Introduction

A bicomponent fiber is a single fiber that contains two different polymer components within the same filament. Sometimes it is also known as a ‘conjugate’ fiber. The concept of producing bicomponent fibers is not very new as Dupont introduced it in mid-1960s. However, the manufacturing processes of bicomponent fibers were not very streamlined, which led to recent research activities developing new material systems and their manufacturing technologies.

Interest in bicomponent fibers have grown mainly with the objective that properties of two different polymer components can be utilized in a single fiber. Choice of the two components can be diverse and can result in many different cross-sectional geometry – such as, side by side, sheath-core, islands-in-the-sea, etc [1]. These different cross-sections are mostly governed by the manufacturing process and their applications. In the present study we focus on single bicomponent fibers with sheath-core cross-sectional geometry, where one polymer component (core) is completely surrounded by another polymer (sheath). The sheath-core geometry is advantageous when different functionalities are needed in the sheath, while the core may contribute to strength, reduced cost, etc [1]. There may be good adhesion between the sheath and the core of the fiber.

However, in absence of adhesion, a contoured interface between the sheath and core is also capable of providing mechanical interlocking between the two phases. The sheath-core bicomponent fibers are used for many different applications. For example, a bicomponent fiber with highly elastic behavior can crimp easily and provides mechanical interlocking in nonwovens [1]. They can also provide strength in nonwovens by heat treatment of the sheath component [1]. Due to the presence to two different materials in the fiber, it has been possible to produce fibers with better thermal insulation or water adsorption [1], without compromising their mechanical integrity.

The understanding of the mechanical behavior of polymer fibers is very important for woven and nonwoven textile industries. Hence, dynamic mechanical analysis has been an integral part in the development of new fiber materials. In recent years, a novel experimental method, known as continuous dynamic analysis (CDA), has shown that the dynamic mechanical properties of a polymer fiber changes significantly with their deformation [3, 4]. The quantification of this variation in dynamic modulus of the material is an important consideration to understand the complete deformation mechanism of any polymeric material. In the present study, we utilize this continuous dynamic analysis to understand the tensile deformation behavior of a bicomponent polymer fiber.
Theory

Before discussing the results on bicomponent fibers, we briefly introduce the theory behind tensile measurements and the continuous dynamic mechanical analysis. The engineering stress in a tensile experiment is defined as:

\[
\sigma = \frac{F}{A_0}
\]  

(1)

where, \(F\) is the applied force and \(A_0\) is the original cross-sectional area. And, the engineering strain is defined as:

\[
\varepsilon = \frac{\Delta l}{l_0}
\]

(2)

where, \(\Delta l\) and \(l_0\) are change in specimen gage length and the original specimen gage length, respectively.

The Young’s modulus of the material is determined from the slope of the initial linear-elastic region of the engineering stress-strain curve.

In addition to the quasi-static stress-strain measurements, the CDA applies a high frequency harmonic force with amplitude of \(F_0\), which causes a harmonic displacement of amplitude \(z_0\). The harmonic force amplitude, \(F_0\), is much smaller compared to the quasi-static force on the fiber specimen. As a result of the viscoelastic nature of polymer fibers, the harmonic displacement lags behind the harmonic force by a phase angle \(\phi\). Hence, the dynamic storage modulus of the specimen is related to the harmonic force and displacement amplitudes and phase angle by \(^3\):

\[
E' = \frac{l}{A} \left[ \frac{F_0 \cos \phi}{z_0} \right]
\]

(3)

where, \(l\) and \(A\) are the instantaneous gage length and fiber cross-sectional area, respectively. The CDA enables the measurement of the dynamic modulus of the fiber over the complete range of strain during one single experiment.

Experimental Method

Bicomponent fibers with different volume percentages of the sheath and the core components were prepared at North Carolina State University. The sheath component is stronger, and it has a lower melting point compared to the core, to make it suitable for thermal binding applications in nonwovens. On the other hand, the elastomer component in the core provides highly elastic nature of the bicomponent fibers. Individual concentric sheath-core fibers with 100, 80, 60, 50, 40 and 20 volume\% sheath were characterized during this study. Figure 2 shows optical micrographs of the cross-section of bicomponent fibers with three different sheath-core ratios. Individual fibers of each sheath-core ratio were carefully mounted on thick paper-based card templates. The gage section of each fiber specimen is measured using a caliper, and the cross-sectional areas of the fibers were measured using an optical microscope. The template was then mounted on the Keysight Technologies, Inc. T150 nanomechanical UTM (Figure 1) using the template-grips and the sides of the template were clipped to release the fiber for testing. The micro-positioner is used to ensure proper alignment of the fibers before testing. Four fiber samples of each sheath-core composition were tested.

The NanoSuite (Keysight Technologies) test method named “UTM T150 Standard Toecomp CDA” was used for tensile testing of the individual bicomponent fibers, along with continuous dynamic analysis. All the tests were performed with a strain rate of 1x10^-2 s^-1. The continuous dynamic analysis during each test was performed using a harmonic force of 4.5 mN at a frequency of 45 Hz.

Results and Discussion

A typical quasi-static stress-strain curve for the fibers with 100% of the sheath component is shown in Figure 3. It exhibits three distinct regimes of deformation, I, II and III, marked by vertical dashed lines in the figure. This behavior is expected due to the semi-crystalline nature of the polymer \(^5\). Regime I represents homogeneous elastic behavior, whereas the amorphous regions realign with the crystalline molecules in regime II. In regime III, the amount of aligned polymer chains in the fiber starts to increase, increasing the stiffness of the fiber \(^6\). This behavior is also confirmed from the continuous dynamic storage modulus measurements during the same experiment (right Y-axis on Figure 3). The initial storage modulus value matches well with the measured Young’s modulus from the quasi-static stress-strain curve. However, the storage modulus starts to increase significantly in the regime III. It is interesting to note the large deformation (about 700%) of the sheath component before failure. The sudden drops in load at very high strains are stochastic in nature and are due to failure initiation in the fibers.

Figure 4a to 4e shows the quasi-static engineering stress-strain curves, along with the dynamic storage modulus measurements, for 80%, 60%, 50%, 40% and 20% sheath bicomponent fibers.
respectively. By comparing the curves in Figure 4, it is evident that the sheath is the load bearing component in these fibers. The initial dynamic storage modulus values for each of these fibers are similar to the quasi-static Young’s modulus measurements. It is also evident that the magnitude of the increase in dynamic modulus with strain also decreases with decreasing volume of the sheath.

The diameter of the fibers, along with the corresponding tensile strength and Young’s modulus are listed in Table 1. The variation in Young’s modulus and tensile strength of the bicomponent fibers are shown in Figure 5.

Table 1. Tensile properties of sheath-core bicomponent fibers with different volume fractions of sheath.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Average Diameter (µm)</th>
<th>Young’s Modulus (MPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Sheath</td>
<td>98</td>
<td>40±5</td>
<td>7.0±0.3</td>
</tr>
<tr>
<td>80 vol% Sheath</td>
<td>102</td>
<td>35±5</td>
<td>6.0±1.0</td>
</tr>
<tr>
<td>60 vol% Sheath</td>
<td>95</td>
<td>20±5</td>
<td>4.0±0.5</td>
</tr>
<tr>
<td>50 vol% Sheath</td>
<td>105</td>
<td>16±7</td>
<td>3.7±0.7</td>
</tr>
<tr>
<td>40 vol% Sheath</td>
<td>102</td>
<td>12±2</td>
<td>3.9±0.6</td>
</tr>
<tr>
<td>20 vol% Sheath</td>
<td>105</td>
<td>8±2</td>
<td>4.1±0.3</td>
</tr>
</tbody>
</table>

Figure 4. The variation in engineering stress and dynamic modulus with increasing strain for bicomponent fibers with different volume fractions of the sheath. Note the decrease in the magnitude of change in dynamic storage modulus with decreasing sheath content.
fibers with different volume fraction of sheath is plotted in Figures 5a and 5b, respectively. The Young’s modulus decreases from about 40 MPa for pure sheath component to about 8 MPa for only 20 volume% sheath. Similar decrease can be observed for tensile strength, as well. However, below 60% sheath, the tensile strength becomes almost constant irrespective of the amount of sheath or core in the fiber. Figure 5 suggests that the increase in the amount of core component significantly influences the modulus of the material. This is also in agreement with the change in dynamic storage modulus in Figure 4.

Summary and Conclusions

Bicomponent fibers with different volume fractions of sheath and core are characterized using the Keysight T150 nanomechanical UTM to determine their quasi-static and dynamic mechanical behavior. The sheath component in these fibers possesses higher modulus and tensile strength compared to the core. While decreasing the volume fraction of sheath in the fibers affects both the quasi-static and dynamic modulus of the material, it does not seem to significantly alter the tensile strength of the bicomponent fibers. Each individual component needs to be characterized further in order to determine the exact underlying deformation mechanisms.

References


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