Dynamic Small Strain Measurements of Kevlar® 129 Single Fibers with a Miniaturized Tension Kolsky Bar

Jaeyoung Lim, Weinong W Chen

Schools of Aeronautics/Astronautics and Materials Engineering
Purdue University, West Lafayette, IN 47907

ABSTRACT

We adopted a non-contact laser technique to measure axial small strain (<~5%) of Kevlar® 129 fibers in a miniaturized tension Kolsky bar. In this optical arrangement, a focused laser beam through the line generator lens, which is known as a powell glass, yields a thin and straight line with uniform intensity along the length of the line. Dynamic strain measurement was made via a high-speed photodetector at very high resolution. High-rate test results performed at three different gage lengths of 2, 5 and 10 mm show that the tensile failure strain of Kevlar® 129 single fibers depends on the gage length. Tensile experimental results at a constant strain rate of ~1500/s demonstrate the capability of the non-contact laser technique combined in a modified Kolsky bar to determine the tensile stress-strain behavior of high-performance single fibers with small strain.

1. INTRODUCTION

DuPont Kevlar® brand para-aramid fiber with highly orient polymer chain has been widely used in body armor and other impact-resistant applications because of their high strength, light weight, and good stability at high temperatures. In fibrous body and vehicle armors, individual fibers must retain their axial strength to retard projectiles during ballistic impact. Therefore, determining mechanical properties of single fibers at high strain rates is important to understand their performance.

Despite the need to understand fiber performance under high rate loading, their axial mechanical properties of single fibers have been studies very little. A modified Kolsky tension bar for single fiber tests, first introduced by Cheng et al. [1], has been developed by Lim et al. [2, 3] to determine the tensile response of single fibers at high rates. In single fiber tests, the strain rate effects on the tensile strength of Kevlar KM2 and A265 single fibers were successfully investigated by Cheng et al [1] and Lim et al. [2,3], respectively. However, there are still some difficulties for measuring small strain within the deformed specimens using the recorded loading signals on the incident bar due to its ambiguous initial point of the reflected loading signal.

The small strain measurement is important in relatively brittle materials such as ceramic and high performance fibers as well as in ductile metal. Hence, direct measurement techniques of the elongation using strain gage on the specimen in the split-Hopkinson-pressure-bar (SHPB) have been studied [4, 5]. Ramesh and Narasimhan [6] have recently developed the direct non-contact measurement technique of radial deformations during a compression Kolsky bar experiment. Chen et al. [7] modified conventional SHPB technique by placing a pulse shaper and obtained valid stress-strain response of a metal specimen even in the small strain region (<~2%).

In this article, we adopted a non-contact laser technique for axial small strain (<~5%) measurements of Kevlar® 129 single fibers under high strain rate loading, together with a miniaturized tension Kolsky bar. The system capability in recording of small stress-strain behavior is discussed and some experimental
results of Kevlar® 129 single fibers at a constant strain rate of ~1500/s are presented.

2. EXPERIMENTAL ARRANGEMENT
2.1 Optical strain measurement system

We adopted a non-contact laser technique to measure axial small strain (<~5%) during the deformation of the fiber. This system can be built on the optical table for ease of alignment, together with a miniaturized tension Kolsky bar. The complete optical arrangement is indicated in Fig. 1. As shown in Fig. 1, the optical arrangement consists of a high power laser with a focus lens, a line generator lens, and photodetector with a collecting lens. This device converts the linear motion of a target attached to the end of the incident bar into a voltage output proportional to the displacement. The strain rate (\(\dot{\varepsilon}\)) and the strain (\(\varepsilon\)) of the fiber specimen are calculated using the following equations [8]:

\[
\varepsilon = -\frac{v}{l_s} = \frac{c_0}{l_s} (\varepsilon_i - \varepsilon_r)
\]

(1)

where \(v\) is the particle velocity at the end of the incident bar, \(l_s\) is the length of the specimen, \(c_0\) is the elastic bar wave velocity in the rod, and \(\varepsilon_i\) and \(\varepsilon_r\) are incident and reflected strains respectively. By integration, we obtain the strain in the fiber specimen as a function of time \(t\).

\[
\varepsilon = \int_0^t \frac{v}{l_s} d\tau
\]

(2)

A rather powerful laser-diode is needed to obtain the output voltage with high gain; we use a 100 mW laser powered by a 5 V dc power supply (UHS-100G-670 Red Laser Diode Module supplied by World Star Tech). A focused laser beam through the line generator lens, which is known as a powell glass, yields a thin and straight line with uniform intensity along the length of the line. In measurement using a laser line, the intensity profile in the direction of the line propagation should be uniform since the accuracy of the measurement is strongly affected by the quality of the laser line. A thin and straight laser line of 1 mm in height and 30 mm in length generated from the system. Uniform light intensity was collected into a sensor area of 0.8 mm² of photodetector through a collecting lens. A voltage output proportional to the axial displacement of the target is obtained; a rise time of about 1 ns is obtained with a 50 \(\Omega\) input impedance into the recording oscilloscope.

3. RESULTS

Output signal obtained from the optical strain measurement system from a typical high-rate experiment is shown in Fig. 2, together with the strain and force signals recorded from the
semiconductor strain gages mounted on the incident bar and the quartz-piezoelectric load cell, respectively. Figure 2 shows the tested results on the single fiber within a gage length of 2 mm at a strain rate of ~1500/s. As shown in Fig. 2, the output intensity signal from the optical strain measurement system monotonically increases as the specimen is deformed. In this test, the axial displacement to the point of failure was 0.14 mm.

![Graph showing strain over time](image)

**Fig. 2 Typical set of signals recorded in a miniaturized tension Kolsky bar using a optical strain measurement system**

High-rate tensile tests are performed at three different gage lengths of 2, 5, and 10 mm in order to investigate the gage length effects on the tensile failure strain of Kevlar® 129 fiber. As shown in these Fig. 3, the single Kevlar® 129 fibers represent a very linear stress-strain relationship up to the point of failure at the gage length of 5 mm. All tests are carried out at the same strain rate of ~1500/s. The slope of the linear portion of a curve is the Young’s modulus and the failure point is the ultimate strength of the fiber along its axial direction. The longitudinal Young’s modulus $E_3$ of Kevlar® 129 fiber is measured to be $99.59\pm7.58$ GPa within 95% confidence interval from the results of 10 repeated tests. The ultimate strength and failure strain of Kevlar® 129 fiber are $4.64\pm0.10$ GPa and $4.72\pm0.36\%$, respectively. The experimental values of longitudinal mechanical properties for Kevlar® 129 fibers under high rate loading are summarized in Table 1.

![Graph showing stress-strain curves](image)

**Fig. 3 Dynamic stress strain curves of Kevlar® 129**

<table>
<thead>
<tr>
<th>Gage Length (l) (mm)</th>
<th>Ultimate Strength (U) (GPa)</th>
<th>Failure Strain (\varepsilon) (%)</th>
<th>Young’s Modulus (E_3) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4.79±0.26</td>
<td>7.15±0.35</td>
<td>67.42±4.03</td>
</tr>
<tr>
<td>5</td>
<td>4.64±0.20</td>
<td>4.72±0.36</td>
<td>99.59±7.58</td>
</tr>
<tr>
<td>10</td>
<td>4.61±0.11</td>
<td>4.03±0.18</td>
<td>114.37±3.45</td>
</tr>
</tbody>
</table>

**Table 1. Longitudinal mechanical properties of Kevlar® 129 fibers deforming at high strain rate**

4. CONCLUSIONS

We have adopted a non-contact laser technique, together with a miniaturized tension Kolsky bar, to measure axial small strain (<~5%) of Kevlar® 129 single fibers with highly orient polymer chain. Using this optical arrangement, we can measure the accurate failure strains under dynamic tensile loading. A high temporal resolution is easily achieved by a high-speed photodetector, without the need for high speed photography. High-rate tensile tests were performed at three different gage lengths of 2, 5 and 10 mm. Experimental results performed on Kevlar® 129 single fibers under high
Rate loading demonstrate the capability of the non-contact laser technique in a modified Kolsky bar to determine the tensile stress-strain behavior of high-performance single fibers with small strain.

REFERENCES