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Analysis of filament arrangements and generation of statistically equivalent composite micro-structures

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ABSTRACT

An efficient method to describe and quantify the filament arrangement in fibre bundles based on the analysis of micrographs was developed. Quantitative measurement of relative filament positions indicated that the initially random arrangement of filaments shows increasingly strong characteristics of square and hexagonal configurations with increasing level of transverse compaction. An existing micro-structure generator was extended to incorporate the measured data allowing statistically equivalent filament arrangements to be generated at any fibre volume fraction. These can be used to determine micro-structural properties of actual fibre reinforced composites.

1. Introduction

Mechanical and processing properties of fibre reinforced composites are strongly influenced by the heterogeneity of the reinforcement. During impregnation of the reinforcement with a liquid resin system, the variability in the filament arrangement leads to local differences in flow velocities and an increased probability of air entrapment which in turn may reduce the service life of the finished part [1]. In addition, published studies showed that the mechanical properties are overestimated if the random filament arrangement at the micro-scale is disregarded [2]. Most material models incorporating micro-scale variability of the filament arrangement are based on artificially generated random configurations [3]. These models do, however, not necessarily exhibit the same statistical filament distribution as present within actual fibre bundles. Owing to the difficulty of gathering data on the intrinsic variability of fibre reinforcements [4], algorithms which can generate statistically equivalent micro-structures are rarely implemented. This study describes an automated method for determination of parameters to describe the micro-structure of a fibre bundle and statistical analysis of the measured data. In addition, an algorithm is proposed to generate equivalent representative micro-structure models which is adapted from the work of Vaughan and McCarthy [5]. These models can be used to predict reinforcement processing properties, e.g. resin flow during impregnation in composites processing, and micro-scale properties of composite parts.

2. Materials and data acquisition

To characterise the degree of heterogeneity in fibre bundles at different transverse compression levels, single layer composite panels were moulded and cured at different cavity heights. Panels with dimensions 125 mm × 60 mm were made from a low-crimp fabric and a low viscosity epoxy resin system. The fabric consisted of uni-directional carbon fibre bundles, stabilized by thin glass weft threads coated with a thermoplastic polymer (Fig. 1).

The specimens were moulded by circumferential injection of the liquid resin into a stiff metallic tool containing the fabric. By varying the mould cavity height, *h*, the level of fabric compression was controlled and three sets of panels with global fibre volume fraction, V_f of 0.45, 0.60 and 0.74 were produced [6]. The influence of bundle compaction on the micro-structure was then analysed based on a total of 26 fibre bundle cross-sections, extracted at random positions. The micro-structure of moulded and cured specimens was determined for entire fibre bundles at high resolution by means of optical microscopy. Other imaging techniques, such as micro-computed tomography [7], were identified to have inferior resolution. Images were acquired with a bright field reflected light microscope equipped with an automated stage and a 12 bit monochrome camera. The pixel spacing, i.e. the distance between pixel centres, of the resulting images was determined to be 0.093 μm. This resolution was considered to be sufficient and the

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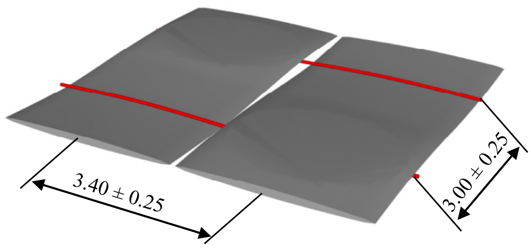

Fig. 1. Idealised unit cell of the quasi UD fabric. Fabric data provided by Sigmatex Ltd.: Areal density, A_f: 300 g/m^2, Warp yarns: T700SC 12 K 50C, Weft yarns: Fusible combi-yarn (225Dtex). Dimensions shown are in mm. Image created with TexGen available from http://texgen.sourceforge.net.

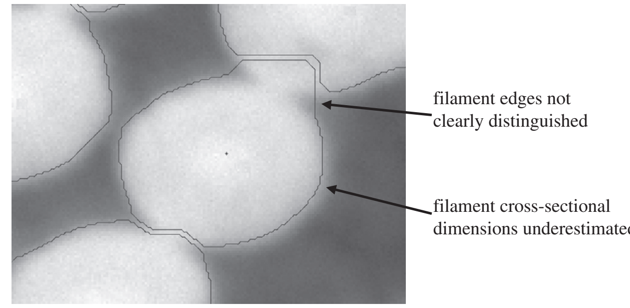

Fig. 3. Magnification of a micrograph of filament cross-sections. Filament boundaries after greyscale thresholding and watershed segmentation are indicated.

method is inexpensive and simple compared to, for example, a Scanning Electron Microscope (SEM).

Large area scanning was enabled by a computer-controlled stage, which allows automated *x*–*y* positioning as well as automated *z*-positioning of the sample. Stitching of overlapping single images enables large areas to be studied [8,9]. A stitching code was implemented based on Fast-Fourier correlations [10] programmed in Matlab®. This allowed the micrographic analysis of entire fibre bundles in cross-sections of the manufactured composite panels. The stitched images were analysed automatically at much higher resolution compared to examples reported in the literature [11].

3. Image analysis

To gain morphological data from the acquired images, a simple colour thresholding technique is often employed [8,12]. However, inevitable differences in lighting, local light reflections and shading [13] make it unfeasible to use a single global threshold for a complete image which can contain up to 250 individual filaments. This effect is amplified locally by the presence or absence of filament cross-sections within the image. This results in different greyscale values for the same object. Fig. 2A shows a section of a captured 8 bit micrograph. The greyscale values are re-coloured in Fig. 2B to emphasise local colour differences of the filament cross-sections. In addition, the theoretical resolution of an optical light microscope is limited by the wavelength of the light used and can be estimated as about 0.2 μm for visible light [13]. It is impossible to distinguish between object edges which are closer to each other than the resolution limit. Employing a greyscale threshold to Fig. 2 and watershed separation of the remaining objects [14] will result in filament edges which are not determined correctly (Fig. 3). For example, areas of adjacent filament cross-sections appear to belong to another filament, leading to erroneous morphological data.

Owing to the problems encountered when a simple thresholding technique is employed, an automated image analysis process was developed in this study. This analysis is based on the edge detection of local colour gradients and overcomes the issues described above. This allows the micro-structure of a fibre bundle containing a large number of filaments to be determined accurately in an automated manner.

3.1. Image processing

Since the simple thresholding technique cannot be applied for accurate detection of filament cross-sections, a different approach is utilised here, based on prior knowledge of the expected filament shape. For the case of carbon filaments a circular cross-sectional shape is presumed, which may appear elliptical if the filament axis is not normal to the cross-sectional plane [15]. A window of defined size is centred on every single filament cross-section estimated by simple global thresholding and a watershed separation [14], and localised image analysis is executed. It is possible to detect filament edges directly in these local images using established algorithms, e.g. Canny's edge detector [16]. Employing this method (Fig. 4A) and fitting an ellipse to the detected edges, it was found, however, that the detected filament radii are underestimated compared to the dimensions of a set of manually fitted ellipses on high magnification SEM images (Fig. 4B). Instead of using the original image, local colour gradients were calculated (Fig. 4C) in these locally confined areas. This allows absolute colour values of the image to be neglected. The problem of different levels of contrast or brightness, which depends on the position of the filament in the overall image, can therefore be overcome. After smoothing the image, edges of the colour gradients were determined using Canny's edge detector. The image of the filament boundary gradients shows two distinct edges (Fig. 4D). Utilising the results in Fig. 4A, the inner edges are eliminated, which leaves

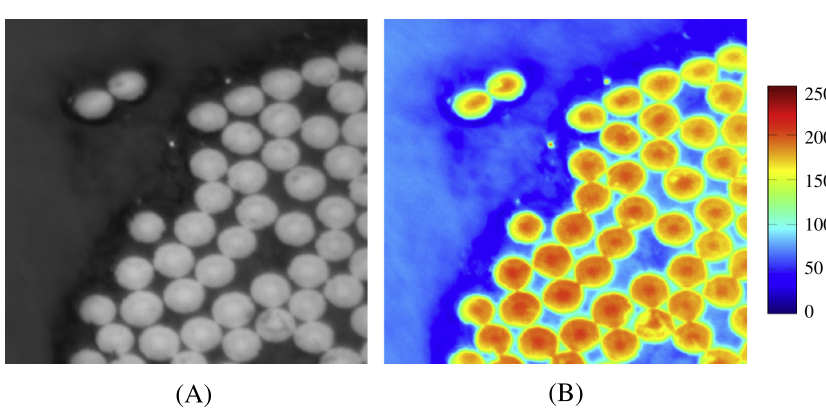

Fig. 2. (A) Part of a 8 bit micrograph of a carbon fibre reinforced composite cross-section and (B) the same image re-coloured to emphasise differences in local colour values.