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The Tensile Behavior of High-Strength Carbon Fibers

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Abstract: Carbon fibers exhibit exceptional properties such as high stiffness and specific strength, making them excellent reinforcements for composite materials. However, it is difficult to directly measure their tensile properties and estimates are often obtained by tensioning fiber bundles or composites. While these macro scale tests are informative for composite design, their results differ from that of direct testing of individual fibers. Furthermore, carbon filament strength also depends on other variables, including the test length, actual fiber diameter, and material flaw distribution. Single fiber tensile testing was performed on high-strength carbon fibers to determine the load and strain at failure. Scanning electron microscopy was also conducted to evaluate the fiber surface morphology and precisely measure each fiber's diameter. Fiber strength was found to depend on the test gage length and in an effort to better understand the overall expected performance of these fibers at various lengths, statistical weak link scaling was performed. In addition, the true Young's modulus was also determined by taking the system compliance into account. It was found that all properties (tensile strength, strain to failure, and Young's modulus) matched very well with the manufacturers' reported values at 20 mm gage lengths, but deviated significantly at other lengths.

Key words: carbon fiber, weak link scaling, tensile strength, Young's modulus

Introduction

High-strength carbon fibers are widely used in composite materials because of their excellent tensile properties. However, understanding their properties for design purposes is not straightforward, as their behavior varies based on how testing is conducted and on individual fiber properties such as the actual fiber diameters and the distribution of flaws. Testing of composites, fiber bundles, and individual fibers all yield different results and the gage length used for testing also has an effect. Similar to the recent work by Parra-Venegas et al. (2012) for the tensile properties of individual E-glass fibers, there is also usefulness in developing this knowledge for individual high-strength carbon fibers. It is advantageous to understand the actual tensile properties of the fibers themselves without the influence of fiber/fiber or fiber/matrix interactions encountered in bundle or composite testing.

Carbon fibers can be made from a number of different precursors, including rayon, polyacrylonitrile (PAN), and petroleum pitch (Lee, 1993). The basic requirement to be converted into carbon fibers is that the precursor fibers carbonize rather than melt when heated (Lachman et al., 1976). In fact, the first filaments used in Edison's incandescent electric lamps were actually carbon fibers made by carbonizing cotton fibers, although they were extremely brittle and were quickly replaced by tungsten wire (Lee, 1993). The majority of carbon fibers available today are based on PAN (Kim & Mai, 1998), and due to this prevalence, PAN-based fibers were evaluated herein.

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The basic structure of carbon fiber material is made up of graphite crystallites, which in turn are composed of layered basal planes. Within the basal planes, the carbon atoms are strongly bonded to each other. Between the basal planes, however, there is only weak Van der Waals' bonding (Flinn & Trojan, 1975). The graphitic structure of carbon fibers lends them to exhibit very anisotropic behavior. The high bond strength between the carbon atoms in the basal plane results in extremely high modulus in this direction (roughly along the fiber axis), whereas the weak Van der Waals type of bonding between the adjacent layers produces a low modulus along the edge plane. The graphitic structure of carbon fibers is not perfectly ordered and usually not perfectly aligned with the fiber axis. To achieve a high modulus, a high degree of preferred basal plane orientation along the fiber axis must be achieved. To improve the orientation of the graphite crystals, various kinds of thermal and stretching treatments are employed (Kim & Mai, 1998). Generally, as the processing temperature increases, the basal plane preferred angle decreases, aligning closer to the fiber axis. There is, however, no rotational order in the radial direction and the carbon atoms stack poorly so that a graphite structure is never totally achieved (Lee, 1993). Figure 1a describes the basal plane angle and Figure 1b provides a drawing that illustrates the carbon fiber radial disorder.

Materials and Methods

Processing variations lead to three general groups of carbon fibers: high strength (Type I), high modulus (Type II), and ultra-high modulus (Type III) types. The type of fiber

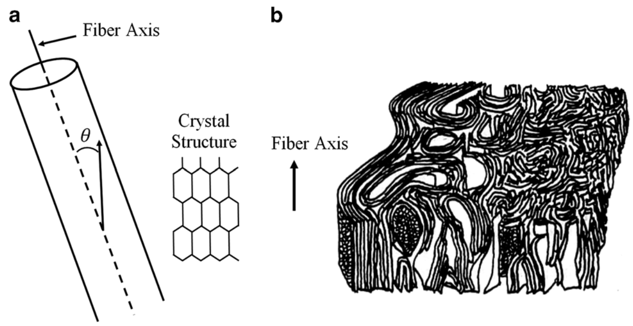

Figure 1. (**a**) Carbon fiber basal plane angle; (**b**) cross-sectional drawing (from Lee, 1993).

attained primarily depends on the temperature of pyrolysis used (Fitzer & Heine, 1988; Oberlin & Guigon, 1988). This study focused on high strength (Type I) fibers, with two sources being evaluated: T700 by Toray Industries (Flower Mound, TX, USA) and AS4D by Hexcel Corp. (Stamford, CT, USA), both of which have similar reported properties.

Mechanical Property Testing

Fiber tensile strength was determined by testing single filaments in a tensile testing machine (MTS Insight 1kN) with a small (2 N) load cell. Individual fibers were first glued to paper test fixtures, whose sides were then cut away after the ends were secured in the testing grips, leaving only the fibers to be stressed. Before testing, the diameter of each fiber was measured by scanning electron microscopy (SEM) at three points along its length. Testing was performed at a crosshead speed of 0.5 mm/min, which resulted in a test time of ~1 min. Depending on the gage length being tested, the resulting strain rate ranged from 2.8×10^{-4} to $4.2 \times 10^{-4}\,s^{-1}$. Testing provided the load at break and strength was determined by dividing the load by the area obtained using the average of the three diameter measurements for each fiber. Testing was initially conducted with a gage length of 20 mm, but additional testing at 25 and 30 mm was conducted for evaluations of the strength dependence on gage length and determination of the true modulus. At least 30 fibers were tested for each length. It has been shown that statistical confidence levels do not significantly improve by increasing the sample sizes beyond this (Masson & Bourgain, 1992).

Results and Discussion

All fibers tested exhibited simple Hookean stress–strain curves, remaining approximately linear with no indication of yield up until failure. Figure 2 provides an example of one of the fibers' stress–strain curves. Table 1 shows the mean values for the experimentally determined fiber properties at 20 mm test gage lengths (tensile strength, strain at failure, and average fiber diameter), along with standard deviations. At this gage length, the mean measured values are in very close agreement with the manufacturer's reported values (0.2 and 12% error for tensile strength, and 0.01 and

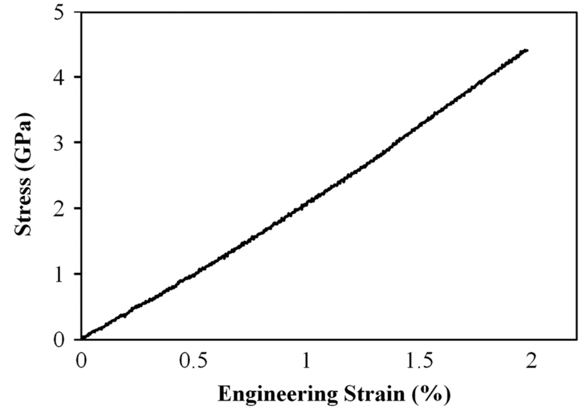

Figure 2. Example of an experimentally tested fiber's stress-strain curve (Toray T700 at 20 mm gage length). There is no indication of yielding before failure.

Table 1. Experimentally measured mechanical properties of the two high strength fiber types at 20 mm test gage length.

	Toray T700	Hexcel AS4D
Average diameter (μm)	6.91 ($\sigma^2 = 0.25$)	7.28 ($\sigma^2 = 0.24$)
Tensile strength (GPa)	4.34 ($\sigma^2 = 1.15$)	4.47 ($\sigma^2 = 0.43$)
Failure strain (%)	2.07 ($\sigma^2 = 0.48$)	1.87 ($\sigma^2 = 0.26$)

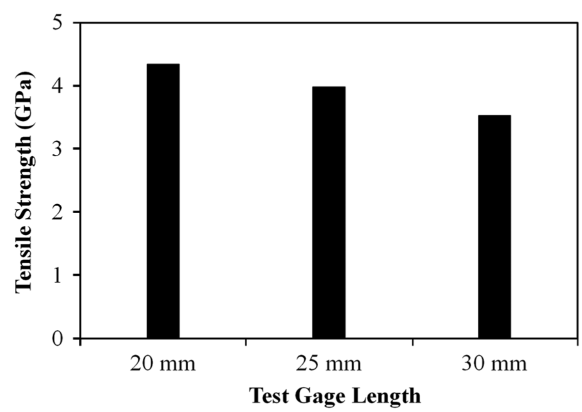

Figure 3. Dependence of fiber strength on test gage length (Toray T700).

0.02% error for the failure strain for the T700 and AS4D fiber types, respectively).

Strength Dependence on Material Flaws

Although carbon fibers are very strong, they are also known to be somewhat brittle and sensitive to material flaws. And as a result, measured fiber strength is dependent on the length of the filament that is tested. This is simply because there is a higher probability of encountering significant material flaws in longer gage lengths. This effect was clearly observed in this work when testing fibers at different gage lengths. Figure 3 shows the mean tensile strengths for fiber groups tested at gage lengths of 20, 25, and 30 mm.

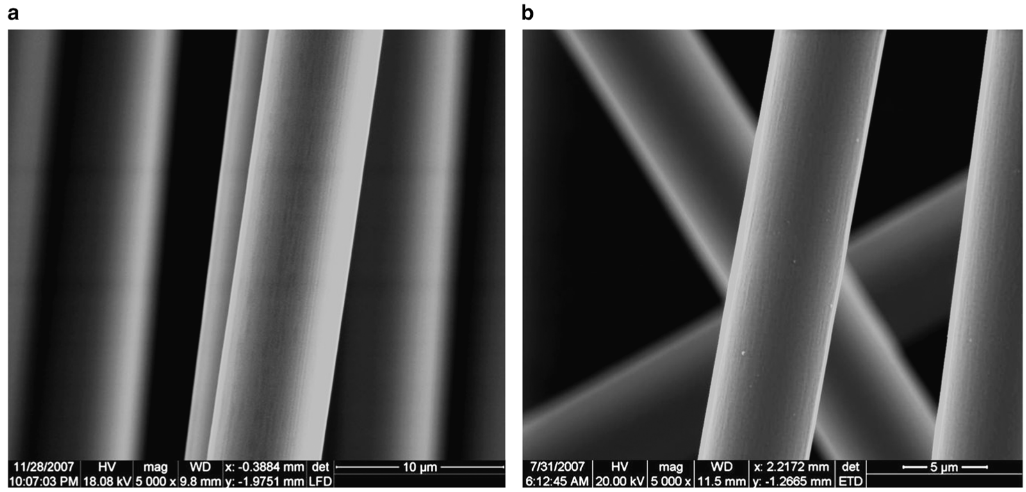

Figure 4. Scanning electron microscope images of fiber surfaces, (**a**) T700 and (**b**) AS4D.

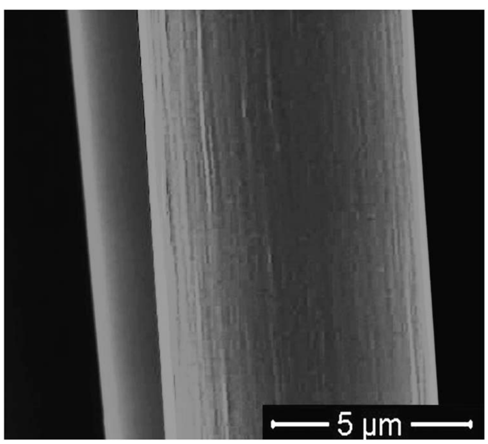

Figure 5. Enlarged scanning electron microscope image of AS4D fiber surface to show longitudinal striations and grooves.

SEM analysis was also performed to evaluate the condition of the fiber surfaces. As can be seen in Figure 4, they were found to be mostly smooth, with some longitudinal striations and grooves. Figure 5 provides an enlarged view to highlight the striations. Other than these surface irregularities, no signs of surface damage were observed. In addition to physical damage and imperfections on the surface, other pertinent fiber flaw types may include, for example, inorganic inclusions, organic inclusions, irregular voids from rapid coagulation, and cylindrical voids precipitated from dissolved gases (Elices & Llorca, 2002).

As shown in Figure 3, tensile properties obtained from one gage length are only applicable to fibers of the same length. To compensate for the variation of strength with fiber length, weak length scaling was applied, which offers a way to analyze the statistical distribution of experimentally determined fiber tensile strengths at one test gage length and predict tensile strengths at other lengths. The theory behind weak link scaling has been described by Pickering & Murray (1999). Carbon fiber, being a brittle material, has strengths that are determined by the distribution of its flaws, as described by the Griffith theory (1921). Weak link scaling considers the fiber to be composed of individual segments and the more segments there are, the higher the probability of encountering a more severe flaw. In this approach, the statistical distribution of fiber strengths is described by the two-parameter Weibull equation. Figure 6 provides the predicted fiber strengths as a function of length based on weak link scaling theory. The resulting curve was almost identical for both fiber types, so only one is shown. The predicted values of Figure 6 are in good agreement with the experimentally determined results of Figure 3. Figures 3 and 6 illustrate how dependent strength is on gage length and provide a much better idea of Type I carbon fiber strength than is achieved by experimental testing at only one gage length.

True Young's Modulus and Test System Compliance

Although all tested fibers presented Hookean stress–strain curves and it is tempting to calculate the Young's modulus by simply dividing the maximum stress by the maximum strain, it is important to account for the system compliance. The compliance of the test system components (grips, paper fixture, glue, etc.) can contribute significantly to a very small measurement such as this. ASTM D 3379-75 offers guidance in determining the test system compliance and applying that information to the determination of the true fiber Young's modulus. Accordingly, three different gage lengths were tested (20, 25, and 30 mm), the true system compliance was determined, and the adjusted Young's modulus was calculated. Table 2 includes the Young's modulus calculations, both those based directly on measured load and extension, and those that account for system compliance. It can be seen that accounting for system compliance leads to an increase in the calculated Young's modulus. Taking system compliance into account also produces moduli values that are remarkably close to the manufacturer's specifications in both cases.

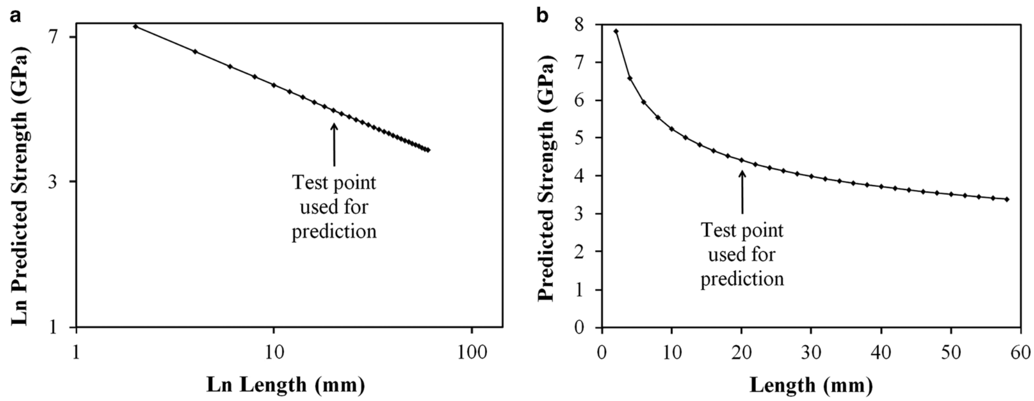

Figure 6. Predicted fiber strengths as a function of gage length, as a result of applying weak link scaling theory. Shown both in (**a**) natural logarithmic and (**b**) linear scales.

Table 2. Young's modulus determinations, with and without accounting for system compliance.

	Toray T700	Hexcel AS4D
Young's modulus (experimentally measured) (GPa)	219.9 ($\sigma^2 = 21.36$)	230.0 ($\sigma^2 = 11.69$)
Young's modulus (accounting for system compliance) (GPa)	230.5	245.3

Toray Industries lists 230 GPa for the T700 fiber and Hexcel Corp. lists its AS4D fiber as having a modulus of 245 GPa.

Conclusions

High-strength (Type I) carbon fibers offer excellent tensile strength and modulus. However, they are very brittle, presenting nearly perfect Hookean stress–strain curves that show no indication of yield before failure. Their brittleness, according to the Griffith theory (1921), also means that they are sensitive to material flaws, both interior and on the surface. In support of this, the standard deviations show that there is significant variability in the tensile strengths and failure strains of these fibers. This flaw sensitivity was also shown to manifest itself when testing fibers at different gage lengths. There is a higher probability of encountering significant flaws in longer fibers and consequently longer test gage lengths resulted in lower strengths during testing. In an effort to better understand the influence of flaws on strength, SEM was conducted to evaluate the fiber surfaces. The fibers appeared to be mostly smooth, except for small longitudinal striations and grooves. No other signs of surface flaws or damage were observed. In addition to surface irregularities, fiber strength may also be affected by flaws that are internal to the fiber, as discussed by Elices & Llorca (2002).

Considering the importance of test gage length on brittle fiber strength determinations, weak link scaling was applied to better understand the overall expected performance of these fibers at various lengths. The weak link scaling predictions agreed well with the experimental testing at different gage lengths. Young's modulus was also determined, taking into consideration the test system compliance. At a test gage length of 20 mm, all of the measured properties herein are in very close agreement with reported values of both the manufacturers (tensile strength, failure strain, and Young's modulus). However, at other lengths, the fiber properties are shown to be somewhat different.

Acknowledgment

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