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Skeleton-based tracing of curved fibers from 3D X-ray microtomographic imaging

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ABSTRACT

A skeleton-based fiber tracing algorithm is described and applied on a specific fibrous material, porous metal fiber sintered sheet (PMFSS), featuring high porosity and curved fibers. The skeleton segments are firstly categorized according to the connectivity of the skeleton paths. Spurious segments like fiber bonds are detected making extensive use of the distance transform (DT) values. Single fibers are then traced and reconstructed by consecutively choosing the connecting skeleton segment pairs that show the most similar orientations and radius. Moreover, to reduce the misconnection due to the tracing orders, a multilevel tracing strategy is proposed. The fibrous network is finally reconstructed by dilating single fibers according to the DT values. Based on the traced single fibers, various morphology information regarding fiber length, radius, orientation, and tortuosity are quantitatively analyzed and compared with our previous results (Wang et al., 2013). Moreover, the number of bonds per fibers are firstly accessed. The methodology described in this paper can be expanded to other fibrous materials with adapted parameters.

Introduction

Porous fibrous media have received increased attention in the past decade because of their easy manufacture (compared with foam materials) and growing use in most areas of science and engineering due to their excellent mechanical and transport properties. Recently, a promising fibrous material, PMFSS [1] was successfully manufactured and applied in fuel cell as crystal support layer in methanol stream reforming. Its unique fibrous architecture and high surface volume ratio were experimentally demonstrated to dramatically improve the production rate of hydrogen [2]. It's generally accepted that the macroscopic performance of the fibrous functional material is in deep correlation with the microstructure. To characterize the microstructure of PMFSS, in our previous work, various structural information of PMFSS concerning fiber segment orientation, length distribution, tortuosity, etc. were quantitatively investigated based on the extracted skeleton representation of the fiber structure extracted from the 3D X-ray images [3].

However, the optimization design of PMFSS needs further characterization of the arrangement of each individual fiber, rather than the fiber segments divided by fiber to fiber bonds. It is because the virtual fibrous material is generally created as the accumulation of individual fibers [4]. Unfortunately, owing to the nature of copper fibers and manufacturing process involving mold pressing and sintering, fibers in PMFSS are plastically deformed into various curved shapes with fiber bonds formed at contact regions, which increase the difficulty of identification of individual fibers.

Several approaches of tracing and identifying single fibers in fibrous material have been proposed taking advantages of various structural characteristics. Tessmann et al. [5] traced the fiber segments from tomographic 3D data of fibrous material composed of fibers with a unique diameter, the Hessian matrix of each voxel (pixel in 3D) was computed to estimate local orientations, fiber paths were finally reconstructed and tracked by connecting voxels with the minimum eigenvectors. Latil et al. [14] detected almost parallel fibers with convex cross sections. Adjoining fiber cross sections on the 2D slice image were separated using the watershed algorithm. More recently, Jerome [6] proposed a skeleton-based fiber segmentation algorithm to deal with low density materials. An extensive use of the DT method was applied to facilitate the identification of spurious segments due to the image noises and linking segments at fiber connecting joints. The remaining paths showed the most similar radius and orientation deviation was connected and merged under a parameterized criterion. Meanwhile,

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Gaiselmann et al. [7,8] extracted curved fibers of non-woven materials. The skeleton voxels with more than 3 neighbors were removed, and the remaining voxel paths were then vectorised into polygonal tracks. These tracks were later connected on either side which made balance between the deviation of angles and the distances. In addition, taking advantage of the same diameter of fibers, fiber bundles composed of parallel adjacent fibers were distinguished according to the DT values instead of misidentifying them as one single fiber.

It turns out that the most critical process in fiber tracing is the detection of the appropriate connecting fiber segment pairs, particularly in curved fibers. Thus, various tracing criterions were proposed [6–8] which aimed at achieving the correct segment links. In this work, we explore the efficient fiber tracing method adapted to our fibrous material, PMFSS. Instead of the complex parameterized tracing criterions used in existing methods [6–8], we reduce all affect factors (deviation of diameters, segment orientations, etc.) into one single parameter, the punishing angle, which is easier to understand and implement. Moreover, a multilevel tracing strategy is also proposed, which could effectively reduce the misconnection caused by the tracing orders. Finally, a further morphology exploration of PMFSS is performed according to the traced single fibers.

Materials and methods

Manufacture and micro-CT scans of PMFSS

The methodology of manufacture and microstructural characterization of PMFSS has been fully described in our previous studies [3]. Generally, after the cutting of continuous copper fibers and subsequent sintering and generation of PMFSS, its 3D images are obtained employing X-ray tomography. After a series of image processing involving selection of ROI, image enhancement of anisotropic diffusion [9] and binaryzation, the skeleton extraction is performed to obtain a topologically identical representation of the fiber structure. Fig. 1a shows the optical photographs of PMFSS samples with 90 porosity, and Fig. 1b shows the 3D geometrical reconstruction of ROI. Additionally, the porosity of PMFSS can be calculated with the mass–volume method as follows [1]:

$$E(\%) = \left(1 - \frac{M_p}{\rho_c V_p}\right) \times 100 \tag{1}$$

where V_p is the volume of PMFSS; M_p is the mass of PMFSS; ρ_c is the density of red copper.

Skeleton and segmentation

The skeletonization of fiber network in 3D binary image is computed using the thinning method [10] based on the DT method [11] and improved by introducing the scale axis transform method [12]. Once the skeleton was obtained, the voxels in skeleton were divided into three groups with respect to the 26-neighborhood of voxel (Fig. 2).

(1) End point, voxels with only one 26-neighborhood.
(2) Curve point, voxels with two 26-neighborhoods.
(3) Junction point, voxels with more than two 26-neigborhoods.

The skeleton network was then segmented into three groups of skeleton segments according to the three types of voxels:

(1) B–B path, both of the two end points are junction points.
(2) B–L path, one is an end point and the other is a junction point.
(3) L–L path, both of the two end points are end points.

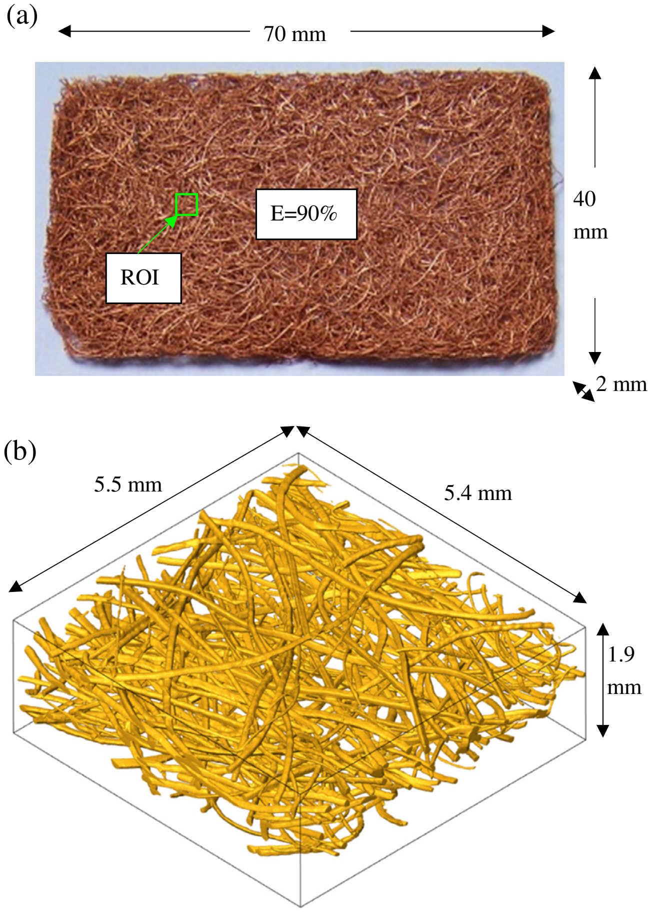

Fig. 1. (a) Optical photograph of PMFSS with 90% porosity sizing 40 × 70 × 2 mm and (b) 3D reconstructed geometrical visualization of ROI sizing 572 × 587 × 205 voxels, 1 pixel = 9.4 μm.

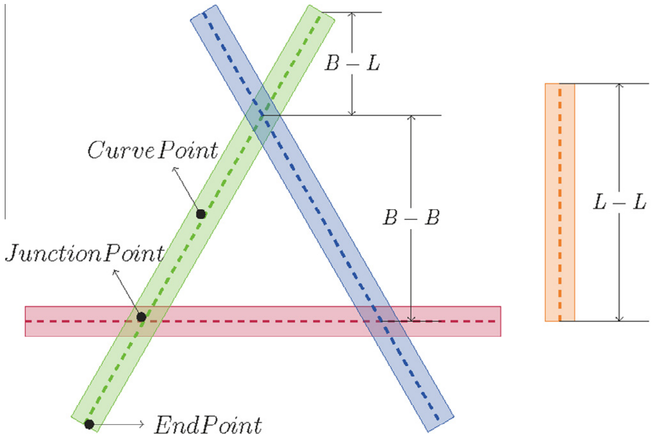

Fig. 2. Illustrations of categories of skeleton voxels and segments determined according to the categorized voxels.

Consequently, short B–L paths with length equal to the mean fiber radius were classified as spurs and removed. These B–L paths are mostly artificial segments due to the effect of digitization near the fiber surfaces. Fig. 3b shows the segmented skeletons of ROI sizing 200 × 200 × 50 with segments distinguished using different colors. The geometrical reconstruction of ROI is shown in Fig. 3a.