Three-Dimensional Fabric Analysis for Anisotropic Material Using Multi-Directional Scanning Line —Application to X-ray CT Image—*1

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In microscopic analysis, materials are characterized by a three-dimensional (3D) microstructure which is composed of constituent elements such as pores, voids and cracks. A material’s mechanical and hydrological properties are strongly dependent on its microstructure. In order to discuss the mechanics of geomaterials on a microstructural level, detailed information on their 3D microstructure is required. X-ray computed tomography is a powerful non-destructive method for determining the microstructure, however it can be difficult to determine a material’s microstructure from the reconstructed 3D image. We successfully evaluated the 3D microstructural anisotropy of porous and fibrous materials using a multi-directional scanning line method that employs straightforward image analysis, and its results were visualized using stereonet projection. [doi:10.2320/matertrans.I-MRA2007842]

(Keywords: X-ray computed tomography, three-dimensional microstructure, stereonet, anisotropy)

1. Introduction

The recent rapid advances in technology have resulted in an increased application of industrial materials having complicated ultrafine structures. Consequently, the demand for non-destructive inspection methods for achieving high-precision quality control, including the detection of minute defects, has increased. Computed tomography (CT) using a microfocus X-ray system has been developed to meet this demand. This X-ray inspection method has enabled visualization of three-dimensional (3D) structures to a spatial resolution of several micrometers. Microfocus X-ray CT has made it possible to observe the 3D microstructures of ceramics and biomaterials (e.g. bone tissue), something that was not possible to do previously because of the extremely fine structures of these materials. This technique has also recently been applied to observe voids in geological materials to relate to oil resource development, methane gas hydrate extraction, and construction of underground excavation for nuclear wastes. Thus, numerous microstructural observation studies have been reported.1–4)

Rapid progress has been made in recent years in non-destructive X-ray inspection technology. Regarding hardware, new microfocus X-ray sources and detectors have been introduced resulting in an improvement in the spatial resolution and other specifications of the technology.5) With respect to software, considerable research has been conducted on the processing and analysis of 3D image data. Image processing methods, such as contour definition and image recognition, have become a powerful tools for detecting material defects.6,7) In order to quantitatively determine the 3D structure from reconstructed 3D image data, voxel units have been used for measurements. Voids in materials or preferred orientation of particles were applied as measuring targets, and it’s geometrical characteristics, such as porosity and the direction of long axis, have been measured.8) However, difficulties are often encountered in extracting individual measuring targets when voxel units are applied to measurements. In particular, performing an extraction along the long axis to evaluate the anisotropy is extremely difficult. In this study, in order to overcome this difficulty, we attempted to perform structural anisotropy measurements by inspecting the 3D structure using multidirectional scanning lines. In addition, the obtained anisotropy of the 3D structure were evaluated quantitatively using a stereographic projection.

2. Microfocus X-ray CT System

The most significant difference between a microfocus X-ray CT system and a conventional X-ray CT system is that the former has the ability to converge the diameter of the X-ray-generating electron beam. Accordingly, the focal spot size can be extremely small (2–50 μm). In this study, the tomography system used the HMX225 system manufactured by Tesco Corporation to obtain X-ray CT images, and a microfocus X-ray system is used to achieve a high spatial resolution. The highest achievable spatial resolution is 2 μm, which is sufficiently small to determine the fine structures of industrial and geological materials. This system essentially consists of an X-ray system, a sample, and an image intensifier (see Fig. 1). The sample is irradiated with X-rays from the X-ray system, X-ray images from the sample are then collected by the image intensifier, and the X-ray CT images are reconstructed by computer processing. In this case, the sample is rotated using a high-precision manipulator, called a third generation system, and cross-sectional X-ray images are acquired by the image intensifier. The
two-dimensional (2D) image data, which is magnified so that it fills the entire area of the image intensifier, is digitized by 12-bit A/D converter using a CCD camera. The magnifying power is given by the ratio of the distance from the X-ray focus to the image intensifier to the distance from the X-ray focus to the sample (see Fig. 1). Accordingly, the closer the X-ray focus is to the sample, the magnifying power will be higher. If a transmissive target is used in the X-ray generation system, the distance between the X-ray-generating metal target and the window through which the X-rays are emitted, can be shortened, resulting in an increase in the magnifying power. In addition, if the X-ray tube voltage is increased, the wavelength of the generated X-rays becomes shorter, and, as a result, the transmissivity of the X-rays through the sample increases.

3. Quantitative Evaluation of the Three-Dimensional Anisotropy

3.1 Evaluation of three-dimensional anisotropy by stereonet projection

A conventional technique for quantitative evaluation of the anisotropy of the 3D structure associated with a measuring target (such as a pore, a particle or a crack) is to assign a unit vector in the direction of the target. For example, if the target structure is ellipsoidal, such as a pore, the unit vector \( \mathbf{n} \) can be assigned so that it is parallel to the major axis of the ellipsoid. As another example, if the target structure is a disk, such as a crack, the unit vector \( \mathbf{n} \) can be assigned so that it is perpendicular to the disk, (i.e., it is a normal vector to the disk). The 3D fabric associated with the targets structures can then be defined in terms of the direction cosines of this normal vector. Here, the probability density function \( E(\mathbf{n}) \), which is defined relative to a set of normal vectors, is introduced to evaluate the fabric associated with the target.

The stereonet projection is employed as a conventional method for visualizing the density function \( E(\mathbf{n}) \); it is one of the most powerful techniques currently available for expressing 3D fabric. The stereonet projection is a general technique and is routinely used to visualize \( E(\mathbf{n}) \) in structural geology and crystallography. However, it is not a popular method in other fields, therefore, we explain the procedure of stereonet projection in order to help understanding. The principle of stereonet projection is shown in Fig. 2(a). There are two types of stereonets, Wulff nets and Schmidt nets. In a Wulff net, also referred to as an equal angle projection, information from a hemisphere is projected onto the plane of the equator. The other kind of stereonet, the Schmidt net, projects onto a plane, the center of which is the pole of sphere, and the error margin of the information increases with distance from the center, however, the area is constant everywhere. Thus, it is termed an equal area projection. In this study, we used a Schmidt net for stereonet projection.
The procedure for stereonet projection is as follows. Let a vector having a unit vector \( n \) through the center of a sphere, such that the vector intersects the surface of the sphere at the point \( P_1 \). That point \( P_1 \) is projected to the point \( P'_1 \) on the Schmidt net by keeping the distance between \( P_1 \) and \( P'_1 \) constant. Then the point projected on the Schmidt net corresponds to a vector in the direction of the target, such as the normal to a crack surface or the major axis of a pore. It is possible to represent the 3D anisotropy in a 2D plane by measuring the directions of many target structures in materials and projecting them on the stereonet.

### 3.2 Three-dimensional fabric analysis by multi-directional scanning line

When drawing a stereonet projection using unit vectors \( n \), we need to obtain the density by calculating for many unit vectors \( n \). If the major axis direction of the target, such as voids or particles, can be determined by image processing, the density function \( E(n) \) can be determined. However, it is very difficult and impractical to extract individual objects (voids and other) from a 3D image and measure their directions. In this study, therefore, we decided not to measure \( E(n) \) but to measure the directions of many target structures in materials and projecting them on the stereonet.

### 3.3 Extraction of the measuring target and porosity

The 3D anisotropy can be expressed quantitatively if \( m(q) \) measured using multi-directional scanning lines is plotted on a stereonet with a contour plot. When measuring the target using scanning lines, we need to detect the measuring target using binarization based on a threshold value. Using image analysis, we discuss how the selection of the threshold value will affect \( m(q) \). Berea sandstone, which is popular rock as a oil reservoir rock, was used for image analysis. This sandstone found in the central region of America and is mainly composed of quartz having an average grain diameter of 1.5 mm. A 2D image (\( x_1-x_2 \) plane) having resolution of 20\( \mu \)m/pixel was used to acquire the CT images. A total of 300 images were acquired at intervals of 20\( \mu \)m along the \( x_3 \) axis. The 300 X-ray CT images were stacked to create a 3D image set. Each X-ray CT image contains information about a 256-grey (8-bit) levels defined by X-ray attenuation coefficient, and each grey level reflects the density. The observed area was composed of voids and solids. The threshold value \( T \) was approximately 105 for the X-ray attenuation coefficient of a void or air. Since the X-ray attenuation coefficient is related to the density of substance, we can say that an area having a value exceeding that of the air threshold value is obviously a solid that is denser than air. Figure 5 shows an initial image acquired from an arbitrary cross-section of a 3D structure along with its binary images at threshold values \( T \) of 85, 105, and 125. In these images, the
black areas are voids and the white areas are solid. The threshold value does not change greatly on a macro scale, but individual neighboring voids are linked. By using these images having different threshold values, \( m(q_1) \) and \( m(q_2) \) in the \( x_1 \) and \( x_2 \) directions were measured (Table 1). Taking the air threshold \( T = 105 \) as the standard, \( m(q) \) varies by about 20% when the threshold value deviates by \( \pm 20 \). However, from the viewpoint of directional ratio \( m(q_1)/m(q_2) \), the error caused by the selection of the threshold value is small. A change in the image as a consequence of varying the threshold value, for example, causes the void linkage or area (volume) to increase, but its effect on anisotropy is very small. By using a 3D image to determine the threshold value, we can measure the porosity in 3D. Table 1 gives the porosities at threshold values of 85, 105, and 125. 

For comparison, we give the actual porosity \( \phi \), which was determined by measuring the porosity using mercury porosimetry for the same sample as the one used for X-ray CT. Mercury porosimetry is a method for determining the specific surface area and the pore distribution based on the pressure and the amount of mercury which is injected into voids. By this method, the porosity of the Berea sandstone, \( \phi \), was 18.4%. The porosity obtained by image processing, \( \phi' \), ranges between 16 to 20% depending on chosen threshold value. The porosity determined for the threshold based on air density \( (T = 105) \) is 18.5%, thus the porosity can be evaluated with high accuracy by this method. From this agreement in the measured porosities, we can say that most voids are linked. If the porosity of an entire sample is known in advance, the threshold value for the X-ray CT images can be set by binarization on the basis of the known porosity.

### Table 1 Summary of \( m(q) \) and porosity depend on threshold value.

<table>
<thead>
<tr>
<th>Threshold value; ( T )</th>
<th>85</th>
<th>105</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m(q_1) \times 10^{-2}/\text{mm} )</td>
<td>7.48</td>
<td>8.30</td>
<td>11.18</td>
</tr>
<tr>
<td>( m(q_2) \times 10^{-2}/\text{mm} )</td>
<td>7.52</td>
<td>8.41</td>
<td>11.50</td>
</tr>
<tr>
<td>( m(q_1)/m(q_2) )</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
</tr>
<tr>
<td>Porosity; ( \phi' % )</td>
<td>16.55</td>
<td>18.14</td>
<td>19.99</td>
</tr>
</tbody>
</table>

Fig. 5 (a); Initial image of X-ray attenuation (resolution; 8-bit). (b)–(d); Binary image after image analysis at each threshold value (resolution; 1 bit). Scale bar is 5 mm.
4. Three-Dimensional Fabric Analysis of Anisotropic Materials

We conducted 3D fabric analysis on actual anisotropic materials by considering the scanning line length and the threshold value. In this experiment, the total scanning line length, \( L(q) \), was set to 10 times the size of the analyzed area \( D \). The analysis sample was a fiber-resin prepared by solidifying carbon fibers with resin. The threshold value between fiber and resin was determined by the resin density. The analysis area was 20.48 mm in diameter and 10 mm high, and the resolution of 2D image (\( x_1 - x_2 \) plane) is 20 \( \mu \)m/pixel. A total of 500 images were acquired at intervals of 20 \( \mu \)m along the \( x_3 \) axis. These images were stacked in the direction of the \( x_3 \) axis to create a 3D image set. Figures 6(a)–(c) show typical images taken from \( x_i \) (\( i = 1, 2, 3 \)). These images were stacked in the direction of the \( x_3 \) axis to create a 3D image set. Figures 6(a)–(c) show typical images taken from \( x_i \) (\( i = 1, 2, 3 \)). In these images, the white areas indicate the substrate resin, while the black areas indicate fibers. Images from different cross sections, particularly ones from the \( x_1 - x_2 \) plane (Fig. 6(a)), show apparent anisotropy of the fiber orientation. The targets of measurement are fibers in resin and appear black in the figure. Figures 6(d)–(f) show the numbers of targets per unit length \( m(q) \), which intersecting with the scanning line in the \( x_i \) cross section, measured every 10'. \( m(q) \) in the 3D image is measured as follows:

1) Arbitrary central coordinates are randomly generated in the 3D image.
2) From the central coordinates, scanning lines are generated using scanning lines having components parallel with the direction vector \( q \) so that the total scanning line length, \( L(q) \), will sufficiently long.
3) The number of fibers intersecting with the scanning lines is measured and used to calculate \( m(q) \). For example, the \( m(q) \) distribution in the \( x_1 - x_2 \) plane shown in Fig. 6(d). This diagram means the anisotropy of the target (fibers, in this case) in a cross section clipped at random by the 3D image. Here, \( m(q) \) in Figs. 6(d)–(f) are measured in 12 directions (every 15°) in each cross-section, making a total of 36 directions for the three cross-sections. Figure 7 shows these measured directions expressed using a stereonet. In this figure, solid
circles (●) represent directional vectors \( q \) in the \( x_1-x_2 \) plane, squares (■) represent \( q \) in the \( x_2-x_3 \) plane, while triangles (▲) represent \( q \) in the \( x_1-x_3 \) plane. The open circles (⊙) in the figure represent the symmetrically in the \( x_1-x_2 \) plane. Rhomboids (♦) represent the direction of scanning line rotated from the \( x_1 \) axis to the \( x_2 \) axis by \(-30^\circ, -60^\circ, 30^\circ, \) and \( 60^\circ \) with the \( x_3 \) axis at the center. In each plane, \( m(q) \) was measured in 12 directions. Scanning lines were chosen in a total of 84 directions and \( m(q) \) was measured for each direction. \( m(q) \) was plotted on a stereonet, and the contour was drawn (Fig. 8). Low values of \( m(q) \) are concentrated near the \( x_1 \) axis. This indicates the direction where the scanning lines cross fibers at low possibility. Therefore, we can say that the major axis orientations of the fibers are concentrated in low-density regions on the stereonet. The major axes of the fibers used in this study are inclined at about 15° from the \( x_1 \) axis to the \(-x_2 \) axis and about 20° from the \( x_1-x_2 \) plane to the \( x_3 \) axis in the coordinate system.

5. Conclusion

In this study, the 3D fabric analysis using multi-directional scanning lines was carried out on a 3D image created from anisotropic materials by microfocus X-ray CT. The analytical error is reduced if the density of air or another material, rather than the measuring target, is used to determine the threshold value for the image. In addition, the RVE can be obtained if the total scanning line length is set to at least 10 times greater than the analytical area. Using a stereonet, we were able to express the anisotropy of materials using multi-directional scanning lines, and could evaluate the principal axis of measuring targets.

The fabric of fibers, pores and cracks in material is related to permeability and mechanical properties. We can confidently say that microstructural-based study on materials will greatly advance if microfocus X-ray CT is used concurrently with that the 3D fabric analysis method.

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REFERENCES