Microstructure of cotton fibrous assemblies based on computed tomography

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Abstract. This paper describes for the first time the analysis of inner microstructure of cotton fibrous assemblies using computed tomography. Microstructure parameters such as packing density, fractal dimension as well as porosity including open porosity, closed porosity and total porosity are calculated based on 2D data from computed tomography. Values of packing density and fractal dimension are stable in random oriented fibrous assemblies, and there exists a satisfactory approximate linear relationship between them. Moreover, poles analysis indicates that porosity represents the tightness of fibrous assemblies and open poles are main existence.

1. Introduction

General fibrous assemblies are made of fibers and air filling in the pores formed by these fibers. These fibrous assemblies are of the first hierarchical level, otherwise known as simple or primary fibrous assemblies [1]. Fibrous materials are some of the most abundantly encountered in both natural and synthetic materials and holding unique physical properties, like mechanical, electrical and thermal properties, which are related to their microstructure. These attributes have opened a wide range of effective applications in the field of insulation, filtering, packing as well as in biology and aviation [2-6]. Analyses of microstructures especially the inside information of fibrous materials are very complex tasks which have been a topic since decades of years and the past provided most sophisticated methods bringing these challenge to a successful solution. The challenge of investigations seems due to the lack of direct observation and parameter extraction of inner microstructures of fibrous assemblies which might be quite complex. The advent of computed tomography (CT) has revolutionized life and materials science. Since the inception of CT in the 1970s, its use has increased rapidly [7]. High-resolution X-ray micro-tomography provides a powerful tool for investigating the microstructure of the materials. Up to now, general fibrous assemblies were rather classified according to its macroscopic behaviour and performance than according to their microstructure in randomly oriented states; Very few CT investigations of general fibrous assemblies have been reported in scientific literature. In these investigations, special emphasis was put on the microstructural parameters of fibrous assemblies based on computed tomography and fractal dimension.

The aims of this paper were to provide (1) a direct three-dimensional visualization when analysing the inside microstructure of cotton fibrous assemblies and (2) an improved knowledge of the
microstructure of randomly oriented fibrous assemblies, like packing density, fractal dimension and porosity including open porosity, closed porosity and total porosity.

2. Experimental details

2.1. Raw materials
High-resolution X-ray micro-tomography experiment was conducted on a randomly oriented cotton fibrous assembly. The length and diameter of its constituent fibers are about 40 mm and 15 μm. The specimen was conditioned at specific climatic conditions (20±2°C, 65%±5% relative humidity) for more than 24 hours until equilibrium temperature and moisture content was reached. Cotton fibrous assembly was put into a cylindrical sample holder sharing a diameter of 18 mm and a height of 67 mm.

2.2. Experiment technique and measurements
Experiment was conducted in Beijing using a high-resolution X-ray micro-tomography whose scanning resolution is down to 3 μm which is sufficient to distinguish single fibers. The high brilliance of the synchrotron X-ray beam allows producing tomograms of high quality in terms of resolution and contrast [8-10]. Small details of inside microstructure can be accurately and clearly rendered. The principal set-up of the tomographic equipment is displayed in Fig.1 [11, 12]. Principle of computed tomography is based on penetration, fluorescence and sensitization effects of X-ray and the differences in density and thickness inside the specimen [13].

Cotton fibrous assembly were adjusted in the sample holder and then mounted on a rotation table. Samples were rotated in equal 0.2° distant steps covering an angular range of 180°. Crystal-clear X-ray images with 14-bit dynamic range can be delivered by cameras using a unique sensor driving technology named CLEANPATH. A set of projections was taken and, subsequently, reconstructed to a 3D volume. Scanning time including exposure and reading out time are about 1h and a half for a complete tomogram. Furthermore, Computer connection through a standard FireWire interface doesn’t require any frame grabber board to be installed inside the PC. Such an approach minimizes the system’s dependence on computer hardware in the near future. A radiographic set of projections are then used to realize the reconstruction based on volume rendering technique. Moreover, non-local means filtering was chosen to decrease noise for better images quality.

![Figure 1. Scheme of the principal experimental set up at the tomographic instrument.](image-url)
3. Results and discussion

3.1. Three-dimensional visualization

High-resolution X-ray micro-tomography experiment with a resolution of 3μm which is sufficient to distinguish individual fibers was conducted on a randomly oriented cotton fibrous assembly to get a series of two-dimensional projections from different angles. The cone-beam (CB) reconstruction algorithm of Feld Kamp [14] was used to reconstruct a set of two-dimensional slices. A visualization technique named volume rendering was used to give a three-dimensional impression of the whole data set without segmentation. The model is based on the emission and absorption of light that pertains to each voxel of the volume. Casting of light rays through the volume from pre-set sources was simulated using this algorithm to determine how much light reaches each voxel on the ray and is emitted or absorbed by the voxel. Then it computes what can be seen from the current viewing point as implied by the current placement of the volume relative to the viewing plane, simulating the casting of sight rays through the volume from the viewing point. Three orthogonal parts of arbitrary point within reconstruction space of cotton fibrous assembly are illustrated in Figure 2. Additionally, Softening and non-local means filtering were used to optimize images for better quality. An arbitrary number of fibers within cotton fibrous assembly then can be individually identified and visualized using this three-dimensional visualization technique. Vertical view, front view, side view and inside structure of cotton fibrous assembly from 3D volume rendering are separately shown in Figure 3(a),3(b),3(c)and 3(d).

![Figure 2](image-url)

**Figure 2.** Three orthogonal part of arbitrary point within reconstruction space of cotton assemblies
3.2. Packing density and fractal dimension analysis

Packing density is a basic characteristic of fibrous assemblies and defined as the ratio of volume of constitutive fibers to volume of fibrous assemblies including air filling in the pores formed by these fibers. Up to now, most attention and investigations are focused on the average packing density when it comes to analysis of fibrous structure. Computed tomography is proved to be a suitable and effective way to give a local packing density of fibrous assemblies. Furthermore, fractal dimension, known as the theory of natural geometry of fractals, is a new branch of modern mathematics, and its essence is a new world outlook and methodology. Fractal dimension reflects the validity of space occupied by complex forms, and it is a measure of the irregularity of complex forms. The concept of fractal geometry was first proposed by American mathematician Mandelbrot in 1975. Sandbox method [15] was chosen to calculate the fractal dimension of the morphology of fibrous assemblies.

Figure 4(a) illustrates the relation of packing density and height (black curve) and fractal dimension and height (red curve). For a random oriented fibrous assembly, packing densities as well as fractal dimensions are about 0.2% and 1.7 with only small fluctuation demonstrating the randomness of single fibers orientation. The fractal dimension increases with the increase of packing density of cotton fibrous assemblies. A linear least square method is selected to fit fractal dimension and packing density curve to a straight line (see Figure 4(b) for an illustration). It can be seen that there exists a satisfactory
approximate linear relationship between the fractal dimension and packing density, with determination coefficient (R2) of 0.99648. Linear fitting results indicates the existence of internal connections between fractal dimension and packing density which are both characterization methods describing the morphology and structure of materials.

Figure 4. (a) Packing density-height curve and fractal dimension-height curve. (b) Fractal dimension-packing density curve and its linear fitting.

3.3. Pore analysis
A general fibrous assembly can be seen as a porous material since it is made of single fibers and air filling in the pores formed by these fibers. Porosity in this kind of materials become particularly important when it comes to transportation and conduction, such as fluid absorption and permeability behaviours [16]. Remarkably, porosity measurement discussed in this paper main refers to 2D micro-computed tomography results. Binarised objects are identified containing fully enclosed spaces, and closed porosity is the area of those spaces as a percent of the total area of binarised objects. Closed porosity measurement ignores space which is not fully surrounded by solid. Furthermore, closed porosity in 2D is usually much larger than the equivalent parameter measured in 3D. An open pore is defined as any space located within a solid object or between solid objects, which has any connection in 3D to the space outside the object or objects. Percent open porosity is the volume of open pores as a percent of the total volume. Total porosity is the volume of all open plus closed pores as a percent of the total volume. A series of peaks can be seen in closed porosity and height curve shows the existence of scarce closed poles, and the percent of open porosity is about 99.75% with some fluctuation proving that poles within this kind of material mainly exist in the form of open poles (see Figure 5(a) and Figure 5(b) for an illustration). Total porosity represents the tightness of fibrous assemblies (see Figure 5(c) for an illustration).
4. Conclusion
High-resolution X-ray micro-tomography experiment with a resolution of 3\(\mu\)m was performed on a randomly oriented cotton fibrous assembly and a direct three-dimensional visualization was given based on volume rendering technique. Results showed that values of packing density and fractal dimension are stable in randomly oriented fibrous assemblies, and there exists a satisfactory approximate linear relationship between the fractal dimension and packing density. Moreover, pore analysis indicates that porosity represents the tightness of fibrous assemblies and open pores holds the maximum proportion in fibrous materials.
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