TIME AND RATE DEPENDENT DEFORMATION

Adolfo Tec, Darren Kong, Jinyu Ni, Jordan Francis, Sonja Davison

19 October 2016

ME108: Mechanical Behavior of Materials

Fall 2016

Prof. Grace O'Connel
TA: Semih Bezci

Introduction:

The mechanical properties of metal do not always suit the needs of engineers so it is important that we understand the mechanical behaviors of other material types. You may want a ductile material that is lightweight, non-corrosive and non-conductive, for applications such as joint replacement. When using a material for such an application you will need to perform tests to evaluate its material properties. Polymers are tested in some of the same ways metals are but their responses are not the same. Materials such as polymers exhibit viscoelastic characteristics. These viscoelastic properties are dependent on the temperature of the material. Polymers are often used at temperatures above the glass temperature because they are tougher and more ductile. By working with polymers below glass temperature the molecules are frozen in place and the sample becomes brittle. At temperatures above the glass region strain-time characteristics are present [2].

The purpose of this lab is to study the mechanical behavior of viscoelastic materials. We will then use the data to compare the measured stress-strain response to what is happening at a molecular level. Polymers like the ones used in our experiment fall into three separate groups, each with their own properties: thermoplastics, thermosetting polymers, and elastomers. Thermoplastics, which are primarily composed of non cross-linked chains, are generally low strength and low modulus. Thermoplastics can also be melted down and reformed. We used ultrahigh molecular weight polyethylene (UHMWPE), a thermoplastic, to perform several different testing modalities while observing the stress-strain relationship. We could see changes in the stress strain curve as the samples were loaded. These changes were caused by what was happening to the molecules that make up the polymer. As the samples were pulled, the polymer chains began to overcome their secondary bonds letting the piece elongate. The chains continue to slide past one another until they are fully extended and finally break [1].

We were particularly interested in seeing the stress strain curve and stress relaxation of the UHMWPE. We applied strain at a constant rate until the sample broke to get a stress strain curve and for stress relaxation, we pulled the material to a length and held constant for a period of time. Stress relaxation is a time dependent characteristic. In applying the tensile test we observed a high amount of elongation in the sample before failure. This was caused by the chains beginning to slide past one another until they were all aligned. From these tests we were able to see how the strain rate changed the materials properties during testing. We also only performed one test at each of the conditions so it is hard to gauge if human error caused problems in our results.

Theory:

In this lab, we establish the unique mechanical properties that are exhibited by polymers under tensile loading. We limit our tests to only thermoplastic materials and examine our material under tensile loading. In performing this test, we wish to understand how a polymer's microstructure affects its viscoelastic properties and in turn how those properties change a polymer's mechanical behavior.

Polymers are macromolecules composed of long-chain molecules of carbon-carbon bonds which are folded together [1]. Thermoplastics have long coiled chains that have no cross networking in the coils which gives them relatively low-strength, high ductility and a low-modulus [3]. Being formed from these chains allows the thermoplastics to display its viscoelastic properties. The ability of these chains to be pulled and stretched give polymers to react viscoelastically which is dependent on its rate of strain and temperature. So by adjusting the temperature or strain rate we can cause a ductile or brittle fracture in our samples.

In tensile testing metals can rarely reach strain values over 50 percent during tensile loading. In contrast to this, thermoplastics can reach values of over 100 percent due to its chain molecules. As the stress is applied to the sample the coiled chains can begin to unravel into long strands. However, the stretching of the chains require time in order to separate which means that the strain of thermoplastics is directly related to the rate of strain [3]. A lower rate of strain gives the polymer more time to stretch and orient itself allowing it to reach high percentage of elongation. On the other hand, if you load a test sample with a rapid strain rate, the chains will not have time to elongate giving it a brittle fracture. In our test, we will perform a tensile loading with various strain rates in order to see how polymer's deformation behavior is dependent on time and its viscoelastic properties.

An additional property that a polymer's microstructure allows that does not occur in metals is stress relaxation. Stress relaxation refers to the decrease of stress needed in order to have a constant strain in the material. This phenomena arises because after the linear coils have been stretched to a point, they restructure themselves over time. The chains begin to break and reconnect making secondary bonds which allow the material to adjust to the strain [3]. The amount of stress relaxation allowed in a material is also very dependent on the rate it was elongated at. The stress relaxation can be modeled using a Maxwell model which is shown in eq.1 and also in fig.1 where σ is the stress after some time t, σ_0 is the steady state stress, and τ is the relaxation time of the material, defined as $\tau \equiv \frac{\eta}{E}$ where E and η are material properties of the polymer. In our lab, we will strain our samples with varying strain rates and address how strain rates will affect the amount of stress relaxation that occurs.

$$\sigma = \sigma_0 + \sigma_1 e^{(-t/\tau_1)} + \sigma_2 e^{(-t/\tau_2)} \quad (1)$$

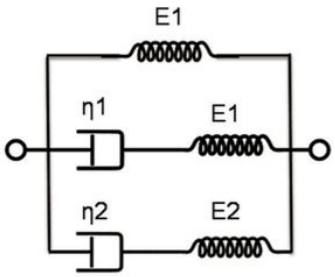

Figure 1. Maxwell Model characterized by a second-order exponential decay function

Experimental Procedures:

The samples for uniaxial tensile loading and stress-relaxation testing were UHMWPE. There were six samples in total, three of which were for uniaxial tensile loading, and the other three were for stress-relaxation. An INSTRON testing machine was used for both tests.

To start the experiments, all six samples' width and thickness were measured. For the uniaxial tensile loading test, we opened and selected the polymer tensile test program and inputted the dimensions of the sample and the loading speed into the program. Next, we loaded the sample into the fixture by tighten the grips on both ends of the sample. However, when we tightened the top end of the sample, we held on the handle while tightening up the top grip because UHMWPE was easy to deflect. If we did not hold the handle to tighten the grip, it would apply shear stress to the sample, which would create some errors in the result. Then, the load and strain on the control panel were set to zero and we pressed "Start" on the software to start the experiment [3]. After that, we watched the sample and waited until it failed, and we collected and saved the data. Finally, we removed the fractured sample from the fixture and used the return button on the INSTRON control panel to return the fixture back to the starting position.

The stress relaxation test was a similar process to the uniaxial tensile loading test in regards to the loading and unloading processes, but the program used for the test was different. Additionally, the test was stopped after the sample had been held for 10 minutes, instead of after failure.

Results:

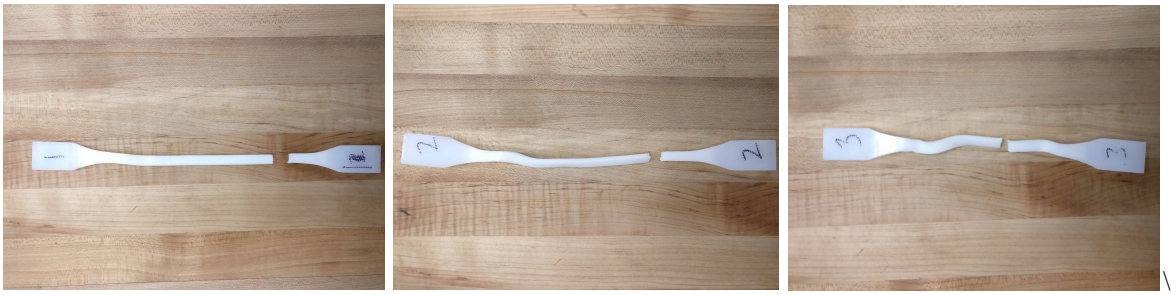

Figure 2. Photographs of the ruptured samples under different testing conditions

The three tested samples were all fractured at different times depending on the testing condition (i.e. the strain rate at which the samples were tested at). Given sample one experienced the slowest strain rate (15 mm/min), we can see that as the strain rate increased, the elongation became smaller and the deformation became more evident.

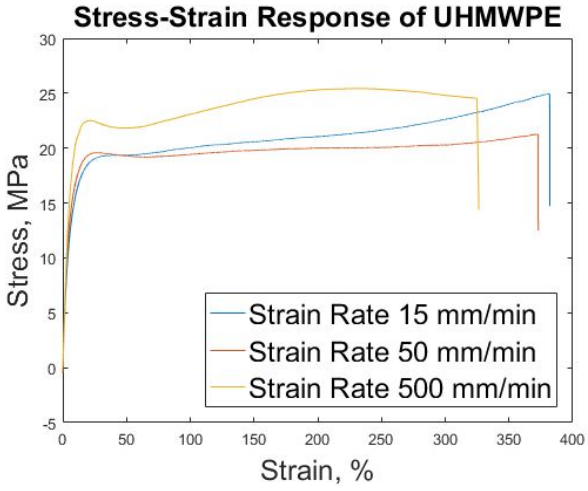

Figure 3. Stress-Strain Response of UHMWPE under different testing conditions

From analyzing the engineering stress-strain response for each sample, we found that for an extension speed of 15, 50, and 500 mm/min, rupture occurred at 14.6, 4.26, and 0.37 min, respectively. The ruptures are represented by the sharp drops in each curve. The stress-strain response confirms the strain rate-elongation relationship observed during the experiment. From figure 2, we can see that no significant necking occurred, as the sample was uniformly stretched until rupture.

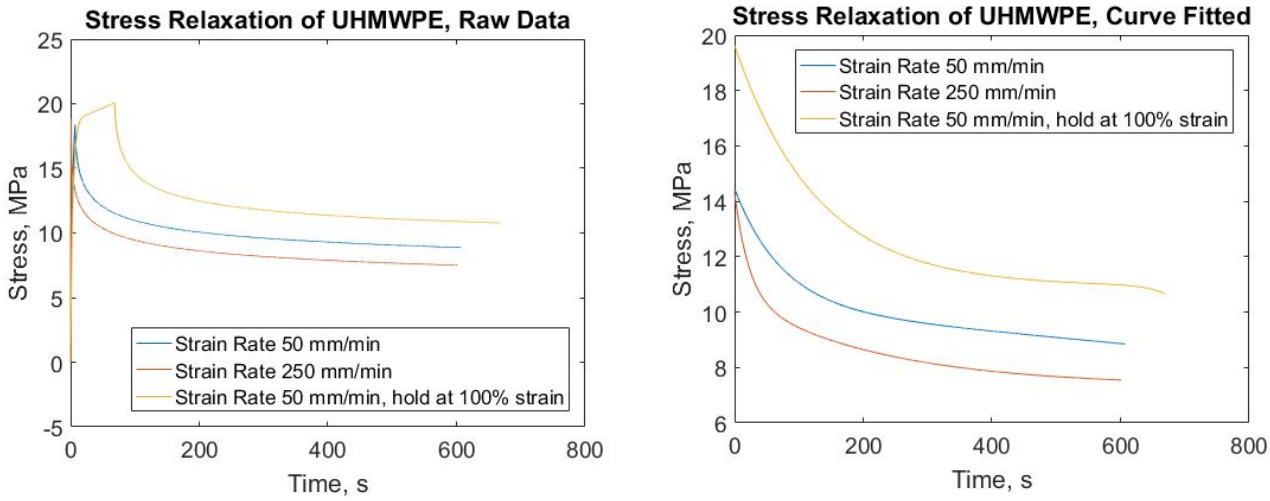

Figure 4. Stress-relaxation curve before and after curve fitting experimental data to the Maxwell model

After using the least square method to curve-fit the experimental data to a generalized Maxwell model of second order form, the relaxation parameters that characterize each sample's curve were found, as depicted in Table 1. From figure 4, we see that the higher the preload strain rate, the faster the stress decreased. when a sample was held at 100% strain, we see that the initial starting stress increased by about 35% as compared to when it was not held at 100% strain.

Testing Condition	Maxwell Model Equation
Strain Rate 50 mm/min	$\sigma = -8674.2 + 4.299e^{(-t/73.931)} + 8684.3e^{(-t/4022100)}$
Strain Rate 250 mm/min	$\sigma = 7.3314 + 3.7746e^{(-t/22.2481)} + 3.2406e^{(-t/221.468)}$
Strain Rate 50 mm/min, hold at 100% Strain	$\sigma = 10.9327 + 7.6171e^{(-t/153.1215)} + 0$

Table 1. Relaxation parameters for Maxwell's model under different testing conditions

Discussion:

The pictures of failed samples from the tensile tests show that the sample loaded at 15 mm/min experienced the largest elongation at fracture, followed by the sample loaded at 50 mm/min, and finally, the sample loaded at 500 mm/min. This follows the expected behavior from theory. Additionally, we note that the sample loaded at 500 mm/min shows the greatest amount of curling after fracture, while the sample loaded at 15 mm/min showed the least. More curious are the ultimate tensile strengths found for each of the materials. We would expect that increasing strain rate would result in a higher ultimate tensile strength for this material. However, the stress-strain response of the sample loaded at 15 mm/min does not follow this trend, and demonstrates highly irregular behavior after yielding. After about 200% strain, the sample experiences a large increase in stress, which is uncharacteristic for a rate of loading this slow. The results from our stress-relaxation tests are in agreement with theory. The sample loaded to 1.5kN at 50 mm/min shows a similar, but slightly slower relaxation response when compared to the sample loaded at the faster rate of 250 mm/min. Additionally, the sample loaded to 100% strain shows a higher initial stress than the other two samples, but a similar relaxation curve.

The failure modes of samples from our tensile tests are in keeping with theory. Because of the slower strain rate, the sample loaded at 15 mm/min experiences the largest elongation at break. This is due to the fact that when a sample of UHMWPE is stretched slowly, the molecular chains comprising it have adequate time to uncoil, and slide along each other. This allows the overall length of the sample to increase. When loaded quickly, the chains do not have time to uncoil, and as a result, remain tangled and short. The sample loaded at 15 mm/min also experienced the least curling after fracture because much of

the residual energy that would have been present in samples with a faster loading rate was instead used to align the molecular chains. In the sample loaded at 500 mm/min, this residual stress and energy is still present, and is released at fracture, resulting in the curling behavior observed. The ultimate tensile strength observed for the sample loaded at 15 mm/min does not follow the expected results, and appears to be higher than the UTS for the sample loaded at 500 mm/min. Generally, we would expect that a sample loaded at a faster rate would have a higher UTS because molecular chains remain tangled and difficult to break. The results from the stress relaxation test are as expected. Among the samples loaded to 1.5kN, the sample loaded at the faster rate shows a slightly faster relaxation response. This is because the sample loaded slowly has had time to uncoil its molecular chains, while the sample loaded quickly has not. Therefore, the sample loaded slowly will take longer to recoil these molecular chains, resulting in a longer stress relaxation time.

Some possible sources of error that could have led to the high UTS observed in the tensile test sample loaded at 15 mm/min include error in measurement of the sample's dimensions or defects in the sample itself. The sample loaded at 15 mm/min is the only sample which had a noticeably higher thickness than the others (6.47 mm compared to an average of 6.36 mm for other samples.) This deviation could be the result of improperly measuring this sample, or could be indicative of a defective sample. Additionally, the sample could have also contained random defects which affected the stress-strain behavior.

Conclusion:

This lab investigated the effect of strain rate on the stress-strain response of polymers. In general, polymers loaded at a faster rate will experience a smaller elongation at break, a higher ultimate tensile strength, and will fracture less cleanly than a sample loaded slowly. Additionally, a sample loaded quickly will experience a faster stress-relaxation than a sample loaded slowly. Both of these results are due to the uncoiling of molecular chains that occurs during slower loading. These results show the importance of considering the expected strain rate when selecting a polymer for use in a given application.

Appendix A: References

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

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

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

Appendix B: MATLAB Code

```
%% Stress-Strain for Different Loading Conditions
% Column 1 = time (s)
% Column 2 = Extension (mm)
% Column 3 = Load (N)
% Column 4 = Tensile Strain (Extension %)
% (1,5) = Rate (mm/min)
% (1,6) = Length (mm)
% (1,7) = Thickness (mm)
% (1,8) = Width (mm)
% (1,9) = Area (mm^2)

figure
for i = 1:3
   data = csvread(['RawData_' num2str(i) '.csv']);
   time = data(:,1); % s
   t = time(end)/60 % Fracture time
   rate = data(1,5);
   stress = data(:,3)/data(1,9); %MPa
   strain = data(:,4); % Extension Percent
   plot(strain, stress); hold on;
   legendInfo{i} = ['Strain Rate ' num2str(rate) ' mm/min'];
end

xlabel('Strain, %'); ylabel('Stress, MPa'); title('Stress-Strain Response of UHMWPE');
legend(legendInfo)
```

```
%% Stress Relaxation Response for Different Testing Conditions
figure
for i = 1:3
   data = csvread(['RawData_' num2str(i+3) '.csv']);
   time = data(:,1); % s
   stress = data(:,3)/data(1,9); %MPa
   plot(time, stress); hold on;
end
legend('Strain Rate 50 mm/min', 'Strain Rate 250 mm/min', 'Strain Rate 50 mm/min, hold at 100% strain');
xlabel('Time, s'); ylabel('Stress, MPa'); title('Stress Relaxation of UHMWPE, Raw Data');
```

```
figure
for i = 1:3
    data = csvread(['RawData_' num2str(i+3) '.csv']);
    time = data(:,1); % s
    stress = data(:,3)/data(1,9); %MPa
    s = exp2fit(time, stress, 2) %Fit data to Maxwell model
    stress = s(1) + s(2)*exp(-time/s(3)) + s(4)*exp(-time/s(5));
    plot(time, stress); hold on;
end
legend('Strain Rate 50 mm/min', 'Strain Rate 250 mm/min', 'Strain Rate 50 mm/min, hold at 100% strain');
xlabel('Time, s'); ylabel('Stress, MPa'); title('Stress Relaxation of UHMWPE, Curve Fitted');
```

Acknowledgements

Team Harambe would like to thank the following individuals for aiding and preparing the lab performed: Kyriakos Komvopoulos, Grace O'Connell, and Mike Neufer. In addition, Team Harambe would like to thank our amazing Graduate Student Instructor Semih Bezci for assisting us when necessary. This phenomenal lab would not have been possible without the incredible hard work from each individual.




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

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

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

I, Jinyu Ni, confirm that Adolfo Tec wrote Results of the lab report. Jinyu Ni

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