

The ability to see a three-dimensional image of a material's microstructure would be an extremely useful tool in the engineering of filtration materials. Russell Kerschmann of Resolution Sciences Corp, USA, discusses a newly developed microimaging system that promises to do just that.

Filter Media Structure in Virtual Reality

Many filtration materials are based on complex three-dimensional (3-D) microstructures that are not always very well understood, despite the fact they may represent important multi-million dollar products. Nonwoven fibre or foam-based filter compositions can be manufactured by processes that introduce a considerable amount of structural randomness at the microscopic scale that can profoundly affect the function of the material. The microscopic structure usually cannot be accurately deduced from the material's macroscopic properties. High-fidelity, digital 3-D models of this microstructure could be important for the rational engineering of filtration materials. However, until now no technology has been available that could provide such replicate spatial data across the size range characteristic of these products.

Standard 3-D microimaging technologies such as scanning electron microscopy (SEM) or confocal microscopy cannot address component interactions hidden

deep within materials that may be a millimeter or more in thickness. The conversion of such materials into accurate digital replicates at the micron range of resolution would allow for a new host of analytical procedures that could revolutionize the way the industry approaches materials engineering. This article describes an entirely new digital volumetric imaging approach to 3-D microimage analysis of manufactured materials.

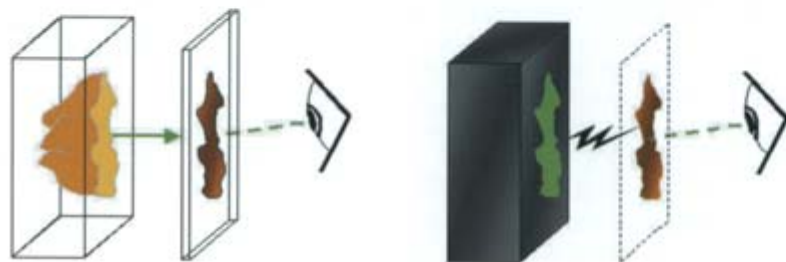
The technique is based on an optical technology that efficiently converts large volumes of material into high-fidelity digital data through a combination of unique chemical processing and serial two-dimensional (2-D) imaging. Precise 3-D digital data on filtration material generated by the system could allow for more accurate modelling and simulation of filter performance [1]. Simulations can best approximate the true function of a material if the data used for such investigations are based on an accurate model of the material; and this new micro-imaging method provides such data.

Digital Volumetric Imaging

In the digital volumetric imaging (DVI) process described here, samples of natural or synthetic fibre-based filtration material, polymer foam, or a wide spectrum of other materials are chemically labelled with fluorescent compounds and embedded in a polymer containing an opacification agent to form a solid sample block. The block is automatically sectioned on a robot-controlled microtome, producing a series of micron-thin slices through the sample. However, instead of imaging these sections, the system collects serial digital 2-D images directly from the cut face of the sample block after each cutting cycle (Figure 1). By removing the necessity to prepare individual 2-D sections, as would be the case in conventional transmission microscopy, this technique makes it possible to extract a large amount of data from an individual sample. Data sets generated may range from hundreds of megabytes to several gigabytes of information. The data constitute the raw material for a new host of microanalytical techniques, allowing for the first time the integrated understanding of important structure-function relationships in filters and other materials.

The imaging system is composed of three major elements: a motion controlled microtome rated for sectioning polymer blocks (Olympus Cut 4060 motorized microtome); fluorescence epi-illumination microscope optics (Nikon Eclipse); and a large-format (2000 x 2000 pixel) CCD array camera (Kodak MegaPlus 4.2i CCD camera).

Embedded samples are mounted on the microtome and sectioned by a diamond



Standard Optical Microscopy

Digital Volumetric Imaging System

Figure 1: Comparing the DVI system with standard optical microscopy.

knife, with a precision of 0.1 microns. After each cutting cycle, ultraviolet (UV) or short-wavelength visible light through the epillumination microscope optics illuminates the face of the block. A 2-D digital image of the sample appearing on the block face is captured by the CCD camera and stored on disk. The process is repeated approximately 1000 times for each sample, which takes between 2 and 4 hours, depending on the number of color channels and the total number of images required to section the sample. Once a large series of such images has been assembled, the image stack is recombined into a 3-D file for display and analysis by custom post-processing software.

The DVI system rapidly generates high-resolution 3-D data for visualization and analysis. The images produced are virtually free of misregistration artifact and replicate the topological features of the sample with a high level of fidelity. The sizes of the volumetric data sets produced are limited only by the data capacities of the imaging and storage systems. Data set sizes of between 1-16 gigabytes are routinely produced, and the present system is capable of generating up to 24 gigabyte images.

Sample Preparation

The key to obtaining high quality images by this method is the staining by immersion of the entire specimen using a mixture of fluorochrome dyes. This is then followed by infiltration and embedment within a solid medium containing high concentrations of opacifiers, which suppress emission of signals deeper within the block. Non-aqueous stains are used where water might alter the structure of the sample. A wide variety of fluorochrome compounds may be employed to label the sample, or some sample types may be inherently autofluorescence. The optimal environment within the block accommodates most of the standard fluorescent stains currently used in other forms of fluorescence microscopy.

The opacification of the embedding medium limits visualization of the tissue to a thin (1-2 micron) layer of the sample just below the cut surface of the block, producing in essence, a digital 2-D slice through the sample. Because the image is recorded from a surface rather than from a slice by adjusting the optical environment within the block the images can be made to approach zero thickness. This produces a greater resolution over conventional sections due to minimization of the overlayering of tissue structures. Furthermore, because the images are formed from a dark-field fluorescence emission, they are of high contrast compared to conventional bright-field microscopy.

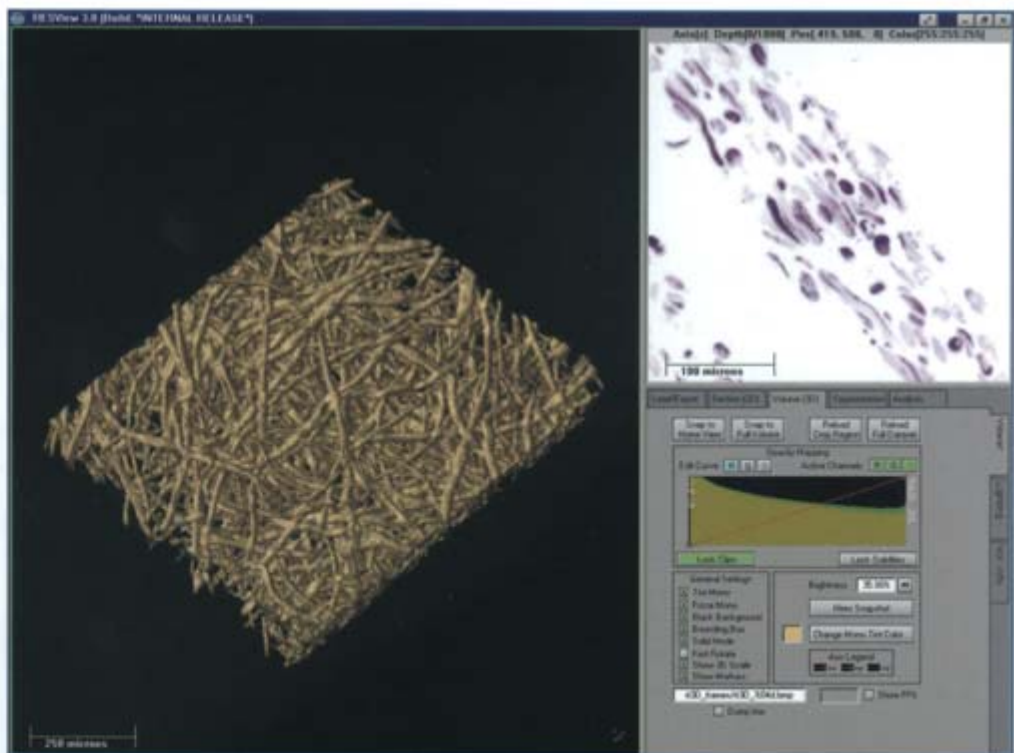


Figure 2: The DVI system's graphical user interface showing a sample of laboratory filter paper.

Visualization/Analysis Software

To visualize and quantify the large amount of spatial data generated by this technology, a high-performance volume rendering and analysis software application has been created. This is an interactive application for the real-time manipulation of volumetric data based upon an integrated 2-D & 3-D graphical user interface (Figure 2). The software is capable of a suite of data reduction routines, including segmentation based on colour, shape, density, and object connectivity, and includes a set of sophisticated analysis tools as described below.

The software is written in C++ for Microsoft Windows 2000 operating system. The optimal system hardware configuration includes a 1.5 gigahertz Pentium IV processor with 512 MB of RAM, a 30 GB or greater SCSI disk, a fast DVD-ROM drive, an accelerated 2-D/3-D video card with 16 MB RAM (e.g. Diamond V550 or V770), and a 21" high end color monitor (e.g. Sony G500).

The window displays an interactive 3-D model of the DVI data volume (Figure 3). The user can rotate and otherwise manipulate the image much as if it was a real object, and subject the model to a set of filters to remove obscuring sample elements. The user selects regions of interest in the model by cropping and re-magnifying the 3-D image. Introducing a crop plane immediately updates the adjacent 2-D window, permitting the user to precisely select full-resolution planar data at any orientation

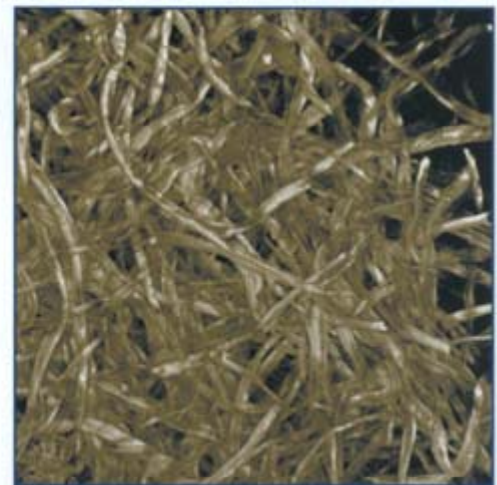


Figure 3: A high magnification 3-D image of a laboratory filter paper sample.

from the data set.

The colour 2-D image closely resembles the view seen through a conventional light microscope. The researcher pans and magnifies the 2-D image much as they would when using a conventional mechanical microscope. However, unlike slide-based microscopes the user has the capability to 'scroll' the plane of view through the entire sample with high accuracy.

The third window is the tools window is the 'tools' window. This tabular notebook-style interface contains all of the tools necessary to import, display, analyze, and export images and data.

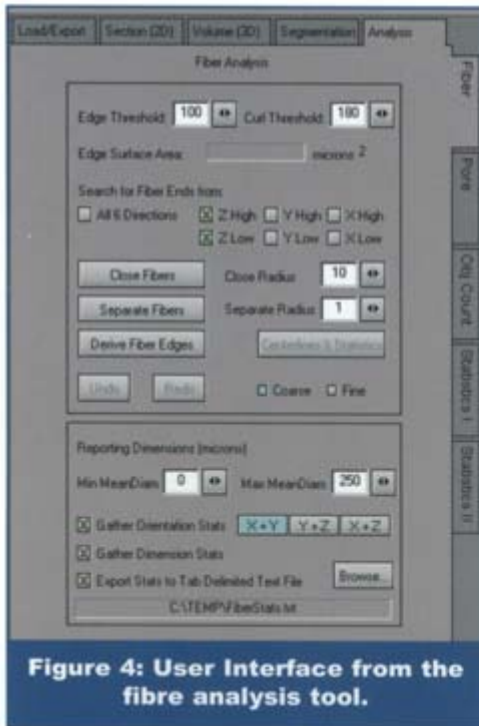


Figure 4: User Interface from the fibre analysis tool.

Filter Analysis

In the analysis of fibre-based materials, the DVI system offers a highly accurate approach for the quantification of standard fibre metrics. Measurements important for other types of materials, such as unit cell size in foam-based filters, can also be determined with precision. A fibre analysis software plug-in module has been created to work with the volume visualization and analysis package (Figure 4). The fibre and pore analysis tools provide a way to simultaneously visualize and analyze fibres and pores in 3-D to produce the following metrics.

a) Fibre Analysis tool:

- Mean fibre diameter in microns
- Fibre orientation in all three axes (Figure 5)
- Fibre statistics (exportable for further analysis)
- Total fibre surface area

b) Pore Analysis tool:

- Pores viewable as objects or as connected networks
- Minimum & maximum diameter of the pores in microns
- Length of the pore branch path
- Pore statistics (exportable for further analysis)
- Total pore surface area

The objectives are to gain a better understanding of how structure relates to function in nonwoven products, other materials composed of synthetic or natural fibres or open-pore structures of other types, and how fibre and pore structure affect bulk characteristics such as filtration and retention properties.

The fibre and pore analysis tools are based on an efficient skeletonization algorithm for the reduction of fibre, pore and other linear elements into single-voxel geometries that tracks the centerlines of the elements [2]. Once the data is reduced to its skeletonized form most of the subsequent analysis is based on an analysis of the 3-D spatial properties of this centerline.

Conclusions

Unlike other types of manufactured goods, nonwovens, foams, and other such materials have a quasi-biological organization resembling natural materials such as trabecular bone or plant tissue. Basing realistic simulation studies on manufacturing CAD files, for example, is not possible with such materials. The only way to gain truly accurate 'anatomical' data is by 3-D imaging of samples of the manufactured material itself. Prior to the development of the DVI system there was no technology that could generate such data. The complete conversion of important manufactured materials into high-fidelity 3-D replicate data represents a pivotal opportunity for research and development in the filtration and separation industry. As it has in other sectors, the capability to work with filtration material entirely in virtual space offers tremendous economies in basic research and opens new avenues for developing highly engineered materials.

References

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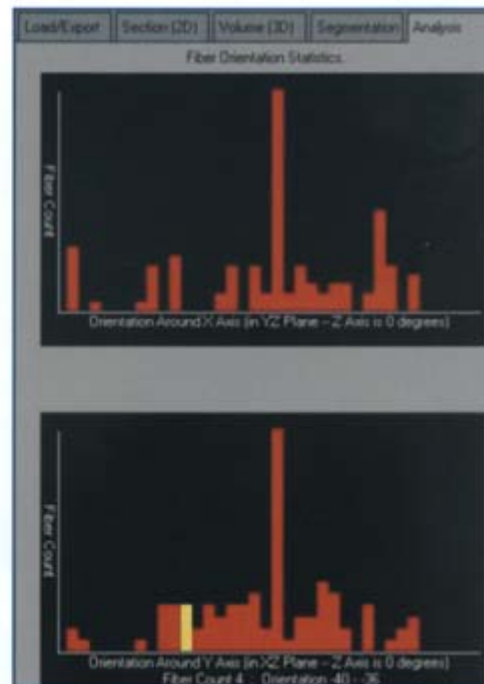


Figure 3: A high magnification 3-D image of a laboratory filter paper sample.