Development of A Test Facility To Study The Mechanical Behavior Of Polymers And Their Composites Under High Strain Rate Tensile Loading

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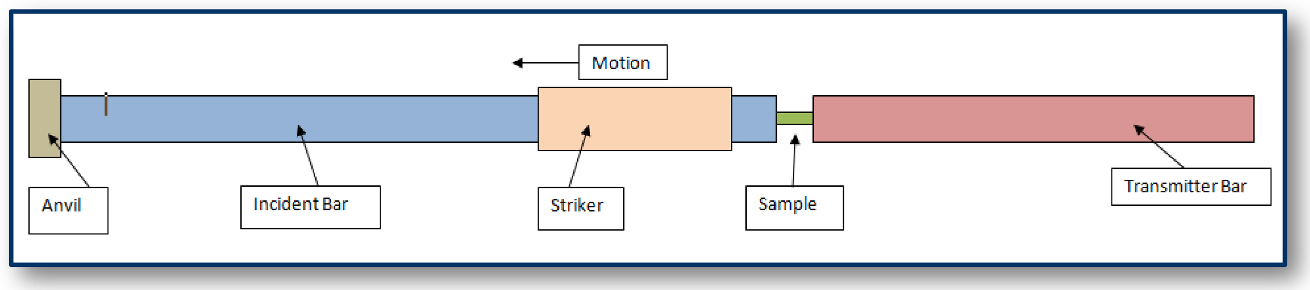
1. Background and Objectives:

It is well known that a material's mechanical behavior is sensitive to how fast the load is applied, i.e. the loading/strain rate. In applications involving impact loading, materials are loaded at a very fast rate. Therefore, it is important to understand how the materials respond to such loading. Due to their high strength to weight ratio, there is a rising interest in using polymers and their composites for manufacturing impact-resistant structures. One particular polymer, high density polyethylene (HDPE) reinforced with carbon nanofibers (CNF), was previously tested[1] in this lab to determine its compressive strength under high strain rates. **The purpose of this work is to develop an experimental apparatus to study the behavior of the same type of polymers and composites under high-strain-rate tensile loading**.

2. Operation Principle of the Split Hopkinson Bar Tensile Test Setup:

Schematic Diagram of the Split Hopkinson Bar Tensile Test Setup

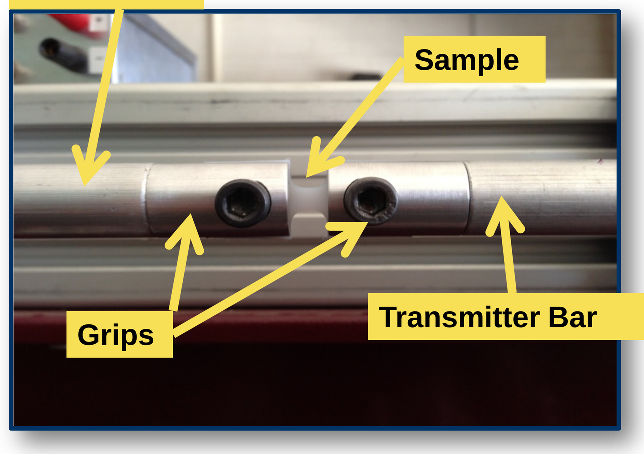


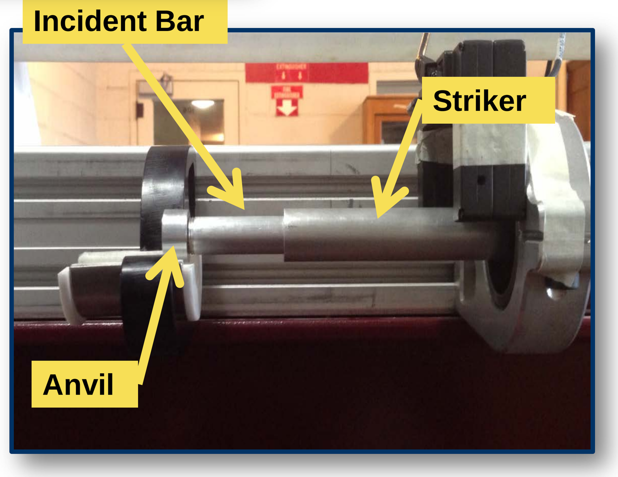
Compressed gas is used to propel the striker, a hollow tube that slides over the incident bar, into the anvil screwed onto the end of the incident bar. When the striker contacts the anvil, a stress pulse is sent from the striker into the incident bar. The pulse travels into the sample where some of the stress wave is reflected back into the incident bar and the rest is transmitted through the sample into the transmitter bar. Strain gauges on the incident and transmitter bars record the strains generated by the stress pulse. The strain gauge data can then be used to calculate the stress and strain characteristics of the sample.

3. Design and Development of the Split Hopkinson Bar Tensile Test Setup:

Pictures of the overall experimental setup and some key parts are shown below. The incident bar's length is144" and the transmitter bar is 84". Both bars are made of 7075 aluminum. The striker used is 36" long and is made of aluminum 2026. The collars on the striker are made of Teflon. The cross sectional areas of the striker tube and the anvil are kept very close in size to maintain a good mechanical impedance match and to ensure a smooth transition of energy.

Split Hopkinson Pressure Bar

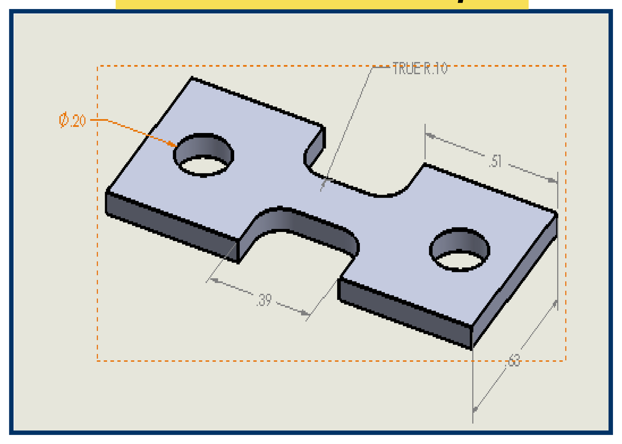




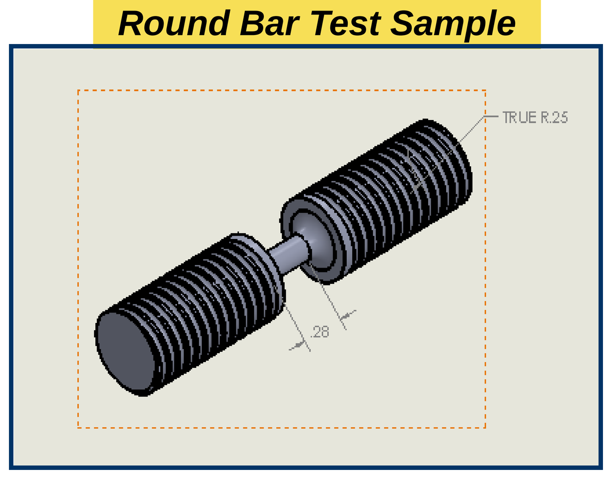
4. Materials and Test Samples:

Three types of materials were tested: a commercial HDPE, a lab processed HDPE, and a lab processed HDPE composite reinforced with carbon nanofibers. The processing was done in Dr. Zhong's lab at WSU. Two commercial HDPE samples were tested: a flat plate sample and a round bar sample. One lab processed material was tested: a flat plate sample.

Flat Plate Test Sample

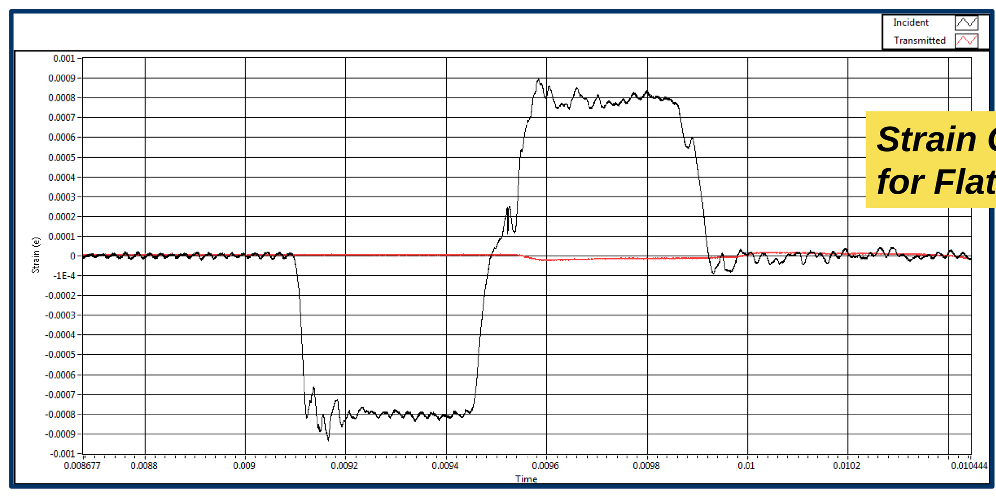


Round Bar Test Sample

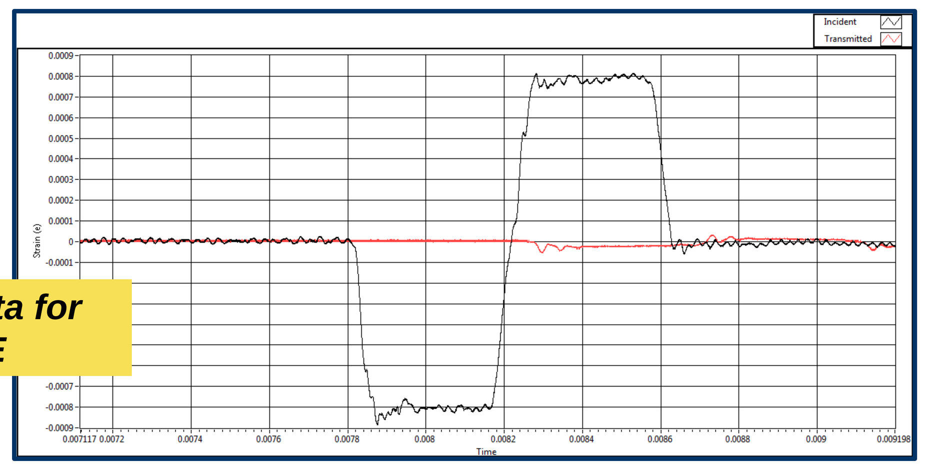


5. Typical Test Results:

Below are the sample data recorded by the strain gauges, one for the plate sample and the other for the round bar sample. The black lines are the strain data recorded from the incident bar and the red lines are from the transmitter bar. The round sample showed less noise than the flat sample. This could be due to the fact that the grips for the flat samples have less smooth geometry resulting from protruding components like the bolts. This non-even geometry could cause some wave reverberation and variations in the strain data.



Strain Gauge Data for Flat Plate HDPE



Strain Gauge Data for Round Bar HDPE

* Both graphs show the strain in the incident bar (black) and transmitter bar (red) as a function of time

6. Analysis of the Test Results:

The strain gauge data recorded from the incident and transmitter bars can be converted to stress, strain, and strain rate using the following formulae[2].

Stress

$$\sigma(t) = \frac{E_b * A_b}{A_s}\varepsilon_T(t)$$

Strain Rate

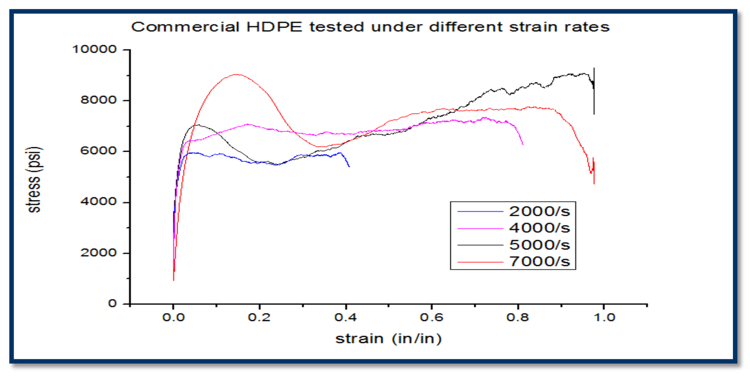
$$\dot{\varepsilon} = \frac{2C_0}{L_s} * \varepsilon_R(t)$$

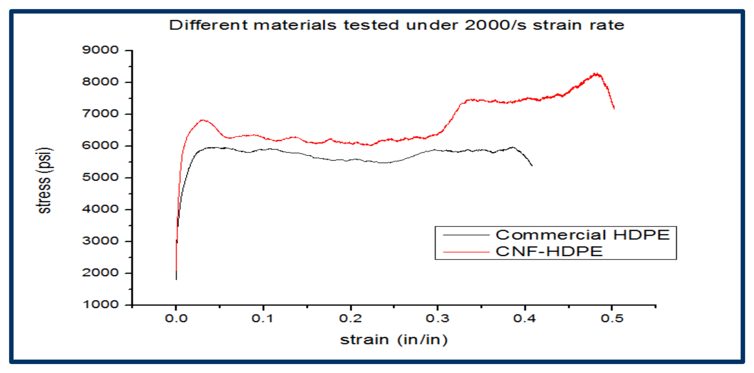
Strain

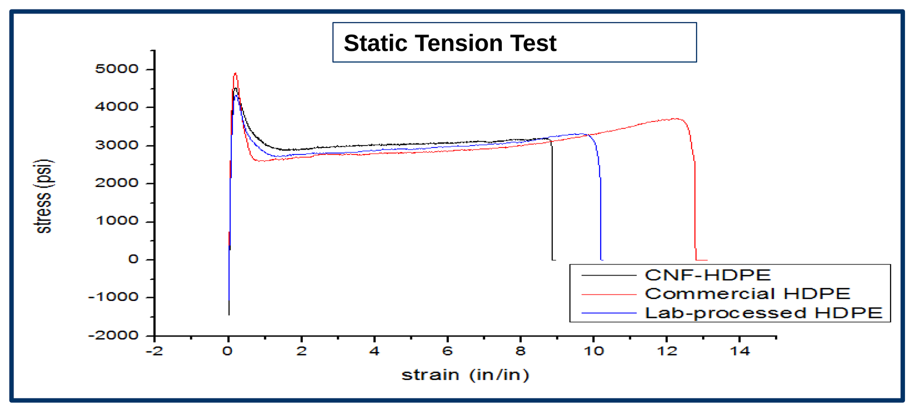
$$\varepsilon(t) = \int_0^{\tau} \dot{\varepsilon}(\tau)d\tau$$

Where C_o= wave speed, L_s = sample length, ε_R= reflected strain,
A_b = area of incident and transmitter bars, A_s= sample area,
E_b = modulus of elasticity of incident and transmitter bars,
ε_T = transmitted strain

7. Deformation Behavior:







The top left plot shows the commercial HDPE flat plate sample tested at different strain rates. The top right plot shows two different materials (CNF-HDPE and commercial HDPE) tested at the same strain rate of 2000/s. The bottom plot shows the three materials (CNF-HDPE, commercial HDPE, and lab-processed HDPE) tested with the static tension test.

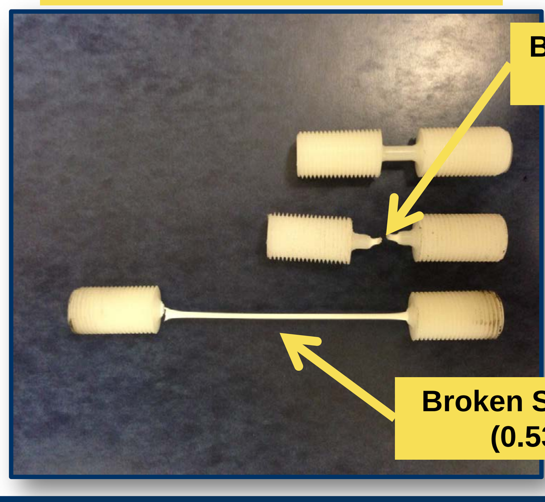
The above figures give insight to the properties of the materials under different testing conditions. It can be seen that as the strain rate increases, the yield strength of the HDPE also increases. From the slowest to fastest loading rate the HDPE's yield strength increased from 4500 to 9000 psi; a 100% increase. The plots also show the difference in the material's strain when it is loaded very quickly (7000/s) vs. a static test (0.53/s). The comparison shows a strain of 1300% when tested statically and 100% when tested at the fast strain rate. This shows that the material loses much of its ductility when it is loaded quickly. The comparison of the CNF-HDPE and commercial HDPE shows that the CNF-HDPE has a higher yield stress (7000psi) than the commercial HDPE (6000psi), which is a 17% increase.

8. Fracture Behavior:

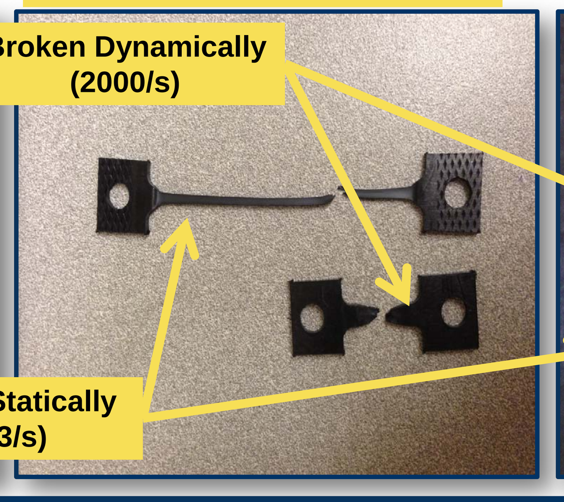
Below are images of samples broken at different strain rates, which show the following:

- Material properties are different at different loading rates.
- The sample stretches very far, about ten times its original length, if it is loaded under static conditions.
- The sample will only stretch about its own length when it is loaded dynamically, proving that the ductility of the material decreases greatly with an increase in loading rate.
- At different strain rates the failure starts at different locations with the sample breaking from the inside out at high dynamic strain rates and from the outside in at slower dynamic strain rates.

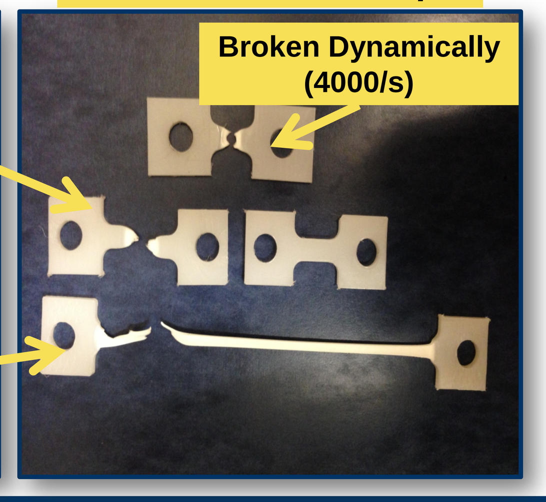
Round Bar HDPE Sample



HDPE Reinforced with CNF



Flat Plate HDPE Sample



9. Conclusions:

- A capability for high strain rate tensile testing has been developed and the preliminary results have demonstrated its functionality. The aluminum proved to have an adequate sensitivity to detect the transmitted stress pulse sent through the sample.
- Both the deformation and fracture behaviors of high density polyethylene exhibit strong rate sensitivity. The strength increased and the ductility decreased as the speed at which the load was applied increased.
- The round bar and flat plate samples showed slightly different responses and noise levels. These are likely due to the different gripping methods used for these two types of samples with the round bar sample showing less noise.
- The carbon nanofiber has been demonstrated to exhibit a strengthening effect for the HDPE composite. On the other hand, it also decreased the ductility of the composite.

10. References:

1. Hu, Y., Liu, T., Ding, J. L., and Zhong, W. H., 2013, Polymer Comp., **34**(3), 417-425.
2. G. T. Gray III, *ASM Handbook* Volume 8, Mechanical Testing and Evaluation, ASM International, Materials Park, Ohio, USA, (2000).

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