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An analysis of the tensile properties of nanofiber mats

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ABSTRACT

Nanofibers have gained increasing attention because of their potential for a wide range of applications. In order to fully exploit the potential of nanofibers, there is a need to understand the relationship between the mechanical properties, especially tensile properties, of an individual nanofiber and that of nanofiber assemblies. In this study, we examined the relationship between a single nanofiber and a nanofiber mat formed by randomly oriented nanofibers through geometric analysis. The analysis showed that the tensile strength of a randomly oriented nanofiber mat is a function of fiber packing density (porosity), test specimen dimension (width to length ratio), and the tensile strength of a single nanofiber. Similar relationship can also be derived for the elastic modulus of individual nanofibers and that of the nanofiber mats. Parametric study was carried out using this fabric geometry model and the applicability of the model was evaluated using published experimental data.

1. Introduction

Increasing attention has been devoted to nanofibers in the academia and the industry since the rediscovery of nanofiber technology in the early 1990's. Through creative use of the advantage of nano-diameter size effect many functional applications have been identified where ultrahigh surface area is required in the field of energy, environment, electronics and health care. Examples of specific applications include filtration, battery, fuel cell, solar cell, tissue engineering, drug delivery, and sensor [1–6]. In order to fully exploit and utilize the potential of nanofibers there is a need to evaluate their ability to endure the stresses and strains experienced during processing and end uses at various structural levels including single nanofiber and nanofiber assemblies.

Due to the fineness of the nanofibers a majority of the mechanical testing have been performed at the fiber assembly level. At the individual fiber level with fiber diameter often below 400 nm we face a multitude of challenges including handling during specimen preparation, griping of specimen, and load cell resolution, just to name a few. Accordingly, only limited studies of the mechanical properties of single nanofiber have been published in the literature. Atomic force microscope (AFM) cantilevers have been used to strain carbon nanotubes (CNTs) in scanning electron microscope (SEM) [7,8], which is not suitable for polymeric nanofibers that can be easily damaged by the strong electron beam [9]. Ko et al. measured the elastic modulus of CNT/polyacrylonitrile (PAN) composite nanofiber with an AFM bending test method [10]. By combining a movable optical microscope stage with a piezo-resistive AFM tip, Tan et al. performed tensile test on a single electrospun polyethylene oxide (PEO) nanofiber [11]. A more direct measurement of electrospun single fibers was also carried out by Tan et al. [12]. These researchers used a commercial nano tensile testing system (Nano Bionix System, by MTS, USA, acquired by Agilent lately, known as Nano UTM) Out of all the tests, only tests performed on the fibers with a diameter above 1 μm were reported. Lin et al. [13] described a novel air-stream-assisted method to perform mechanical measurements on electrospun fibers. Electrospun fibers were captured during electrospinning and mechanically tested by simultaneous stretching the fibers and measuring the tensions in the fibers through observing the deflection of the fiber in a transverse stream of air moving at a measured velocity. The validity of the measurement results need to be further verified by traditional tensile testing or theoretical estimation results.

In view of challenges that we face with the testing of single nanofibers it would be desirable to develop a quantitative relationship between the tensile properties of an individual nanofiber and that of a nanofiber mat. Therefore the tensile properties of random nanofiber mats, which can be easily obtained by

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conducting tensile test on the nanofiber mat, can be used as an indicator of the mechanical properties of individual nanofibers [14–18].

The mechanistic study of fiber mat or nonwoven owes it origin to the work by Petterson and Backer [19,20]. They introduced the concept of unit cell of a nonwoven fabric and deduced mechanical property models relating fiber orientation and fiber mechanical properties to the mechanical properties of a nonwoven. Based on Petterson's work, Hearle and Stevenson [21] introduced a strain theory for prediction of the Young's modulus of a nonwoven fabric through analyzing fiber orientation effects on the strain ratio of an individual fiber and a nonwoven fabric. However, there are many factors that affect a tensile test result of a randomly oriented fiber nonwoven mat. A model only considering fiber orientation is not enough for prediction of the tensile strength of an individual fiber lies in a random nonwoven mat. First of all, the packing density, or the porosity, of a nonwoven mat can significantly alter the test result even if the fiber mat is composed of exactly the same nanofibers. Secondly, the test result can vary when the sample dimension such as the length and the width of the nanofiber mat specimen vary due to the change of the number of nanofibers in the specimen that participate in resisting the tension deformation. Therefore, practical analysis that can be used to predict the mechanical properties, especially tensile properties of a single nanofiber through known testing parameters are needed.

In this paper, we analyzed the geometric properties of an idealized nanofiber mat with all the nanofibers randomly distributed and oriented. Specifically, based on of this analysis, we developed a fiber geometry model which relates the tensile strength of a nanofiber mat to a single nanofiber in terms of fiber volume fraction (porosity) and test specimen dimension. With the established model parametric studies were carried out on the factors influencing the tensile strength of nanofiber mats, and estimated the tensile strength of a single nanofiber. The applicability of this model was examined using published experimental data.

2. Geometry and tensile strength analysis

As shown in Fig. 1 (a), the geometry of a nanofiber mat is similar to that of a traditional nonwoven, therefore its structure can also be analyzed by investigating a unit cell [22], Fig. 1 (b)

For theoretical analysis, a few assumptions were made:

1) All the fibers are straight in the unit cell and have the same diameter.
2) The nanofibers are randomly oriented and uniformly distributed.
3) The thickness (T) and porosity (void volume fraction) of the nanofiber mat is uniform.
4) The variation in the fiber length in the unit cell is regular enough that it can be modeled as an arithmetic progression.
5) The interactions between nanofibers in the testing specimen are negligible.

2.1. Total number of nanofibers in the unit cell

If a nanofiber mat has a porosity of P, then

$$V_u(1-P)=V_f \tag{1}$$

That is

$$\frac{\pi D^2}{4}T(1-P)=\pi r^2\sum_{i=1}^{N_f} l_i \tag{2}$$

Where, V_u is the volume of the unit cell, D is the diameter of the unit cell, r is the fiber diameter, N_f is the total number of nanofibers in the unit cell and l_i is the length of the ith nanofiber.

Redistributing all the nanofibers in the unit cell such that all the fibers lie parallel to the tensile testing direction with every fiber maintains its original length in the cell, as shown in Fig. 1 (c), and assuming the length of all the fibers forms an arithmetic progression with a common difference of Δl, the total length of the nanofibers in the unit cell is

$$\sum_{i=1}^{N_f} l_i = N_f l_{N_f} - \frac{N_f\left(N_f-1\right)}{2}\Delta l \tag{3}$$

Where

$$l_{N_f}=D \tag{4}$$

$$l_1=\Delta l \tag{5}$$

$$\Delta l=\frac{D}{N_f} \tag{6}$$

Substituting Eqs. (4)–(6) to Eq. (3), from Eq. (2) and Eq. (3), we get

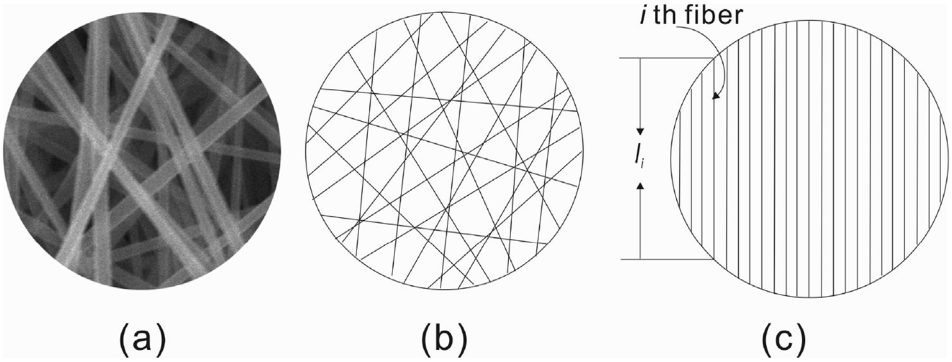

Fig. 1. (a) SEM image of PAN nanofiber, (b) unit cell of nanofiber mats with nanofibers uniformly oriented and distributed, and (c) unit cell of nanofiber mats with nanofibers re-distributed and oriented.