Journal of Membrane Science 497 (2016) 421–429

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

# Deformation modeling of polyvinylidenedifluoride (PVDF) symmetrical microfiltration hollow-fiber (HF) membrane

Shouichi Iio [a], Akio Yonezu [a,*], Hiroshi Yamamura [b,**], Xi Chen [c,d,***]

[a] Department of Precision Mechanics, Chuo University, 1-13-27 Kasuga, Bunkyo, Tokyo 112-8551, Japan
[b] Department of Integrated Science and Engineering for Sustainable Society, Chuo University, 1-13-27 Kasuga, Bunkyo, Tokyo 112-8551, Japan
[c] Department of Earth and Environmental Engineering, Columbia University, 500W 120th Street, New York, NY 10027, USA
[d] International Center for Applied Mechanics, SV Lab, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

*Article history:*
Received 16 May 2015
Received in revised form
3 September 2015
Accepted 19 September 2015
Available online 25 September 2015

*Keywords:*
Symmetrical microfiltration hollow-fiber membranes
Three-dimensional porous structure
Tensile deformation
Finite-element method
Water permeability

ABSTRACT

The tensile deformation behavior of polyvinylidenedifluoride (PVDF) symmetrical microfiltration hollow-fiber (HF) membranes was studied. The membranes had submicron pores with a three-dimensional open-cell structure. The surface and cross section of the porous membranes were observed by FESEM (field emission scanning electron microscope) to investigate the microstructure of the cell, namely, its size and ligament geometry. During uniaxial tensile tests, the membranes underwent elastic deformation and plastic deformation. Large deformation induced pore growth along the tensile direction, resulting in an increase in water permeability. In order to establish a mechanical model for tensile deformation, the finite element method (FEM) was employed. In this model, the Kelvin polyhedron (truncated octahedron structure) was used to mimic a three-dimensional open-cell structure. A one-unit cell based on this structure was created, and a periodical boundary condition was employed for the FEM computation. The FEM model could reproduce the overall elastoplastic deformation behavior of the porous membrane and provide useful insight into the fabrication of porous membranes and reliable operation of water purification.



## 1. Introduction

Membrane filtration is a promising technology in the treatment of drinking and waste water, because it removes suspended solids without the addition of any chemicals [1]. Among the various types of polymeric membranes (i.e., flat sheet, hollow fiber and tubular type), hollow-fiber (HF) membranes are often used for water purification processes because they provide a large membrane area in a limited space [2,3]. In practical operation, the accumulation of foulants on the membrane is a major obstacle to the efficient use of membrane processes. Such accumulation is routinely mitigated by physical cleaning [4–7], which includes air scrubbing, which causes the HF membranes to mechanically vibrate, consequently leading to detachment of accumulated contaminants from the membrane surface. Strong repetitive cleaning also potentially leads to fatigue damage of the HF membrane; in practice, breakage of the HF membrane on the edge of the potting in membrane modules is common [8]. To improve the fracture properties of HF membrane, membranes with high elongation and high strength have been developed by fabrication of prototypes; however, structure optimization of such membranes is still in an early stage.

Both macroscopic and microscopic dimensions of the membrane govern the mechanical strength of the membrane, and the inherent pore structure has inferior mechanical property compared with “solid” counterparts (matrix materials) [3,9–13]. However, there is still a lack of knowledge of the relationship between three-dimensional structures of porous matrixes and their mechanical characteristics (i.e., macroscopic deformation and fracture strength of the entire fiber membrane). As a result, optimization of the physical properties of porous membranes is done by trial and error.

Our previous study examined the mechanical deformation and inherent pore structure of polytetrafluoroethylene (PTFE) hollow-fiber membranes used for water purification [14]. Structural analysis using the finite element method (FEM) based on a simple pore structure model was carried out. Insight from this study may

* Corresponding author. Fax: +81 3 3817 1820.
** Corresponding author. Fax: +81 3 3817 7257.
*** Corresponding author at: Department of Earth and Environmental Engineering, Columbia University, 500W 120th Street, New York, NY 10027, USA. Fax: +1 212 854 7081.
*E-mail addresses:* yonezu@mech.chuo-u.ac.jp (A. Yonezu), yamamura.10x@g.chuo-u.ac.jp (H. Yamamura), xichen@columbia.edu (X. Chen).

http://dx.doi.org/10.1016/j.memsci.2015.09.048
0376-7388/

provide new guidelines for improving the physical and mechanical properties of hollow fiber membranes. However, our model consists of a very simple structure with only two dimensions; it needs to be extended to three-dimensional space and structure to account more accurately for the relationship between microscopic property and macroscopic deformation.

The present study examined the deformation behavior of a polyvinylidenedifluoride (PVDF) symmetrical microfiltration hollow-fiber (HF) membrane under uniaxial tensile loading, experimentally and numerically. We used the HF membrane, which has a symmetrical structure, fabricated by a thermally induced phase-inversion process. Tensile tests with various strain rates were carried out to observe the mechanical properties of the membrane (i.e., stress–strain curve), including yield stress and tensile strength. Furthermore, we investigated how the pore structure changed according to the applied tensile strain. Water permeability as a function of the applied strain was also investigated. On the basis of experimental results, we propose a three-dimensional mechanical model with a porous structure and studied its behavior by using FEM. The predictive model may be useful for designing structures with a given polymer and porosity. The present study shed light on the structural design of pores for physical cleaning and on the reliability of water purification.

## 2. Materials and experimental setup

The materials used in this study were hollow-fiber (HF) membranes for purification of drinking water (UNA-620A, microza®, Asahi Kasei Chemicals Corporation, Tokyo, Japan). These are commercially available module components for water purification [15]. The matrix was crystalline PVDF (polyvinylidenedifluoride). A thermally induced phase-inversion process was used to create a pore structure for the filtering process. The membrane cross section had a symmetrical microstructure. Fig. 1(a)–(d) shows the configuration and microstructure of the tested material. It resembles a tube and transports water through its wall. The inlet is the outer tube surface and the outlet is the inner tube surface. During use, a number of HF membranes assemble into a bundle and form a purification module. As shown in Fig. 1(a), the outer diameter is 1.23 mm and the inner diameter is 0.67 mm. The wall thickness is approximately 0.28 mm. The outer surface (Fig. 1(b))

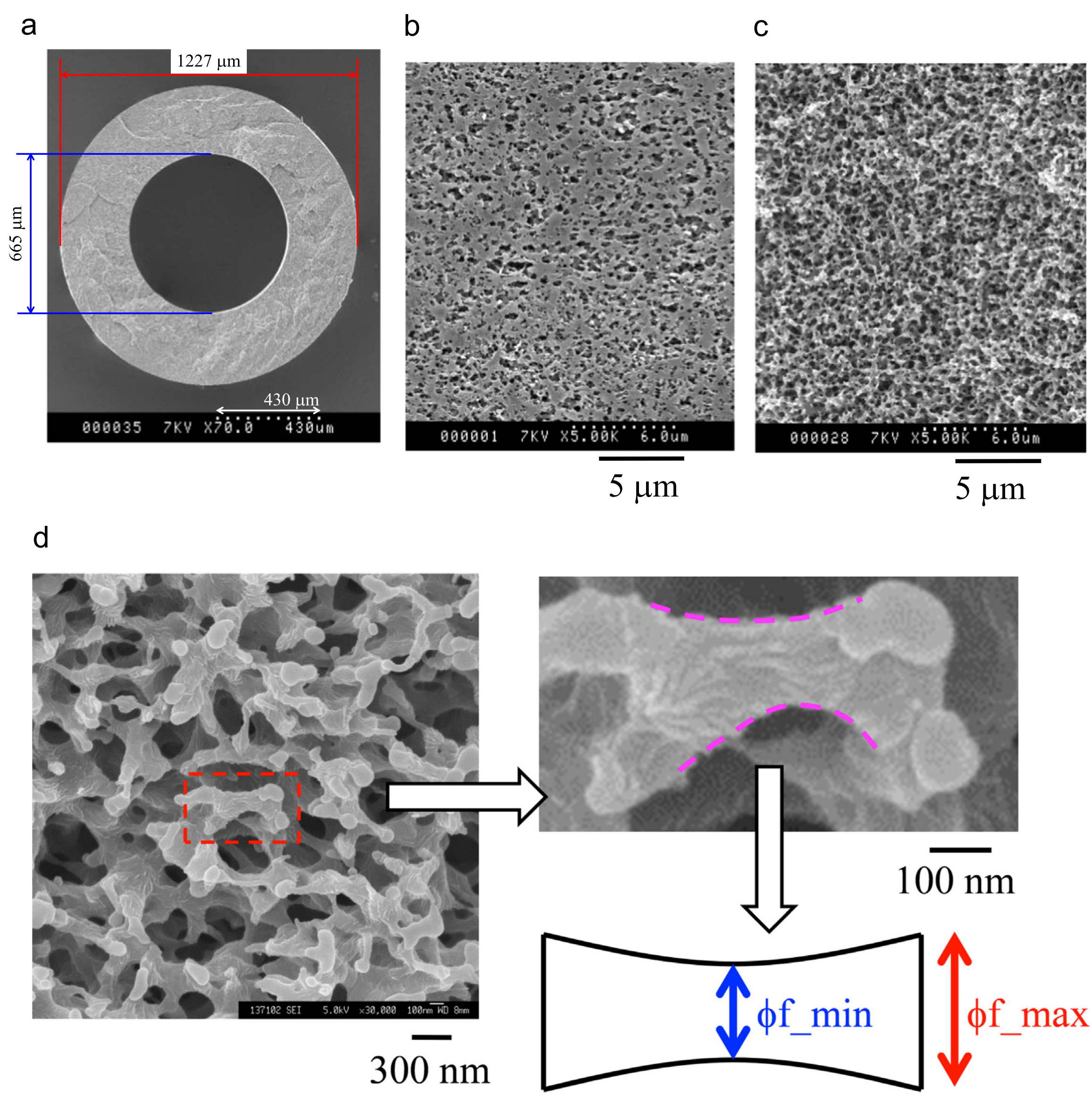


**Fig. 1.** Configuration and microstructure of the hollow-fiber membrane; (a) macroscopic view of cross section, (b) outer surface, (c) cross section, and (d) magnified view of (c).