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Test method

Measurement and quantitative analysis of fiber orientation distribution in long fiber reinforced part by injection molding

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ABSTRACT

The fiber orientation distribution is one of the important microstructure variables for thermoplastic composites reinforced with discontinuous fibers. In this paper, the long fibers in the injection molded part are measured in detail by micro X-ray CT. A three dimensional (3D) structure of the sample is built and two dimensional images are generated for image analysis. The orientation tensor of fibers is calculated in the flow plane. It shows a symmetric distribution of fibers through the thickness direction, which consists of outer skin, transition zone and the core. The skin layer is so thin that it has only one layer of highly oriented fibers. The core layer also has highly oriented fibers but the direction of fibers is different from that in the skin layer. Nevertheless, the clustering of the fibers is characterized quantitatively in the core. The transition zone can be divided into two subzones by the principal directions of the tensor.

1. Introduction

Use of fiber reinforced thermoplastics has greatly increased in recent years in the automotive industry due to the requirement of weight reduction. Since fiber orientation is critical for the mechanical and thermal properties of a composite, prediction of the fiber orientation is drawing more and more attention in Computer Aided Engineering. The fiber orientation distribution is important for building microstructure models of composite strength [1,2], warpage and shrinkage, thermal conductivity [3], etc. Prediction of fiber orientation is challenging for long fiber reinforced polymer manufactured by injection molding because the fibers are able to bend during the processing [4].

The fiber orientation in injection molded parts is affected by the shear and extensional flows during processing, leading to the formation of a layered structure. It is reported that the layered structure plays an important role in the mechanical behavior of the composites [3,5]. Thus, it is essential to find a way to characterize the layered structure.

During recent decades, many researchers [3,6–11] have adopted destructive ways of characterizing fiber orientation. Usually, the sample is cut and polished in order to take a microphotograph of the ellipse mark of the fibers left on the cross section, which can be used for image analysis. This approach is still being used by many researchers because of its simplicity and low cost. For short fibers, each ellipse mark indicates one single fiber because the fiber is straight in the composite. However, a single elliptical mark cannot be used to describe the direction of a long fiber because the fiber leaves different sizes of ellipse in the cross section at different locations due to its bending in the matrix.

In 1995, H. Yaguchi etc. [12] proposed a non-destructive method based on soft X-ray photographs for short fibers. The fibers and matrix were distinguished by the gray value

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of the pixels in the image. On the boundary between the fiber and matrix, the pixels would have different gray value than the adjacent one. However, this method provided the fiber orientation information on the projection plane only. As computer technology continues to advance, X-ray computed tomography (X-ray CT) is proposed, which is based on a series of radiographic projections taken at varying angles [13–15]. It provides an increasingly practical solution to characterize fiber orientation. Using X-rays as a penetrating probe, this technology affords detailed microstructure information from almost any material. Also, the technique eliminates tedious sample preparation and associated artifacts. Moreover, micro-CT data can be used for reconstruction and presented in one, two and three dimensional formats, suitable for observation and measurement for a variety of purposes. The whole fiber could be analyzed by image analysis, whether or not the long fiber bends.

In this paper, micro X-ray CT is adopted to characterize the fiber orientation of long fiber reinforced polypropylene. Then, the layered structure of the fiber distribution is analyzed in detail by the reconstruction of the target samples. Finally, the fiber orientation distribution of each layer is described quantitatively by eigenvalue and eigenvector.

2. Experiment and simulation

2.1. Material and sample

Two 16 mm × 16 mm specimens were cut from different locations of an auto instrument panel manufactured by injection molding, which are highlighted in Fig. 1. The plane zone was chosen to simplify the work. Furthermore, the structure at these points could be related to further mechanical tests (tensile etc.).

The long fiber reinforced polypropylene STAMAX 20YK270E was supplied by Saud Basic Industries Corporation (SABIC), in which the fiber was 20% in weight and 6 mm in length originally.

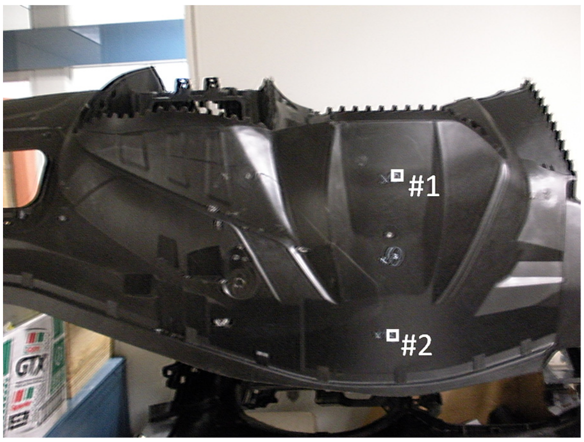

Fig. 1. Injection molded instrument panel and the sample positions.

2.2. CT scanning

A SkyScan 1172 micro-CT was employed to take images of the fibers in the instrumental panel. The X-ray source was fixed. A CCD (charge-coupled device) radioscopic detector detected the X-ray absorption radiographs through the object on a rotating stage. The relative positions of the X-ray, object and 2D detector are shown in Fig. 2. Between each radiograph, the specimen was rotated by a small angle (0.3 degree) to provide a different view. When more than half of the circle was completed, the entire set of radiographs was read and synthesized in VG Studio to build a three-dimensional (3D) structure of fiber distribution. The 3D structure consisted of numbers of cubic volumes called voxels, whose size was set as 6 μm × 6 μm × 6 μm to capture the fibers clearly, considering that the diameter of the fiber was about 30 μm. In VG Studio, the image in any preferred plane of the 3D structure could be generated and exported. The pixel in the image was as small as 6 μm × 6 μm.

2.3. Image analysis

For the two dimensional tensor, the angle θ is enough to define the direction of a single fiber in the planar polar coordinate (Fig. 3). The components in fiber the orientation tensor are calculated by using Equation 1 [9,16–19]. The orientation tensor is shown as an ellipse (see Fig.4), where the smallest and largest diameters are the eigenvalues (λ_1, λ_2) of this tensor and the directions of these axes are the eigenvectors ($\vec{e}_1$, $\vec{e}_2$).

$$\left[a_{ij}^k\right] = \begin{bmatrix} cos^2\theta_k & cos\theta_k sin\theta_k & 0 \\ cos\theta_k sin\theta_k & sin^2\theta_k & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}; \left[\vec{e_1}\ \vec{e_2}\ 0\right] \tag{1}$$

When there is more than one fiber, the orientation tensora_{ij} is calculated by averaging all fiber orientation tensors, as shown in Eq. 2.

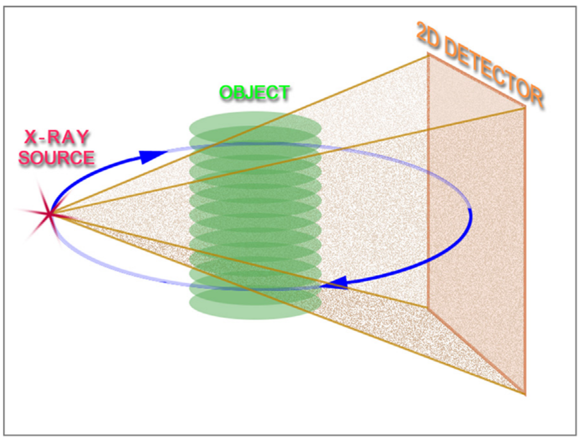

Fig. 2. The diagram of X-ray CT scanning from the company Materialise.