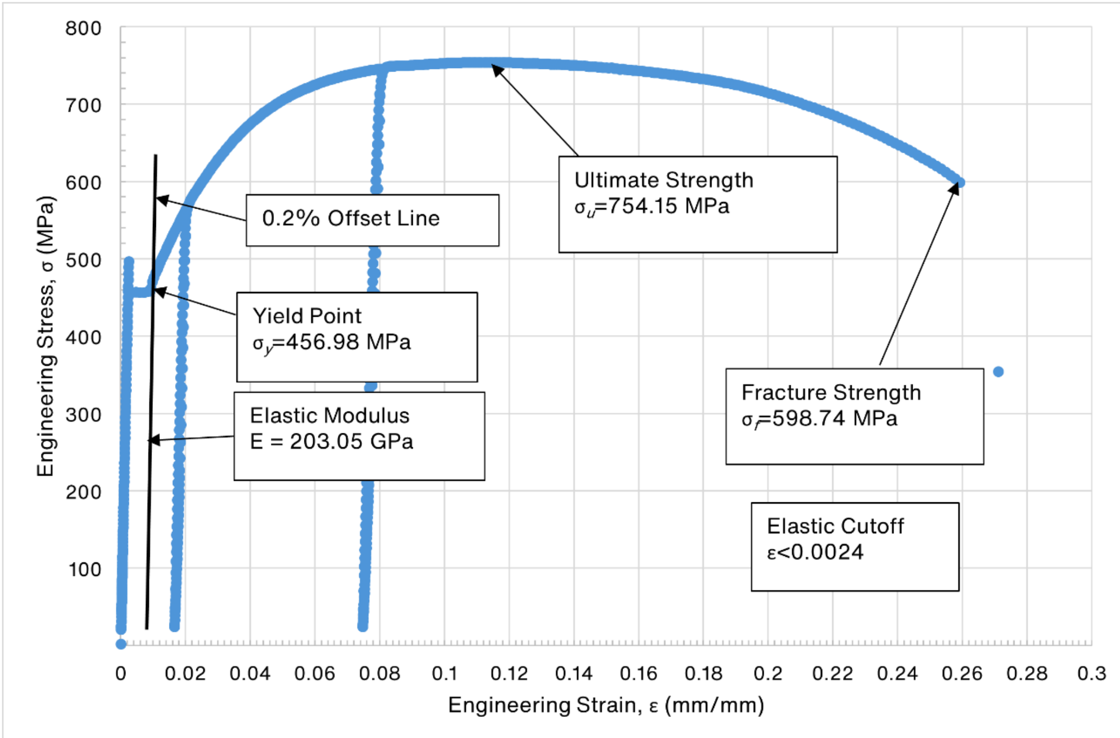


**Figure 13: Engineering Stress and Strain Diagram for AISI 1045 Steel (UNS G10450) with Normalized Heat Treatment in Tension**

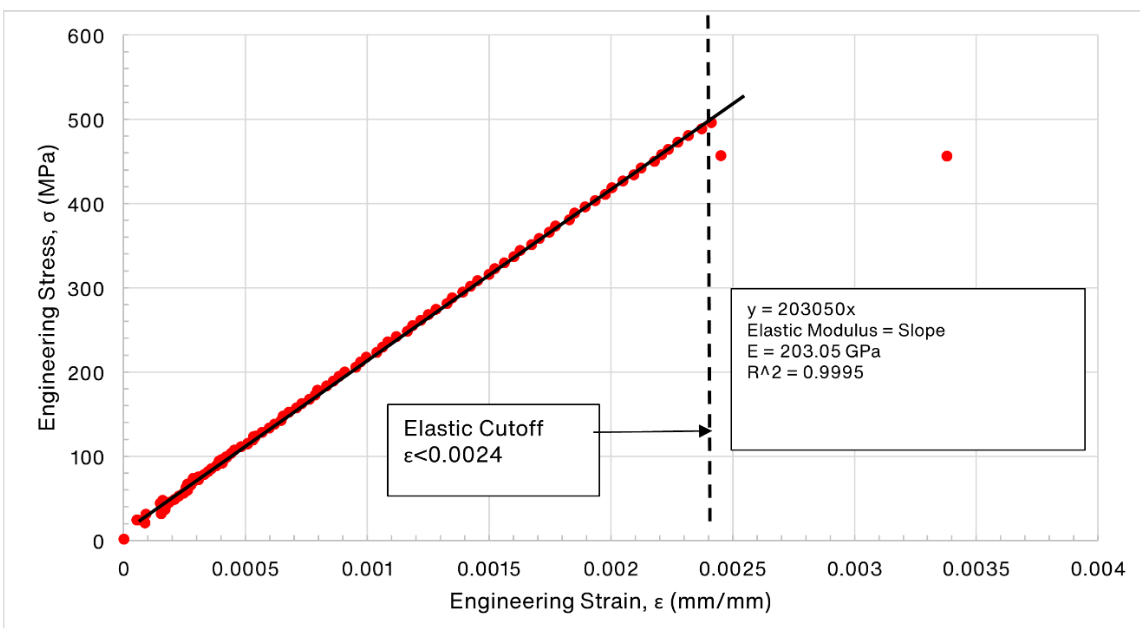


**Figure 14: Elastic Region of Engineering Stress and Strain Diagram for AISI 1045 Steel (UNS G10450) with Normalized Heat Treatment in Tension**

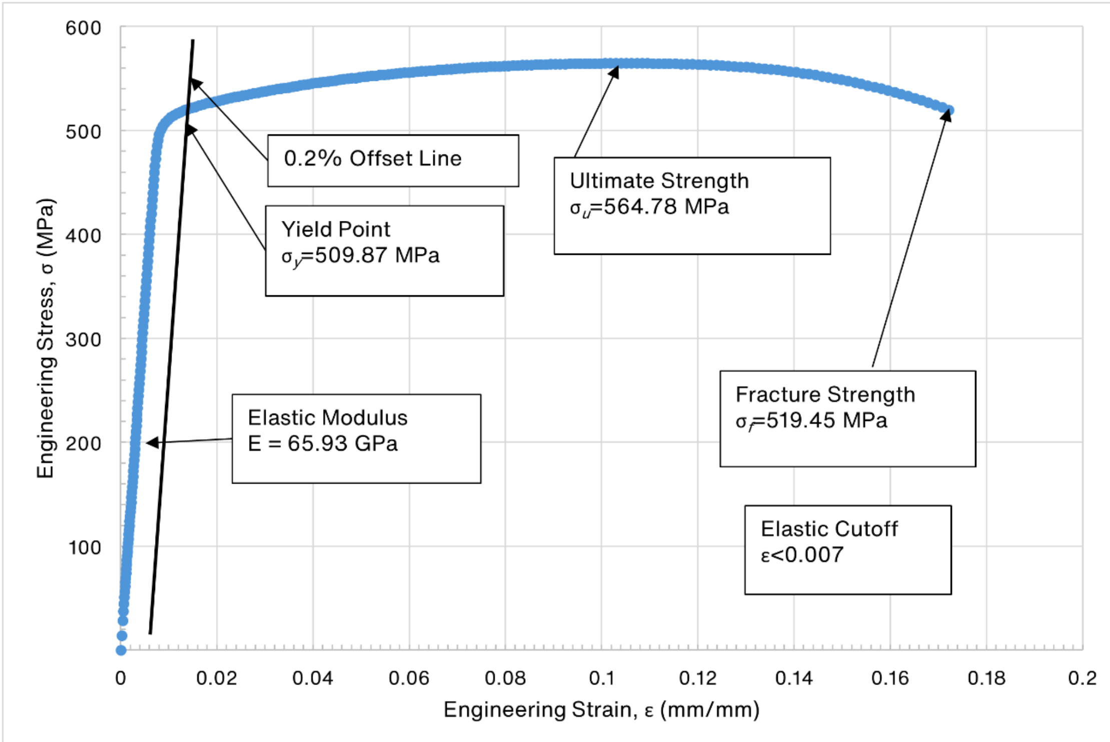


**Figure 15: Engineering Stress and Strain Diagram for 7075-T6 Aluminum (UNS A97075) in Tension**

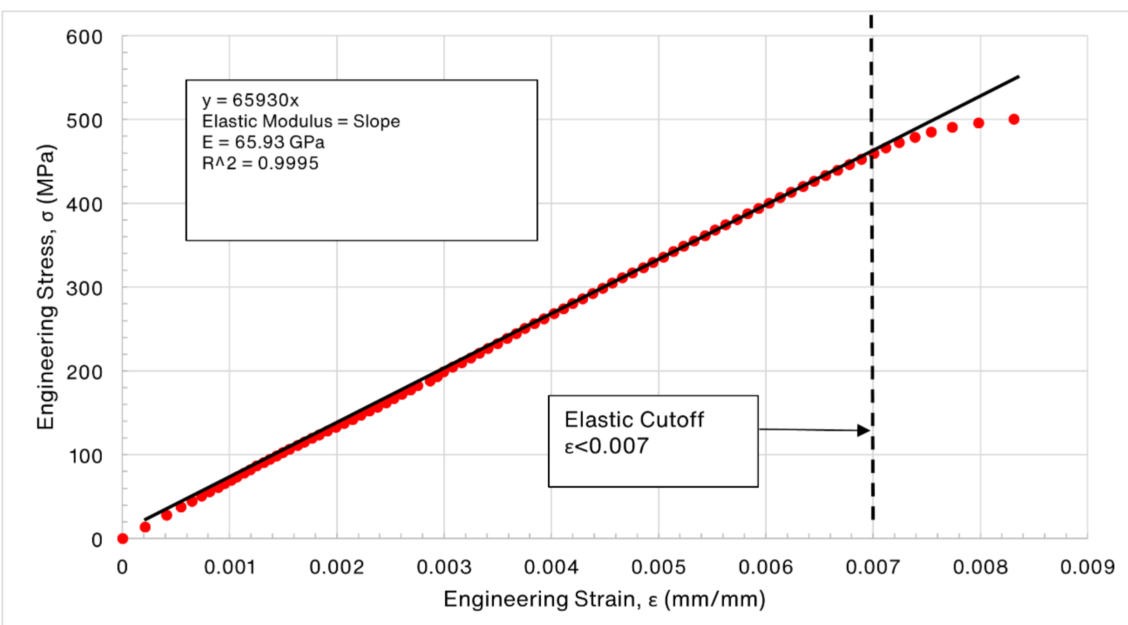


**Figure 16: Elastic Region of Engineering Stress and Strain Diagram for 7075-T6 Aluminum (UNS A97075) in Tension**

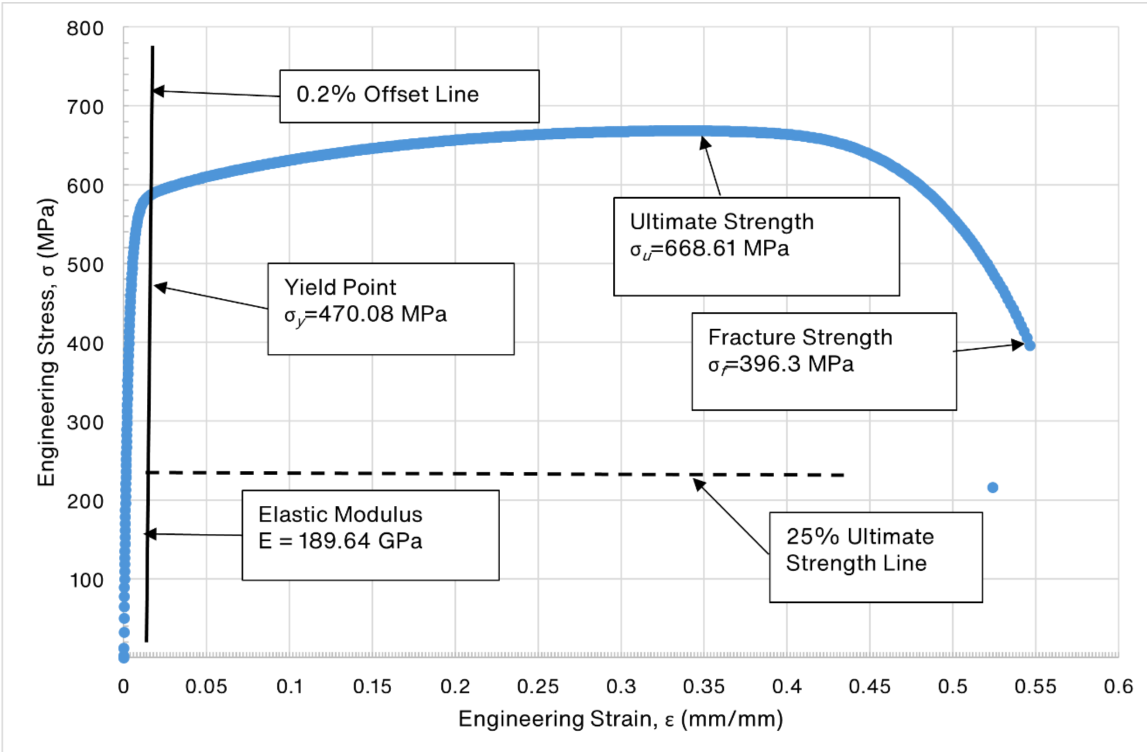


**Figure 17: Engineering Stress and Strain Diagram for SAE 304 Stainless Steel (UNS S30400) in Tension**

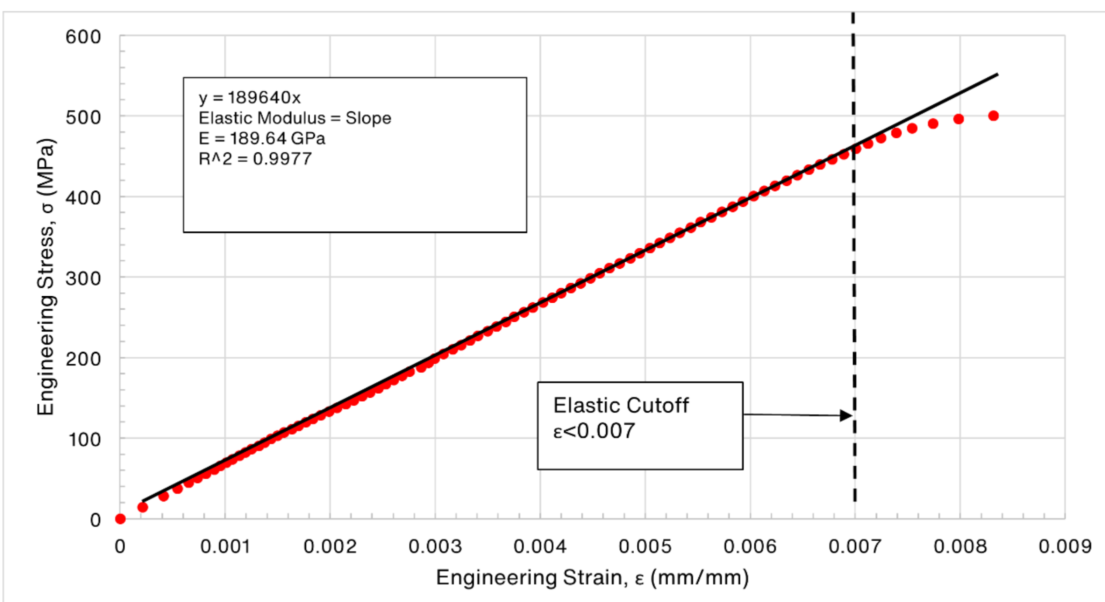


**Figure 18: Elastic Region of Engineering Stress and Strain Diagram for SAE 304 Stainless Steel (UNS S30400) in Tension**

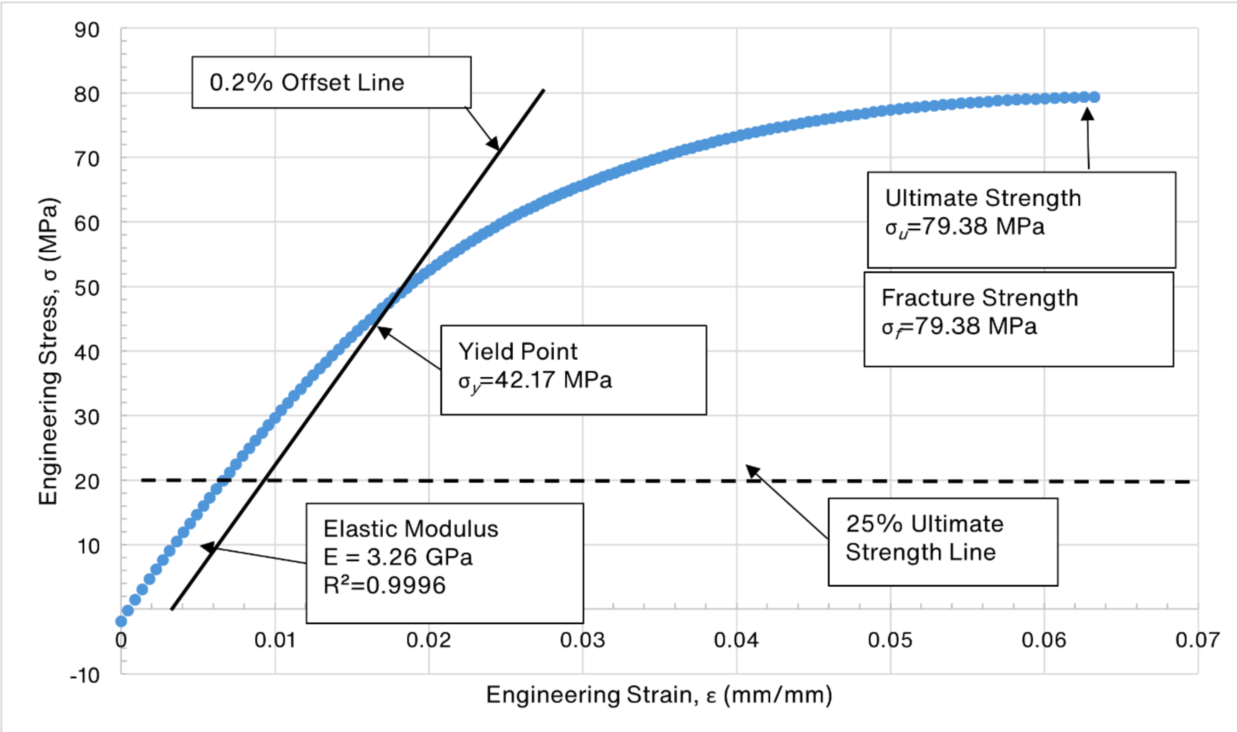


**Figure 19: Elastic Region of Engineering Stress and Strain Diagram for Polymethyl methacrylate (PMMA) in Tension**

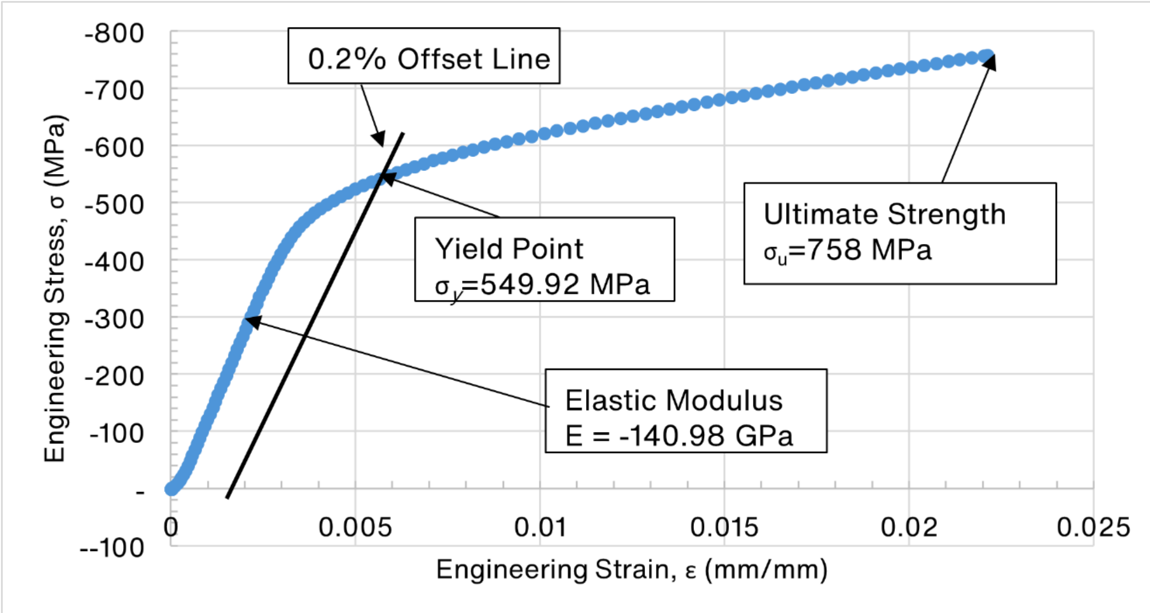


**Figure 20: Engineering Stress and Strain Diagram for Grade 40 Gray Cast Iron (UNS F12801) in Compression**

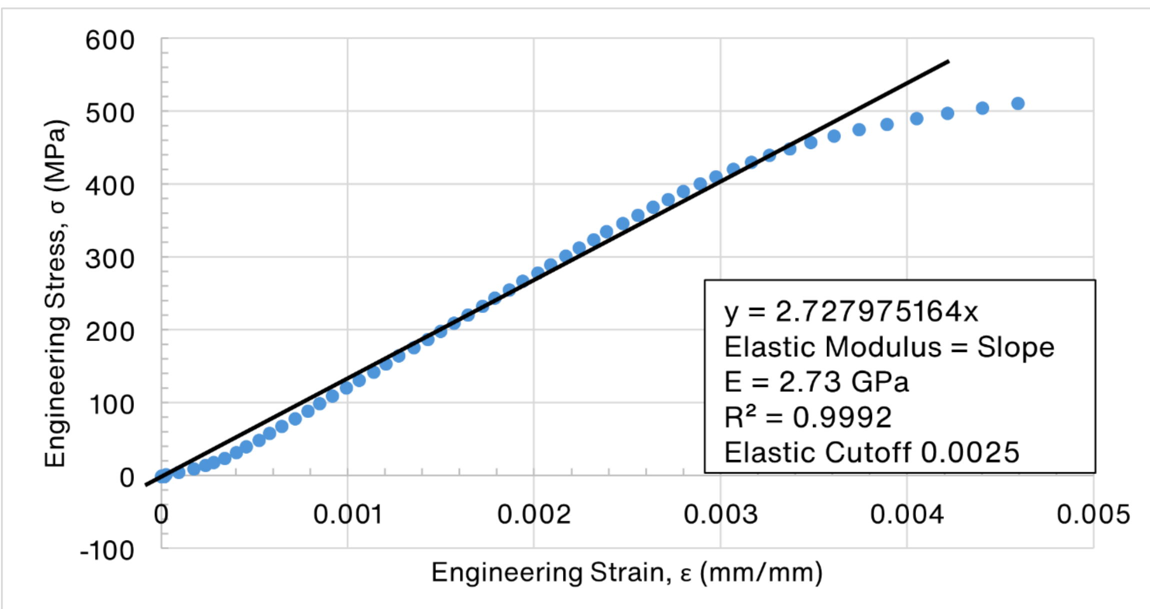


**Figure 21: Elastic Region of Engineering Stress and Strain Diagram for Grade 40 Gray Cast Iron (UNS F12801) in Compression**

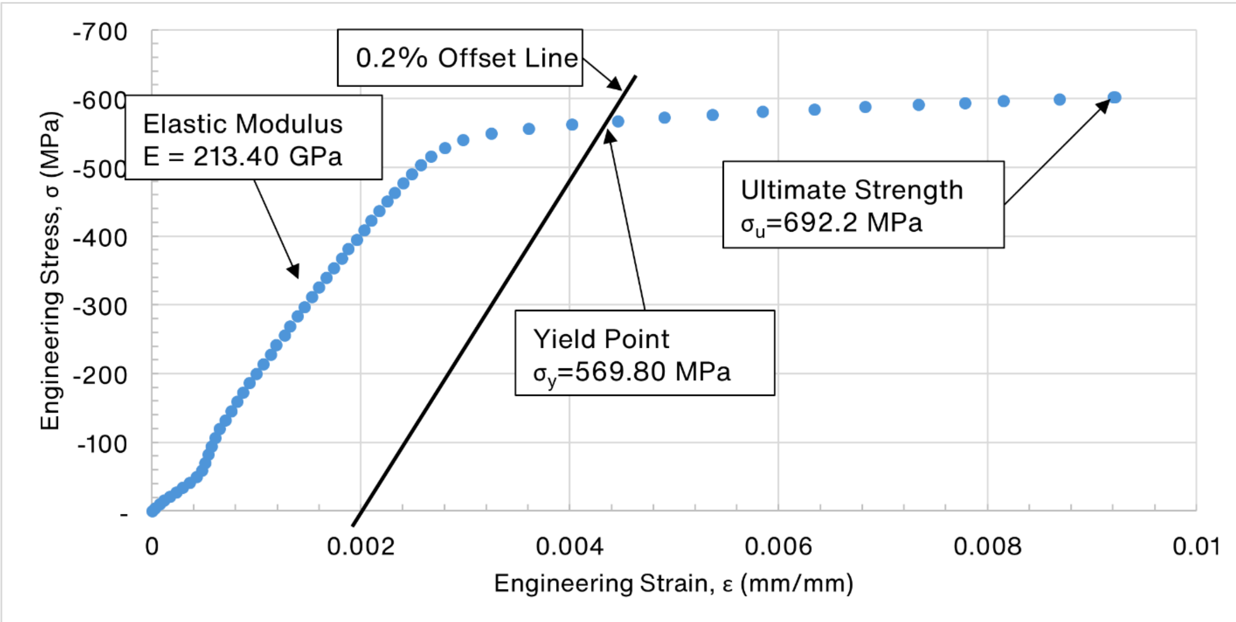


**Figure 22: Engineering Stress and Strain Diagram for Cold Rolled AISI 1018 Steel (UNS G10180) in Compression**

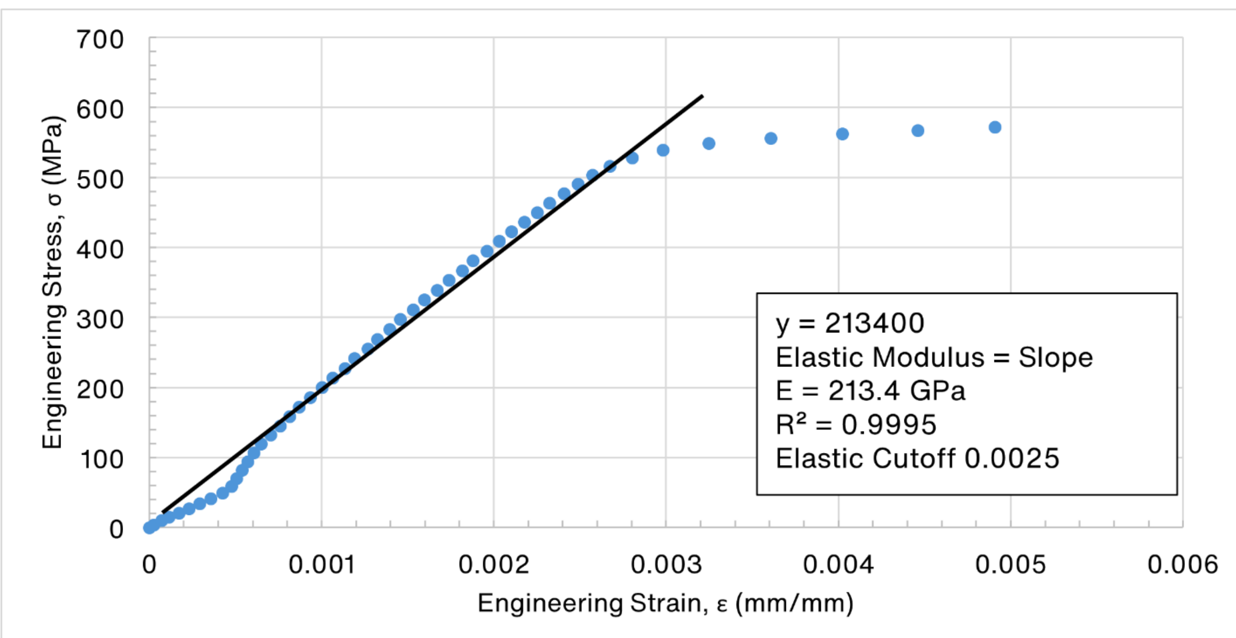


**Figure 23: Elastic Region of Engineering Stress and Strain Diagram for Cold Rolled AISI 1018 Steel (UNS G10180) in Compression**

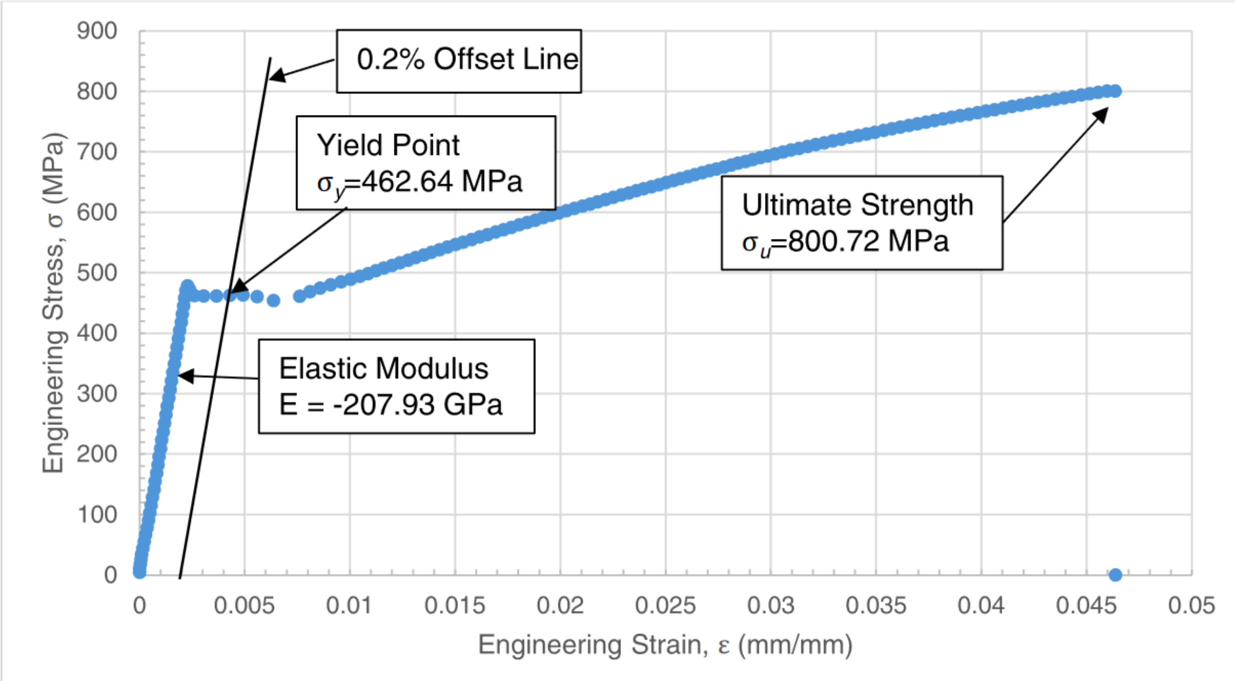


**Figure 24: Engineering Stress and Strain Diagram for AISI 1045 Steel (UNS G10450) with Normalized Heat Treatment in Compression**

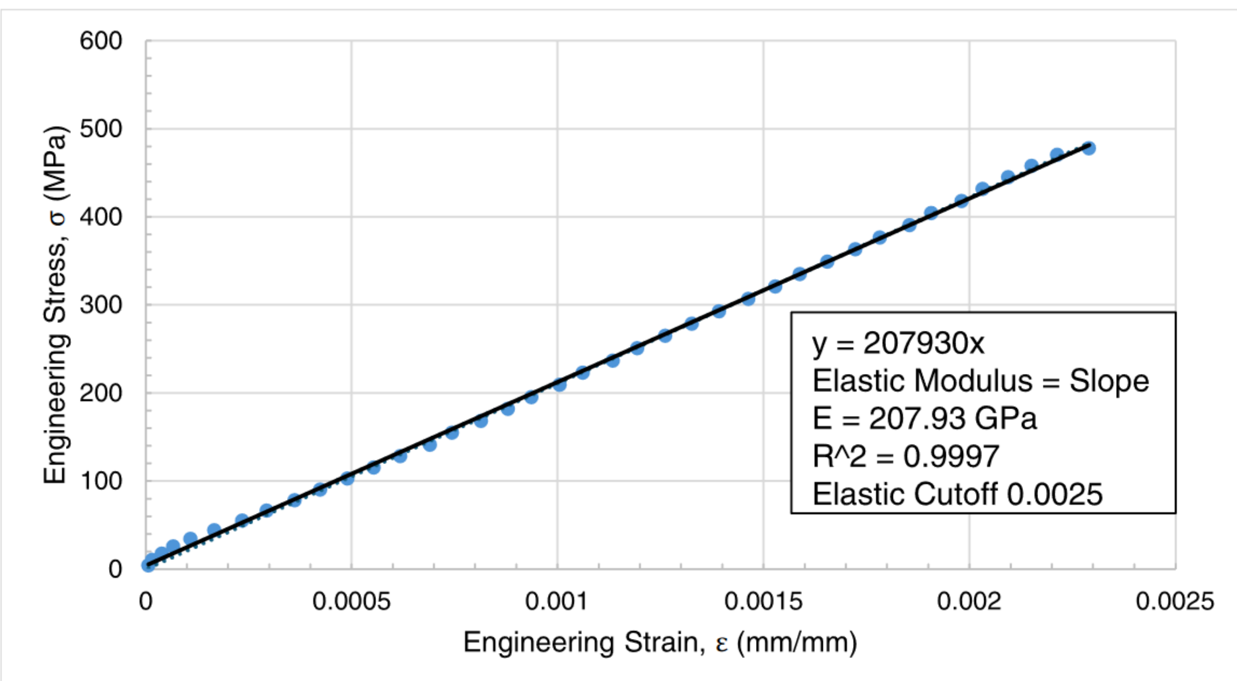


**Figure 25: Elastic Region of Engineering Stress and Strain Diagram for AISI 1045 Steel (UNS G10450) with Normalized Heat Treatment in Compression**

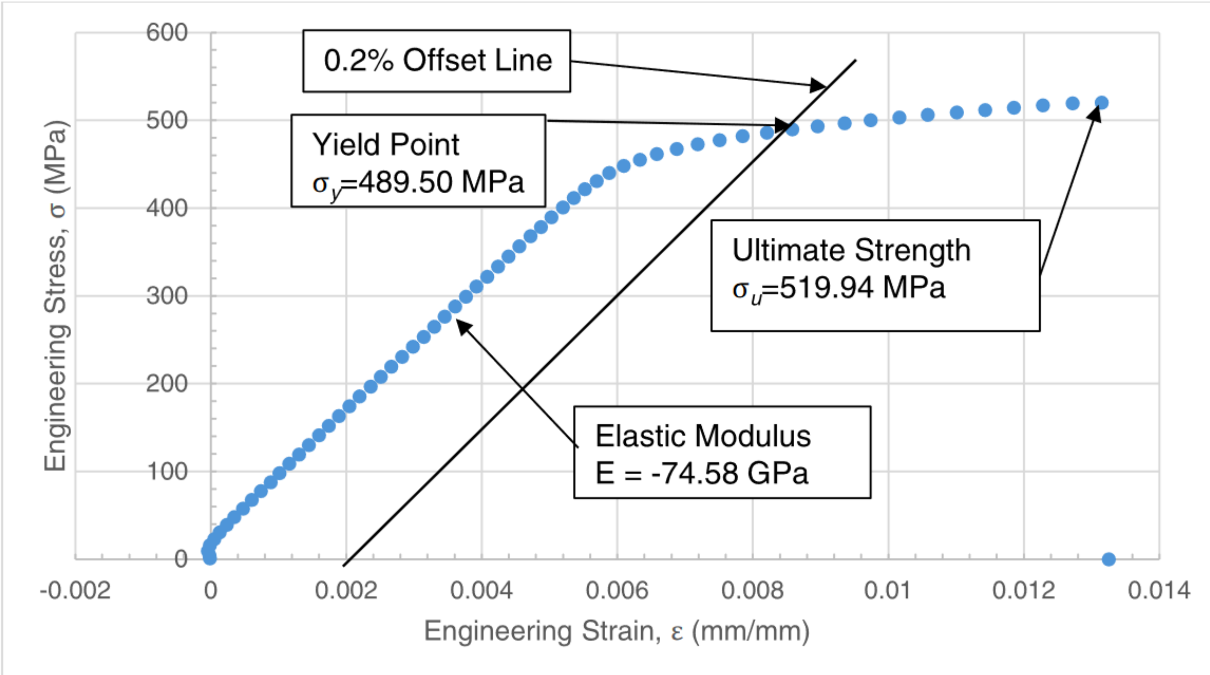


**Figure 26: Engineering Stress and Strain Diagram for 7075-T6 Aluminum Alloy (UNS A97075) in Compression**

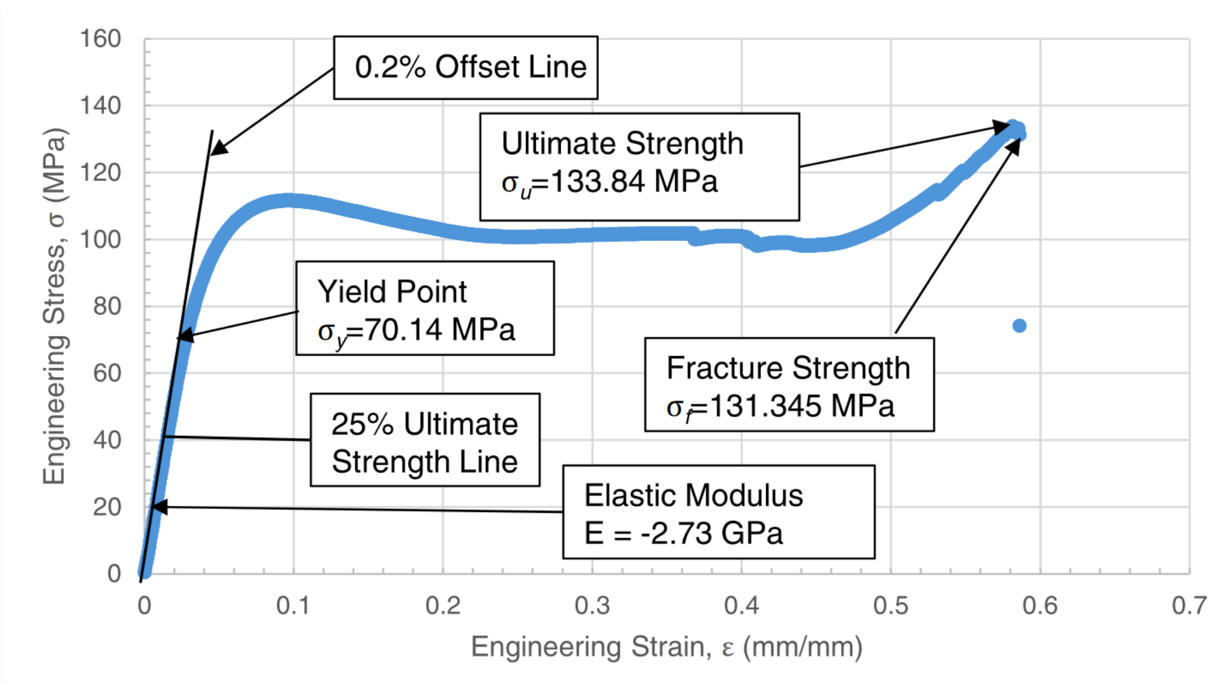


**Figure 27: Engineering Stress and Strain Diagram for Polymethyl Methacrylate (PMMA) in Compression**

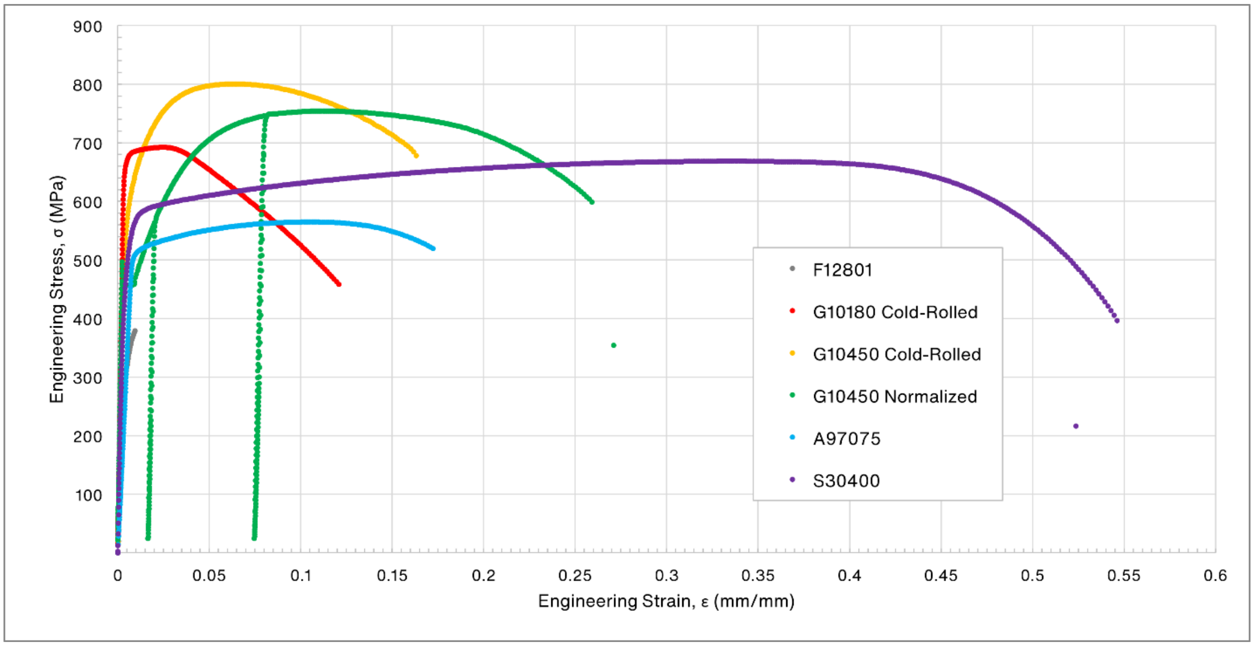


**Figure 28: Engineering Stress and Strain for Class 40 Gray Cast Iron (UNS F12801), AISI 1018 Steel (UNS G10180) Cold Rolled, AISI 1045 Steel (UNS G10450) Cold Rolled, AISI 1045 Steel (UNS G10450) Normalized, 7075 Aluminum Alloy (UNS A97075), SAE 304 Stainless Steel (UNS S30400), and Poly(methyl-methacrylate) in Tension Tests**

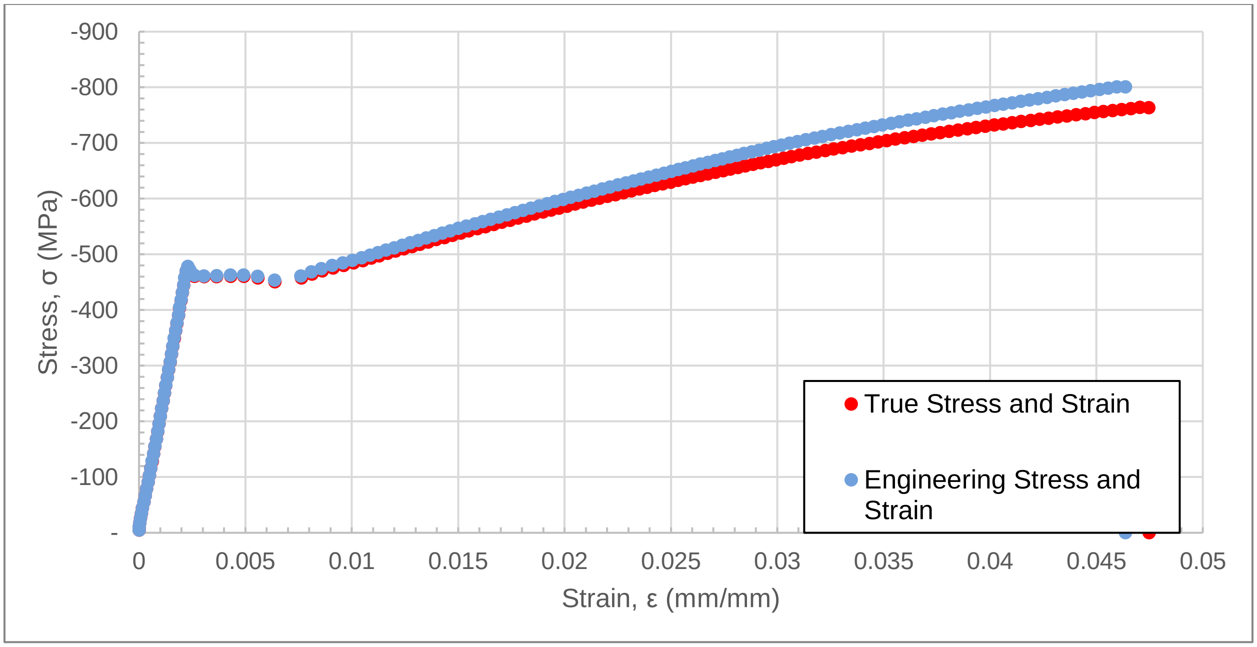


**Figure 29: Diagram of Engineering Stress and Strain Compared with True Stress and Strain for Normalized AISI 1045 Steel (UNS G10450) in Compression**

## A.2 Sample Calculations

### A.2.1 Engineering Stress

Engineering stress is elaborated on in section 1.5, Engineering Stress. To calculate engineering stress, one must obtain the original cross-sectional area and the applied force. The original cross-sectional area was calculated from a diameter measurement made with digital calipers before every test. The applied force is found from the raw test data. A sample calculation is shown for a data point from the compression test of 1045 normalized steel:

$$\sigma = \frac{F}{A_0}, \sigma = \frac{F}{\pi\left(\frac{d}{2}\right)^2} = \frac{2.255\text{kN}}{\pi\left(\frac{12.21\text{mm}}{2}\right)^2} = \mathbf{26.023\ MPa} \tag{1}$$

### A.2.2 True Stress

True stress is elaborated on in section 1.12, True Stress and Strain. A sample calculation is shown for a data point from the compression test of 1045 normalized steel:

$$\sigma_t = \sigma(1+\varepsilon) = 26.023\ \mathrm{MPa}(1+0.0000669) = \mathbf{26.025\ MPa} \tag{2}$$

### A.2.3 True Strain

True strain is elaborated on in section 1.12, True Stress and Strain. A sample calculation is shown for a data point from the compression test of 1045 normalized steel:

$$\varepsilon_t = \ln(1+\varepsilon) = \ln(1-0.04636) = \mathbf{0.04531} \tag{3}$$

### A.2.4 Percent Elongation

Percent elongation is elaborated on in section 1.7, Percent Elongation. The percent elongation is equal to the axial strain at the fracture point. A sample calculation is shown for the tension test of SAE 304 stainless steel:

$$\%EL = \frac{L-L_0}{L_0} \cdot 100\% = \varepsilon_f \cdot 100\% = 0.5463 \cdot 100\% = \mathbf{54.63}\% \tag{4}$$

### A.2.5 Percent Reduction in Area

Percent reduction in area is elaborated on in section 1.8, Percent Area Reduction. The percent area reduction is the percent change in cross-sectional area from before the test and after fracture. The cross-sectional area is calculated from the diameters measured by the digital calipers. A sample calculation is shown for the tension test of normalized AISI 1045 Steel:

$$\%RA = \frac{A - A_0}{A_0} \cdot 100\% = \frac{\left(\left(\frac{d}{2}\right)^2 - \left(\frac{d_0}{2}\right)^2\right)}{\left(\frac{d}{2}\right)^2} = \frac{\left(\left(\frac{5.18\text{ mm}}{2}\right)^2 - \left(\frac{7.19\text{ mm}}{2}\right)^2\right)}{\left(\frac{5.18\text{ mm}}{2}\right)^2} \cdot 100\% = \mathbf{48.21}\% \quad (5)$$

### A.2.6 Curvature Correction for Rockwell Hardness Number

Curvature correction is elaborated on in section 1.11, Hardness Testing. A sample calculation is shown for the hardness test of the tension specimen of gray cast iron:

$$\text{Correction} = 6.5 - 0.05(\text{HRB}) = 6.5 - 0.05(98.4\text{ HRB}) = \mathbf{1.58} \quad (6)$$

### A.2.7 Percent Error

Percent error is elaborated on in section 1.9, Percent error. A sample calculation is shown for the converted Brinell hardness number of 4340 steel:

$$\delta = \left|\frac{v_O - v_E}{v_E}\right| \cdot 100\% = \left|\frac{658\text{-}694.7}{694.7}\right| \times 100\% = \mathbf{5.28}\% \quad (6)$$