Evaluation of Material Properties of Pantograph Contact Strip by Microscopic Structure Model

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Most frictional materials used in railways such as pantograph contact strips and wheel tread brakes are made of composite material. It is well known that macroscopic properties of the composite material largely depend on their geometric microscopic structure such as size, shape and distribution of their constituents. Conventionally, railway materials have tended to be developed experimentally by trial and error. However, to make the process of material improvement or development more effective, it would be useful to clarify the relationship between a material's microscopic structure and macroscopic material properties by numerical simulation.

In recent years, despite the increased use of various simulation methods to assist material design, few methods have been applied for railway materials. One example for railway material does exist, which is the application of atomic scale methods such as molecular orbital methods and molecular dynamics methods to evaluate the behavior of materials [1]. However, it is difficult to interpret macroscopic phenomena using an atomic scale model. In this study, we attempted to model composite material in a micro-meter scale structure and develop a method to calculate the material properties to be compared with macro-scale values. The procedure of the method is shown in Fig. 1. Firstly, a three-dimensional microstructure of a sample of a contact strip is visualized using high-resolution X-ray computed tomography (CT). Secondly, a part of the CT images obtained is extracted as a region for modeling. The extracted region is segmented into each constituent material, and then meshed to make an FEM model. Finally, the material properties are calculated using the homogenization method [2].

This paper describes the results of applying the method to metalized carbon, which is one of the pantograph contact strip materials (Chapter 2 to 5). Using the microscopic model, the stress, temperature and current density distribution in the microscopic model are also calculated (Chapter 6).

2. Material

The material used in this study is a metalized carbon (PC78A, manufactured by Toyo Tanso Co., Ltd.), which is widely used for pantograph contact strips on Japanese railway lines. This material is made by impregnating porous carbon with copper and is regarded as almost isotropic. Figure 2 shows the material structure of PC78A by an optical microscope. The yellow parts are copper, the black parts are voids, and the other gray parts are carbon.

Table 1 shows the material properties of PC78A and the volume fraction of each component estimated from the bulk density.

3. Observation of microstructure by X-ray CT

3.1 Observation method

The microstructure of PC78A was observed by X-ray CT. Table 2 shows the X-ray CT measurement conditions. SkyScan 2211 (Bruker Corporation) was used. A schematic diagram of X-ray CT is shown in Fig. 3. It irradiates the sample with X-rays and detects the transmitted X-rays to
know the internal structure. Since the X-ray transmittance depends on the density and atomic number of each constituent material, the two-dimensional transmission image visualized by the detector reflects the internal structure of the sample. By rotating the sample to collect transmission images from multiple directions and reconstructing the images by computer, a three-dimensional image of the sample can be obtained. The brightness of the grayscale image corresponds to the X-ray transmittance at each position in the sample. The higher the transmittance, the lower the brightness, and the lower the transmittance, the higher the brightness.

3.2 Result of observation

Figure 4 shows a part of the 3D and 2D image of PC78A. The white parts seem to be mainly copper, the black parts seem to be mainly voids, and the gray parts seem to be mainly carbon. But the boundary between the void and carbon was unclear. Since the black parts also have a continuous brightness distribution as will be described later, the black parts may contain low-density carbon in addition to void.

4. FEM modeling based on X-ray CT image

4.1 Modeling method

First, in order to reduce the image processing time, the image resolution was lowered by changing the voxel spacing of the image from 1 μm to 3 μm, and then a median filter was applied to remove the impulse noise of the image. After that, a cube with a side of 600 μm was extracted from the CT image as a region representing the microscopic structure. Next, the image was segmented into voids, carbon, and copper regions on the basis of the difference in their X-ray transmittance. The threshold value of the image brightness was set so that each segmented region would have the volume fraction shown in Table 1. Each segmented region was composed of many connected parts with various size of volume. Since the connected part with a small volume will generate many finite elements on the subsequent meshing process, the part connected with less than 10 voxels in the void region and the part connected with less than 50 voxels in the copper region were reassigned as carbon regions. By meshing the carbon and copper regions, an FEM model was created (hereinafter referred to as model 600). FEM models with a side of 300 μm (hereinafter referred to as models 300① to 300⑧) were also created to evaluate the difference in the volume fraction of the model and the accompanying physical property values depending on the extraction position from the CT image. These models were created by dividing the area of the above model 600 into eight as shown in Fig. 5. Simpleware (Synopsys, Inc.), 3D image processing software, was used for the above image processing and meshing.

4.2 Result of modeling and discussions

Figure 6 shows the image brightness histogram of the cubic region of the model 600 as frequency on the vertical axis and brightness on the horizontal axis. Note the range of brightness assigned to voids, carbon, and copper is also shown on the horizontal axis. Figure 7 shows an image segmented into the void, carbon, and copper regions and a microscopic structural model of 300①. The cross-sectional segmented image is shown in Fig. 8 together with the microstructure photograph by an optical microscope, although it is a different sample from the CT-imaging sample shown in Fig. 7. The volume fractions of each component after meshing for each model are shown in Table 3.

As shown in Fig. 6, the boundaries in brightness between voids,
carbon, and copper are not clear, and multiple components may be in the same brightness region. However, even with the simple segmentation method using the brightness threshold shown above, the obtained model had a distribution and volume fraction of each component close to the actual material as shown in Fig. 8 and Table 3. Comparing the volume fractions of model 600 and models 300① to 300⑧ from Table 3, the average values of models 300① to 300⑧ are close to the values of model 600, but the volume fractions of copper of models 300① to 300⑧ vary widely from 12% to 20%. These variations occur due to structural non-uniformity by the extraction position of the model in the sample. Although the variation due to the position can be reduced by increasing the modeling area, it is considered that the material properties of PC78A can be evaluated reasonably in feasible calculation time by using the average value of eight 300 µm size models.

In creating an image-based model of a material, the larger the size of the modeling area, the smaller the effect of material non-uniformity. However, as the size of modeling area increases, the computational load for image processing and material property calculation increases. Hence, it is necessary to determine the appropriate size of the modeling area according to the structural characteristics and purpose of calculation.

5. Calculation of material properties by homogenization method

5.1 Calculation method

Figure 9 shows a schematic diagram of the homogenization method. In the method, it is assumed that the inhomogeneous material has a periodic microstructure, and the scale of the microstructure is sufficiently smaller than that of the macroscale. Considering that the microscopic structure is replaced with a homogeneous material having the same properties, the equivalent material properties of the inhomogeneous material are obtained.

The elastic constants of replaced homogeneous material $D_{ijkl}$ are derived by (1), where $y$ is the coordinate in the microscopic structural model (region $Y$) and $E_{ijkl}(y)$ (each index=1,2,3) are the elastic constants at $y$ [2].

$$D_{ijkl} = \frac{1}{|Y|} \int_Y \left( E_{ijkl}(y) - E_{ijmn}(y) \frac{\partial X^{ij}_{mn}}{\partial y_i} \frac{\partial X^{ij}_{mn}}{\partial y_j} \right) dy$$

The characteristic displacement function $X^{ij}_{mn}$ in (1) is obtained by solving (2) under periodic boundary conditions.

$$\int_Y E_{ijmn}(y) \frac{\partial X^{ij}_{mn}}{\partial y_j} \frac{\partial \delta u}{\partial y_i} dy = -\int_Y E_{ijmn}(y) \frac{\partial \delta u}{\partial y_j} \frac{\partial X^{ij}_{mn}}{\partial y_i} dy$$

where $\delta u$ is virtual displacement. For isotropic materials as PC78A, the elastic constants are reduced to two components, Young’s modulus and Poisson’s ratio.

The thermal conductivity and electrical conductivity can be also derived by the same method. For the microscopic structure model created in Chapter 4, the homogenization analysis of (1) and
(2) was performed to calculate the material properties using Simpleware module.

To calculate the material properties of PC78A by (1), the material properties of carbon and copper are required. For copper, the nominal value was used. For the carbon parts of PC78A, which are polycrystalline carbon and contain micro voids below the resolution of X-ray CT, a suitable value cannot be determined from the relevant literature. In general, the material properties of polycrystalline carbon greatly depend on the raw material, manufacturing process, heat treatment temperature, density, void ratio and crystal orientation. Furthermore, the material properties of carbon part only cannot be measured experimentally.

Therefore, the material properties of the carbon part were estimated by the carbon substrate before impregnation with copper. Specifically, a model of the carbon substrate was created using only the carbon part of the CT image of PC78A in Chapter 4, and the material properties of carbon were determined so that the calculated material properties of the carbon substrate model by the homogenization analysis would reproduce the measurements.

The material properties of copper and carbon were applied to the PC78A model and homogenized analysis was performed to calculate the material properties of PC78A.

### 5.2 Results of calculations and discussions

Table 4 shows the estimated material properties of carbon by homogenization analysis using the model of carbon substrate. Table 4 also shows the material properties of copper used for the analysis below.

Some measurements and estimates of carbon material properties are described in several documents. For example, the Young’s modulus of an isotropic pyrolytic carbon is experimentally 13.5 GPa and theoretically 16 to 74 GPa [3]. The thermal conductivity is 6 to 420 W/mK for a polycrystalline graphite [4]. The electrical resistivity is estimated to be 2.2 to 234 μΩm corresponding to the thermal conductivity 6 to 420 W/mK by the relationship between the thermal conductivity and the electric resistance for the artificial graphite [5]. The estimated material properties of carbon in Table 4 are considered reasonable because they are within the range of these literature values.

Table 3 shows the results of calculated material properties of each model of PC78A by the homogenization method with the values in Table 4.

|                  | Young’s modulus (GPa) | Poisson’s ratio | Thermal conductivity (W/mK) | Electrical resistivity (μΩm) |
|------------------|-----------------------|----------------|-----------------------------|-----------------------------|
| C                | 24                    | 0.22           | 3.8                         | 38.46                       |
| Cu               | 118                   | 0.33           | 391                         | 0.0171                      |

Figure 10 shows the relationship between the volume fraction of copper and calculated material properties together with the measured values in Table 1. The larger the ratio of copper, the higher the Young’s modulus (the slope of linear regression is 0.43 GPa/%) and thermal conductivity (the slope of linear regression is 1.7 W/ mK/%), and the lower the electrical resistivity (the slope of linear regression is -0.14 μΩm%). Compared to Young’s modulus, thermal conductivity and electrical resistivity depend more on the volume fraction of copper. The difference based on the influence of the copper ratio can be considered to be due to the difference in the ratio of the material property value of copper and carbon. That is, this is because the Young’s modulus of copper is 5 times that of carbon, the thermal conductivity of copper is 110 times that of carbon, and the electrical resistivity of carbon is 2250 times that of copper.

As shown in Fig. 10, in the range of the volume fraction of copper of 12% to 16%, each calculated material property is close to the measured value.

Figure 11 shows the average of calculated material properties for models 300① to ⑧ (indicated as “Hom.” in figure) in comparison with the measured values (indicated as “Exp.” in figure) and the estimated values by the classical rule of mixture based on the Voigt model [6] (indicated as “Mix.” in figure), which estimates the material properties by the volume fraction of the constituents. The calculated values by the homogenization method are closer to the measured values than the values by the rule of mixture. This result is because the rule of mixture uses only the volume fraction of the components, whereas the homogenization method reflects the microscopic structure such as the arrangement and shape of each component in addition to the volume fraction.

### 6. Other analysis examples of the microscopic model

The pantograph contact strip slides along the contact wire while collecting electrical current. Therefore, in addition to the mechanical load caused by the contact with the contact wire, the con-
tact strip is subject to Joule heat caused by energization, and thermal load by arc discharge when the contact strip is separated from the contact wire. The distribution of stress and temperature in the contact strip can be calculated by FEM analysis using a macro model with homogeneous material properties. However, a more detailed distribution considering the inhomogeneity of the material will be necessary to understand the frictional phenomenon near the surface. Therefore, we calculated the distribution of stress, temperature, and current density on μm scale using a microstructural FEM model, to which the boundary conditions were given.

6.1 Calculation method

Model 300-3 described in the previous chapter is used. The stress distribution is calculated by structural analysis, and the temperature and current density distribution are calculated by thermal analysis with Joule-heat. The material constants in Table 4 are used for the analysis. The boundary conditions for structural analysis are shown in Fig. 12 (a). The bottom is completely restrained, and a pressure simulating the contact force with the contact wire is applied to the top. A static analysis is performed assuming the conditions shown in Table 5.

The boundary conditions for thermal analysis with Joule-heat are shown in Fig. 12 (b), and the assumed conditions are shown in Table 6. Since the contact wire is placed in a zigzag manner with respect to the rail direction, the contact position between the contact wire and the contact strip moves left and right on the strip in the sleeper direction. Under the conditions shown in Table 6, the contact time of the contact wire at a certain position on the strip is 4.5 ms. Therefore, a transient analysis was performed by applying the time-dependent heat flux and current density shown in Fig. 13 to the top of the model. The initial temperature is 20°C, the potential on the bottom is 0 V, and the target time of transient analysis is 6.5 ms.

6.2 Results and discussions

Figure 14 (a) shows the model used, and Fig. 14 (b) shows the equivalent stress distribution. The stress in the copper region was higher than that in the carbon region because the Young’s modulus of copper is higher than that of carbon.

Figure 15 (a) and (b) show the temperature distribution and current density distribution at t = 5 ms. The temperature distributions are also shown in Fig. 15 (c) and (d), which are divided into copper regions and carbon regions. The temperature of the carbon regions was higher than the copper regions. It is considered that the heat transfer from the top surface to the bottom surface is slower in the carbon region because the thermal conductivity of carbon is lower than that of copper. The electrical current mainly flows in the copper region since copper has a higher electrical conductivity than carbon.

It is difficult to directly observe and measure the distribution of temperature near the friction surface on a microscopic scale. Hence, the estimation of it expected to be useful for understanding phenomena such as wear, damage, and deterioration due to friction. In this study, the results are qualitative because only the cube region with a side of 300 μm is modeled and the boundary conditions are directly imposed on the model. In order to make a quantitative estimation on a micro scale, it is necessary to obtain the physical quantity distribution in the micro region inside the macro model that simulates the actual phenomenon. For that purpose, it is not feasible to model the entire strip with a mesh of μm size, but it is reasonable to perform zooming analysis using another macro model or to use a model in which only a part is meshed on a microscale.
7. Conclusions

We constructed a method to calculate the material properties of copper-impregnated carbon using a microstructure model using X-ray CT images. The results are summarized as follows:

1. X-ray CT imaging was performed to obtain a three-dimensional microscopic structure.
2. A microscopic structural model based on X-ray CT images was created.
3. Using the created model, the Young’s modulus, thermal conductivity and electrical resistivity were calculated by the homogenization method. The calculated values were closer to the measured values than those from the estimation by the rule of mixture.
4. The distributions of stress, temperature and current density in micro-meter scale were calculated by finite element analysis using the model.

The calculations using the microscopic model enable the estimation of the material properties before their trial production in the material development process and the proposal of the material structures having more desirable properties.

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