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X-ray computed tomography based microstructure reconstruction and numerical estimation of thermal conductivity of 2.5D ceramic matrix composite

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ABSTRACT

In this study, the X-ray computed tomography was adopted to build 3D finite element models of the 2.5D ceramic matrix composite. The threshold segmentation method was used to identify the SiC matrix. An approach was developed to identify and number the matrix regions. The geometrical features of the 2.5D microstructure such as symmetry and periodicity were utilized to identify the boundaries of warp and weft. The warp, weft and porous matrix were denoted by different colors. The finite element model of 2.5D microstructure was built based on the color of each pixel. The finite element models combined with homogenization method were then used to predict the thermal conductivity of material. An element compression method was developed to reduce the total number of elements. The in plane and out-of-plane thermal conductivities were estimated by both numerical and experimental methods. The comparisons show that the numerical results fit experiments well.

1. Instruction

Ceramic matrix composites (CMCs) have excellent mechanical behavior at elevated temperature, which are among the most potential materials for high-temperature structure. Thermal conductivity is the basic parameter of the CMCs for thermodynamics analysis [1]. However, the anisotropic and heterogeneous characteristics of CMCs make great challenges to measure or calculate the thermal conductivities.

Many researchers were devoted to estimating the thermal conductivity of composites by numerical methods. The key to predict thermal conductivity of CMCs is to establish a model close to the actual structure. The thermal conductivity of 3D four direction braided CMCs was predicted by Ref. [2] based on "*" model. However, the average error between the simulation and experiment results is 26.7%, which is slightly large, for the model is far from the actual structure. Ref. [3] established a model based on Ref. [4,5] which could similarly represent the actual structure to predict the thermal conductivity of 3D four direction braided CMCs. And the average error is improved greatly but still about 11.5%. The cross section of the yarns is assumed to be hexagon in Ref. [3]. To the cross section of yarns, several assumptions that they are ellipse [6,7], hexagon [8,9] or octagon [10] were made. Ref. [11] made a comparison about the influence of cross sections of different shapes on thermal conductivity of CMCs. And Ref. [11] found the difference could be almost ignorable. Besides, there are large quantities of holes distributing in internal material due to the complicated manufacturing process. Hence, porosity is another important factor that affects the prediction of the thermal conductivity of CMCs. Ref. [12] considered that poles only existed in matrix. Then the effect of the porosity fraction on the thermal conductivity was investigated and proved to be huge in Ref. [12]. Besides, the pores analyzed by SEM were incorporated to the model of braided composites by Ref. [13]. The predicted results agree relatively well with the experiment.

It should be noted that the arrangement of the constituent materials in all RVE models established above is assumed to be regular and ordered. Moreover, the cross section of yarns is supposed to be uniform and regular. However, constituent materials are not arranged regularly in actual material. And there exists serious deformation on cross section of yarns during the fabricating process. Furthermore, small

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voids are distributed randomly in internal material. Therefore, a RVE close to the real structure still need to be established.

The recent developed X-ray computed tomography (XCT) has ability to detect the internal structure as small as 1 μm, which provides a feasible method to build models based on actual microstructure [14–25]. In those works, XCT data were used to calibrate the numerical models [17–21,25] or obtain the geometrical parameters such as porosity characterization [22–24]. However, those methods can not translate the XCT data to FEM model directly.

Gao et al. [15] have developed a method that the XCT data can be translated to FEM model directly, but it requires an artificial approach to identify the fiber bundles. The work of identifying is huge if the XCT data contain hundreds or thousands of slices. This study is an expansion of paper [15]. In order to identify the fiber bundles automatically, the ceramic matrix regions were recognized firstly by the threshold method. Then the matrix regions were numbered and divided into several groups. The geometric features of matrix were utilized to identify the boundaries of fiber bundles. Then, the XCT slices with information of fiber bundles and matrix were translated to FEM model directly. The homogenization method was adopted to estimate the thermal conductivities of material. An element compression method was also developed in this study to decrease the total number of elements. The comparison between numerical method and experiment shows that the method developed in this paper is reasonable.

2. Experiment and material

The material in this paper is C_f/SiC which was produced by the Chemical Vapor Infiltration process. The material is provided by Institute of Metal Research, Chinese Academy of Sciences. The carbon fiber is T700-6K (Toray Company) and the diameter is about 6 μm. The fiber volume fraction of the composite is 30%. The cross section of the material is shown in Fig. 1, which indicates that many voids distribute randomly in the material.

XCT is used to obtain slices of the internal structure of material. The choice of resolution depends on the ability of XCT equipment and the size of the specimen. The XCT equipment is YXLON-Y Cheetah system which has ability to detect the structure as small as 1 μm. The maximum size of the slice is 1024×1024 in pixel. In order to construct the model which contains several periods of the microstructure of the material, the resolution is set to 5 μm in this paper. Then the size of the model is $5 \times 5 \times 5$ mm^3 which contains enough geometry information of the microstructure. The parameters of the XCT equipment are listed in Table 1.

The total number of XCT slices is 800. Fig. 2 shows one XCT slice where the voids and matrix can be recognized clearly. Colors of the matrix, fiber bundles and voids are white, grey, and black respectively. After trimming the useless regions, the final size of the model is 580×301×800 in pixel.

The thermal conductivity is measured by the Hot Disk instrument (TPS 2500S) which is produced by Hot Disk AB company. The shape and size of the specimen for thermal conductivity test are shown in the Fig. 3. Three specimens were tested and the average values are shown in the Table 2.

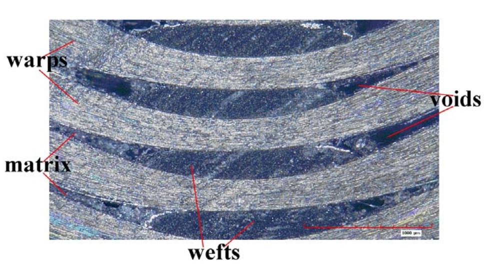

Fig. 1. Microstructure of the 2.5D CMCs.

3. Microstructure reconstruction

3.1. Structure characteristics of 2.5D CMCs

Fig. 2 shows that in the XCT slices grey levels of the warp and weft are similar. So it is difficult to distinguish the warp and weft by their grey level only. The geometrical features of 2.5D preform should be utilized. Based on Fig. 4, the geometrical features of 2.5D CMCs in microlevel are summarized below:

(1) The grey level of the matrix is much higher than that of other parts; (2) the matrix regions are almost quadrangular. The four corners of matrix region are denoted by A, B, C and D in this paper; (3) the adjacent matrix regions are approximately parallel and the matrix regions in adjacent columns are almost symmetric about the center line of the slice; (4) The regions between two vertical adjacent matrix regions are the warps. (5) The regions between two horizontal symmetric matrix regions are the wefts.

Based on above features, the following steps are developed to identify the fiber bundles, matrix and voids in material: (1) threshold segmentation algorithm is used firstly to identify the matrix regions and then the matrix regions are numbered; (2) boundaries of the warp and weft are identified by fitting the boundaries of matrix regions; (3) the finite element model is rebuilt.

3.2. Identify and number matrix regions

We assume that the pixel with grey level g which is greater than a threshold g_{cr} is matrix. The value g_{cr} is an integer and ranges from 0 to 255. The OSTU method [26] is used to estimate the optimal threshold g_{cr} of one XCT slice. After the threshold segmentation, the grey value of a pixel only has two levels, e.g. 0 or 255. The pixels with the grey level of 255 are set to be matrix.

The following approach is used to number the matrix pixels: First, identify the vertical symmetric axis of the image. The vertical symmetric axis divides the image into two parts i.e. left part and right part. In the left part, search the matrix pixels from bottom to top and from left to right. If a pixel is belonged to matrix, then search the matrix pixels with group number in the area around the current matrix pixel within the radius of R. If there is no matrix pixel with group number, it means that the current matrix pixel belongs to a new group. Then give a new group number to the current pixel. This case is shown in Fig. 5(a). If there exist several matrix pixels with group numbers, the minimum group number is chosen and given to all the matrix pixels in the area around the current matrix pixel within the radius of R (see Fig. 5(b)).

Fig. 6 shows the case in which two parts of one matrix region separate. The above approach will identify these two parts as different groups since the distance between the two parts is larger than R. In order to combine these two parts into one group, first, calculate the average slope of the matrix region, and then search the other matrix groups in the region shown in Fig. 6. The searching region is enclosed by the two lines which offset from the center line, the edge and vertical symmetry line of the slice. The offset distance is defined as d_{offset}. All the matrix groups in the searching region are merged into one matrix group.

3.3. Identify the boundaries of the warp and the weft

Fig. 4 indicates that regions between the vertical adjacent matrix groups are the warps. In order to identify the boundaries of the warps, firstly, the corners of a matrix group i.e. the left, top, right and bottom corners are denoted by A, B, C and D respectively, which is shown in Fig. 7.

It should be noted that the matrix groups near the edges of the slice are probably cut by the boundary of the slice. There exist six cases which are shown in Fig. 8. In the first case, the B–C boundary is cut by the upper edge of slice (Fig. 8(a)). The matrix region becomes a