# The Effects of Strengthening Mechanisms and Time Rating on the Mechanical Properties of Metals and Polymers Using Tensile Tests

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## Abstract

The objectives of this experiment were to conduct tensile tests for metals and polymers and to illustrate the differences between the mechanical properties of two classes of materials, and more precisely between 1018 cold-rolled and annealed steel and between 1100 pure aluminum and a 6061 aluminum alloy. The experiment also discussed the time-dependence of polymer mechanical properties by examining remolded samples of polyethylene at crosshead speeds of 1, 2, at 0.625 in/min. The machines used for tensile testing were RSL (Digital Displacement Loading Frame) for the metal samples and 4201 INSTRON for the polyethylene samples. Data was collected and stress verses strain curves were plotted for all the samples. The results of the tensile tests showed that the cold rolled steel was stronger and had a higher ultimate tensile strength (474.49MPa) compared to the annealed steel with an ultimate tensile strength of 386.06 MPa. The stress verses strain curve for he annealed steel showed an upper yield stress of 306.0 MPa and a lower yield stress of 292.7 MPa. The tensile tests showed that the 6061 Al alloy had a higher ultimate tensile strength (447.71MPa) compared to the 1100 pure Al with an ultimate tensile strength of 333.15 MPa. The polyethylene sample tested with a crosshead speed of 2 in/min showed the highest yield strength (28.06 MPa) and the smallest young's modulus (0. 372 Gpa) , while the polyethylene sample tested with a crosshead speed of 0.625 in/min showed the lowest yield strength (20.07 MPa) and the largest young's modulus (0.750 Gpa). This experiment suggested that an extensometer is necessary to obtain an accurate result for the young's modules and ductility because it measures the true sample strain rather than measuring the strain of both the sample and the machine.

## Introduction

Materials are frequently chosen for structural applications because they have desirable combinations of mechanical characteristics. Mechanical properties of a material can be determined by a tensile test, which measures how the material will response to an axial force being applied in tension. [1] A tensile specimen is a standardized sample cross-section, which has two shoulders and a gauge section in between. The shoulders are large so they can be readily gripped, whereas the gauge section has a smaller cross-section so that the deformation and failure can occur in this area. The result of such a tensile test is documented as load or force versus elongation, which corresponds to the engineering stress in units of Pascal versus engineering strain (unit less) by the following relationships. [1,2] The engineering stress is defined as the following:

$$\sigma = \frac{F}{A_o} \tag{1}$$

where F is the instantaneous load applied perpendicular to the specimen cross section, in units of newton and $A_o$ is the original cross-sectional area before any load is applied in units of $m^{2.}$

The engineering strain is defined as the following:

$$\varepsilon = \frac{L - L_o}{L_o} \tag{2}$$

where $L_o$ is initial gauge length and L is the instantaneous length.

Properties that are directly measured through stress-strain tensile tests are the ultimate tensile strength (MPa), yield stress (MPa), young’s modulus (GPa), ductility (% strain) and Toughness ($J/m^3$). [1,2] The ultimate tensile stress is the maximum stress on the engineering stress–strain curve, where “necking” begins. This relates to the maximum stress that can be sustained by a structure in tension. The yield stress is the transition from the linear elastic region to the plastic deformation part of the curve, which is commonly determined by the 0.002 strain offset method. [1,2] The young's modulus is the slope of the initial linear part of the curve. ductility is a measure of the degree of plastic deformation that has been sustained at fracture, which is expressed quantitatively as the percent elongation. Toughness is the energy required to fracture a sample, which corresponds to the area under the curve. Figure 1 illustrates how these mechanical properties can be obtained from the engineering stress vs strain curve.

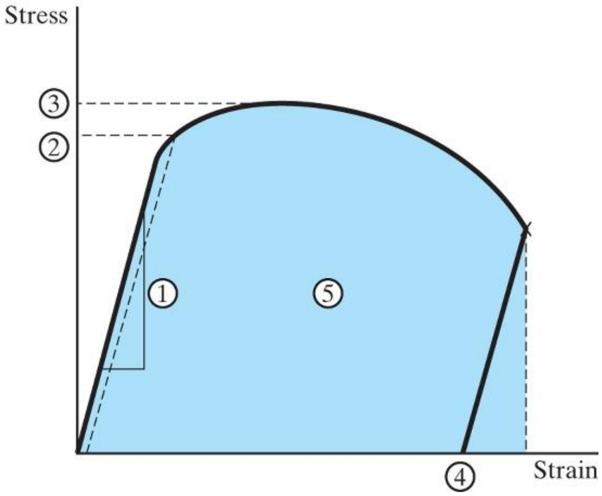


Figure 1. Mechanical properties obtained by the stress vs strain curve include (1) young's modulus (GPa), (2) yield stress (MPa), (3) tensile stress (MPa), (4) ductility (% strain) and (5) toughness (J/m$^3$). [1]

The behavior of materials in response to facture can be classified as ductile and brittle. Different factors including strengthening mechanisms particularly in metals and temperature and time rating particularly in polymers. [2] Strengthening mechanisms in metals include cold rolling, solid solution strengthening and alloying and precipitation hardening. As strength increases, ductility decreases. [1,2,3] Therefore, stronger metals exhibit less ductile behavior. For a polymer, the mechanical properties are time dependent due to its viscoelastic nature. [1,2] If the testing time is larger than the molecular response time, there will be enough time for plastic deformation, which results in a ductile behavior. Therefore, at high testing rate, short time is available for plastic deformation; therefore, the polymeric material will exhibit brittle behavior. [1]

The objectives of this experiment were to conduct tensile tests for metals and polymers and to illustrate the differences between the mechanical properties of two classes of materials, and more precisely between 1018 cold-rolled and annealed steel and between 1100 pure aluminum and a 6061 aluminum alloy. The experiment also discussed the time-dependence of polymer mechanical properties.

## Experimental procedure

In this experiment, the samples examined were a 1018 cold rolled plain carbon steel, a 1018 annealed plain carbon steel, a 1100 pure aluminum (1100 Al), a 6061 precipitation-hardened alloy aluminum (6061 Al) and three remolded samples of polyethylene. The machines used to perform the tensile tests were RSL (Digital Displacement Loading Frame) for the metal samples and 4201 INSTRON for the polyethylene samples. The RSL and 4201 INSTRON software uses a graphical interface combining a unique control of all testing parameters and ease of operation. The experiment was conducted at room temperature and an absolute pressure of 1 atm.

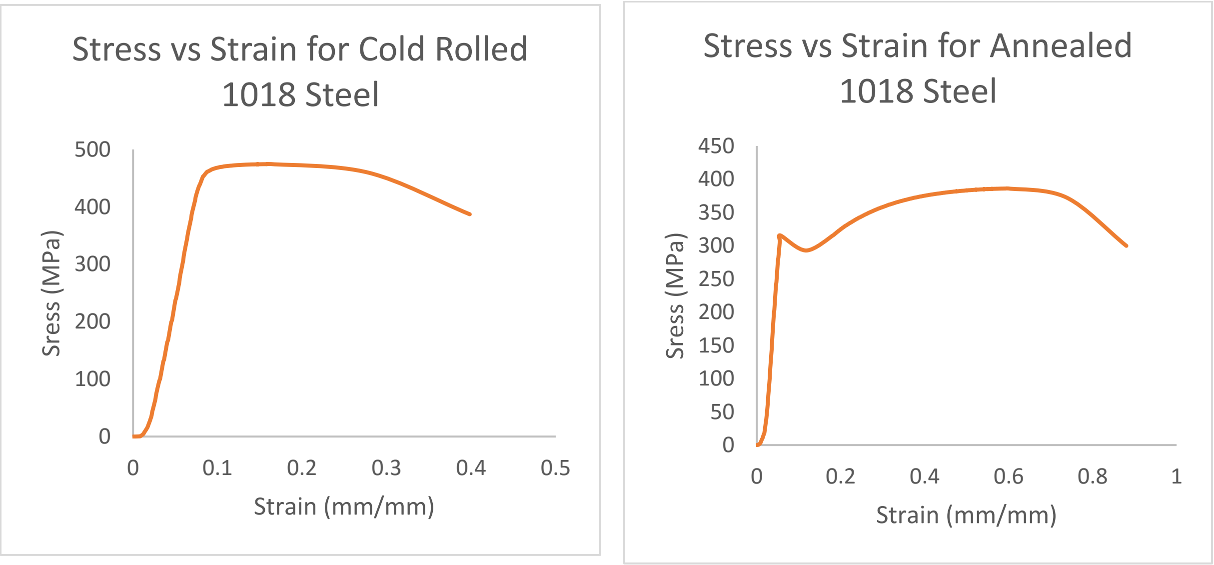
First, each specimen was measured with the micrometer to determine the width of the gauge cross section and the thickness. A gauge length was determined and scribed into the specimen so that the distance between the two marks could be measured after the tensile test was completed. It is worthwhile to note that the samples had a curvature of 10 feet radius in the gauge region. Second, the RSL tensile test machine was programed to run at a fixed crosshead speed for all the tests performed in metals. Each metal sample was clamped into the grips of the RSL. The extensometer was not used because it was broken. The initial gauge length used was 1 inch, which was the distance between attachment points. The test was run until each sample broke. The two broken pieces of the samples were removed and kept for later inspection and measurements. Next, each of the polymer samples was clamped into the grips of the INSTRON tensile tester. An extensometer was not used. The initial gauge length was 2.0 inches. After the sample was mounted, the INSTRON tensile test machine was run to deform and break the sample at a crosshead speed of 1 inch/minute. The test was repeated for the other two polyethylene samples at crosshead speeds of 2 and 0.625 inch/minute

Finally, the data was collected in a txt files for load in pounds and displacement in motor extensions (steps). The conversion factors used to convert motor extensions were 246624 moto extensions per 1 mm for the RSL machine and 630000 motor extensions per 1 cm. The data was gathered into an Excel spreadsheet and then plotted on engineering stress-strain curves to compare the samples and find the mechanical properties.

## Results and Discussion

The average width of the gauge cross sections for all the samples was determined to be 12.45 mm and the average thickness was measured to be 3.10 mm. The values for stress in units of Mpa and strain in units of mm/mm were determined using Equation 1 and Equation 2. The cross sectional area of each sample was calculated by multiplying width by thickness. Strain was found by dividing the crosshead displacement by the initial length. The stress verses strain curves were generated for each sample. To find the young’s modulus, a small portion of the stress-strain curve was plotted to only include the linear region around zero strain. The slope of this portion of the stress-strain curve, representing the young’s modulus, was found by adding a trend line to best fit the data. To find the yield stress, a line was plotted with the modulus of elasticity as the slope, but it was offset 0.002 mm/mm of strain. Ductility was found by multiplying the strain at failure by 100.

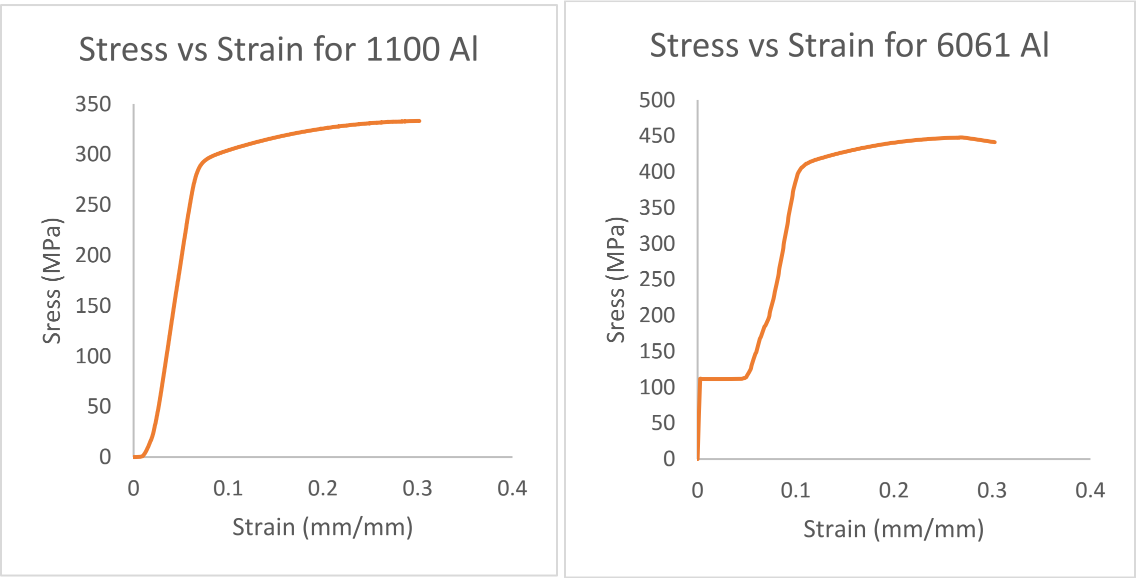
As illustrated in Figure 2, the results of the tensile tests showed that the cold rolled steel was stronger and had a higher ultimate tensile strength (474.49MPa) compared to the annealed steel with an ultimate tensile strength of 386.06 MPa. The stress verses strain curve for he annealed steel showed an upper yield stress of 306.0 MPa and a lower yield stress of 292.7 MPa. The cold rolled steel exhibited a brittle behavior while the annealed steel exhibited a ductile behavior. It was observed that the surface at which the cold rolled steel fractured was jagged and brittle while the surface at which the annealed steel fractured was smooth.



(a) (b)

Figure 2. The stress versus strain curves (a) for the 1018 cold rolled plain carbon steel sample and (b) the 1018 annealed plain carbon steel sample.

The tensile tests showed that the 6061 Al alloy had a higher ultimate tensile strength (447.71MPa) compared to the 1100 pure Al with an ultimate tensile strength of 333.15 MPa. The 6061 Al alloy exhibited a brittle behavior and broke at 45° while the 1100 pure Al exhibited a ductile behavior. The facture surface of the 6061 Al alloy was sharp and stiff while the fracture surface of the 1100 pure Al was smooth. Table 1 summarizes the mechanical properties obtained for the metal samples from their stress verses strain curves.



(a)

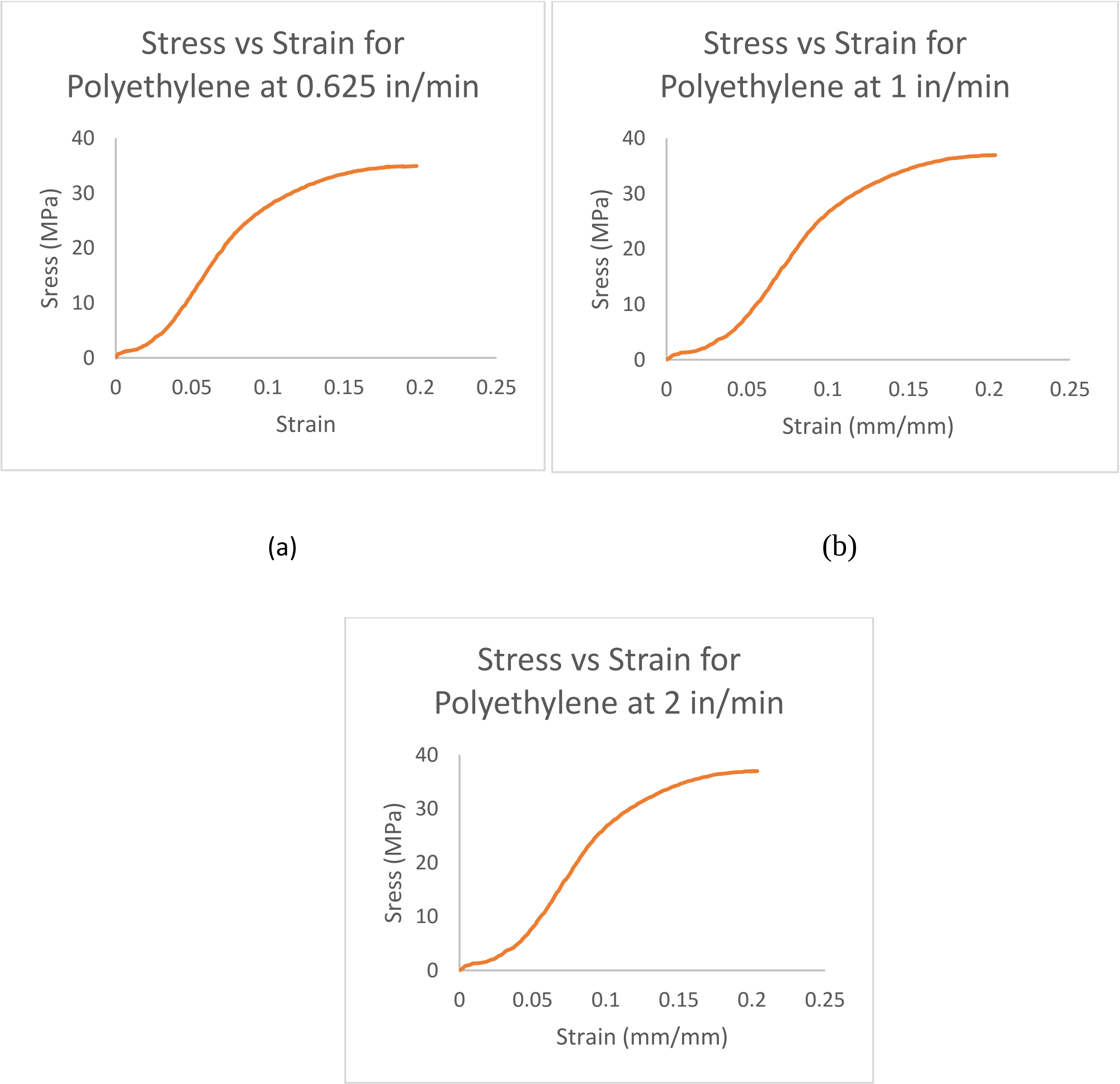
(b)

Figure 3. The stress versus strain curves for the 1100 pure aluminum sample and 6061 precipitation-hardened alloy aluminum sample.

Table 1. Mechanical properties for the metal samples.

| Sample | Young's modules (GPa) | Yield Stress (MPa) | Tensile Stress (MPa) | Ductility (% strain) |
|---|---|---|---|---|
| Cold rolled steel | 7.344 | 419.0 | 474.49 | 29.5 |
| Annealed steel | 8.159 | 306.0 , 292.7 | 386.06 | 70.1 |
| 1100 aluminum | 6.231 | 302.0 | 333.15 | 29.5 |
| 6061 aluminum | 6.521 | 398.2 | 447.71 | 19.0 |

During the tensile tests for the polyethylene samples, it was observed that as the rating time increased, the polymeric material became more brittle and more elastic, as shown in Figure 4. The polyethylene sample tested with a crosshead speed of 2 in/min showed the highest yield strength (28.06 MPa) and the smallest young's modulus (0. 372 Gpa) , while the polyethylene sample tested with a crosshead speed of 0.625 in/min showed the lowest yield strength (20.07 MPa) and the largest young’s modulus (0.750 Gpa). The polyethylene samples were found to relax and shrink after fracture with an increasing order of a decrease in the timing rate. A summary of the mechanical properties for the polyethylene samples can be found in Table 2.



(a) (b)

(c)

Figure 4. The stress versus strain curves for polyethylene samples with crosshead speeds of (a) 0.625 in/min, (b) 1 in/min and (c) 2 in/min.

Table 2. Mechanical properties for the polyethylene samples.

| Sample | Crosshead speed (in/min) | Young’s modules (GPa) | Yield Stress (MPa) | Ductility (% strain) |
|---|---|---|---|---|
| 1 | 0.625 | 0.750 | 20.07 | 35.4 |
| 2 | 1 | 0.652 | 25.07 | 33.1 |
| 3 | 2 | 0.372 | 28.06 | 30.2 |

Elastic deformation in metals is due to the reversible stretching of interatomic bonds. [1] The strain is small due to strong metallic bonds. Plastic deformation in metals is due to irreversible shearing caused by the motion of dislocations on slip planes, which can cause large plastic strains. The upper and lower yield stress points are due to the interaction of C atoms with dislocations. The wired behavior of the 6061 curve can be explained by the hypothesis that the sample may have fractured partially across the cross section before complete failure. [1, 3] The tensile results of the metal samples illustrated two fundamental strengthening mechanisms, which are cold rolling and solution hardening. Annealed sample had a lower ultimate tensile stress because annealing reduce dislocation density. [1,2,3] The higher ultimate stress of the 6061 Al is due to grain boundaries introduced by precipitation as the material is plastically deformed. The introduction of dislocations reduces their motion, and hardens the material. The toughness was estimated to be the largest for the annealed steel while the smallest for the Al alloy. It can be concluded that If a material has high fracture toughness, it will probably undergo ductile fracture. [3]

The literature values of the young’s’ modulus were found to be 69 GPa for both 1100 Al and 6061 Al, 200 GPa for 1018 steel and GPa for polyethylene. [3,4] The literature values of the yield stress were found to be 350 MPa for 1018 steel and 15 MPa for polyethylene. [4] The values of the young’s modulus and ultimate tensile stress determined in the experiment are very different from to the recorded values found in the literature. An extensometer was necessary to obtain an accurate result for the young's modules because it measures the true sample strain rather than measuring the strain of both the sample and the machine. [1,2]

The observations made on polyethylene suggested that polymers are generally capable of absorbing a large amount of energy before failure compared to metals. An amorphous polymer may behave like a glass at high time rating, a rubbery solid at intermediate and a viscous liquid at low time rating. From the results obtained for polyethylene samples, it can be concluded that if the testing time is larger than the molecular response time, there will be enough time for plastic deformation, which results in a ductile behavior. [1,2,3]

## Conclusion

The objectives of this experiment were to conduct tensile tests for metals and polymers and to illustrate the differences between the mechanical properties of two classes of materials, and more precisely between 1018 cold-rolled and annealed steel and between 1100 pure aluminum and a 6061 aluminum alloy. The experiment also discussed the time-dependence of polymer mechanical properties by examining remolded samples of polyethylene at crosshead speeds of 1, 2, at 0.625 in/min. The machines used for tensile testing were RSL (Digital Displacement Loading Frame) for the metal samples and 4201 INSTRON for the polyethylene samples.

Overall, the experiment succeeded in showing the general trends but failed in determining the mechanical properties. The results of the tensile tests showed that the cold rolled steel was stronger and had a higher ultimate tensile strength (474.49MPa) compared to the annealed steel with an ultimate tensile strength of 386.06 MPa.  The stress verses strain curve for he annealed steel showed an upper yield stress of 306.0 MPa and a lower yield stress of 292.7 MPa. The tensile tests showed that the 6061 Al alloy had a higher ultimate tensile strength

(447.71MPa) compared to the 1100 pure Al with an ultimate tensile strength of 333.15 MPa. The polyethylene sample tested with a crosshead speed of 2 in/min showed the highest yield strength (28.06 MPa) and the smallest young's modulus (0. 372 Gpa), while the polyethylene sample tested with a crosshead speed of 0.625 in/min showed the lowest yield strength (20.07 MPa) and the largest young's modulus (0.750 Gpa). There were many factors that can explain why this experiment failed. First of all, the displacement data only included the displacement measured by displacement of the crosshead. The extensometer was unavailable. This caused inaccurate calculations for the young's modulus and ductility. Second, the curvature of 10 feet radius of the metal samples introduced more errors. Third, the software limitations caused inaccurate results. Forth, the tensile tests for two samples of polyethylene failed unexpectedly. The machine stopped even before the failure of the sample when a crosshead speed of 0.625 in/min was used.

Further experiments are needed to determine accurate values for the mechanical properties of these samples. This experiment implied that an extensometer is very critical in determining mechanical properties using tensile testing. [1,3]

## References

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