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Geometrical characterization and micro-structural modeling of short steel fiber composites

Y. Abdin [a,*], S.V. Lomov [a], A. Jain [a,b], G.H. van Lenthe [c], I. Verpoest [a]

[a] KU Leuven, Department Materials Engineering, Kasteelpark Arenberg 44, BE-3001 Leuven, Belgium
[b] Siemens Industry Software nv, Interleuvenlaan 68, BE-3001 Leuven, Belgium
[c] KU Leuven, Biomechanics Section, Celestijnenlaan 300c, BE-3001 Leuven, Belgium

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ABSTRACT

Short steel fiber reinforced polymer composites are a newly introduced class of materials which combines outstanding properties of stiffness and ductility. The first step in modeling composite mechanical properties is the generation of a representative volume element (RVE) which accurately describes the distinctive microstructure of the material. Injection molded short steel fiber composites exhibit a complex microstructure due to the three-dimensional orientation, waviness and entanglements of the fibers. The present work proposes a data structure for description of the RVE geometry and algorithms for RVE random generation. The micro-structure of short steel fiber reinforced polycarbonate samples was determined using X-ray micro-computed tomography (micro-CT) and the model input parameters were identified using a specialized image processing methodology, based on the Mimics software package. Model generated RVEs were satisfactory compared qualitatively as well as quantitatively against the real micro-CT reconstructed volumes.

1. Introduction

Steel fiber reinforced polymers (SFRP), composed of annealed stainless steel fibers embedded in a polymer matrix are a novel class of materials with high strength and stiffness properties. The inherent ductility of the annealed stainless steel fibers is an added advantage in comparison with the brittle glass and carbon fibers [1,2]. Steel fibers and steel fiber reinforced polymer composites have been widely used in strengthening of concrete structures to improve their durability and toughness. The addition of steel fibers results in conversion of the failure behavior of concrete from brittle to more ductile [3–7].

The diameter of steel fibers used in the reinforcement of concrete is at least 10 times larger than the micron-sized steel fibers used in this study. It has been shown that in addition to their favorable mechanical properties, micron-sized stainless steel fibers have intrinsic electrical conductivity, heat and corrosion resistance [1]. Commercial steel fibers used in this study are highly efficient in electromagnetic (EMI) shielding applications: up to 60 dB EMI shielding for 1.5% volume fraction (V_f) of fiber concentration (15% weight fraction – W_f) [8].

In the last decades, short fiber reinforced composites have been widely used especially in the automotive sector [9,10]. Among various processing methods considered for this category of materials, the injection molding process has been increasingly used due to its versatility in high volume production of complex shapes at low costs [11]. The performance of short fiber composites is governed by the complex geometry of the fiber distribution in the part [12–18]. Unlike continuous UD or textile fiber reinforced composites, short fiber reinforced composites depict stochastic geometrical features that evolve during processing [19]. Moreover, during the injection molding process, high shear stresses exerted in the melt by the screw rotation, in addition to fiber–fiber interactions, lead to fiber breakage, resulting finally in a range of fiber lengths (l), characterized by a length distribution function ψ_L [20–22]. The complex flow of the melt, both in the screw area and in the mold, results in variations of fiber orientations over the part, locally characterized by a fiber orientation distribution function $\psi(\theta, \Phi)$, where θ and Φ are the fiber orientation angles in a spherical co-ordinate system [10,20,23].

Owing to the high aspect ratio of annealed stainless steel fibers, their low bending rigidity, low yield stress and high ductility, the fibers are plastically deformed into very curved shapes. Hence, an important characteristic of injection molded short steel fiber composites is the high waviness of the fibers, which adds to the complexity of the short fiber geometry.

* Corresponding author.
E-mail address: Yasmine.Abdin@mtm.kuleuven.be (Y. Abdin).

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Precise knowledge of the microstructure, needed for accurate predictions of the mechanical properties of a short fiber composite, imparts a particular challenge for the three-dimensional wavy steel fiber thermoplastic composites. In the past decades, different techniques have been investigated for acquiring such information for composites with short straight fibers. For measurement of the fiber orientation distribution, microscopical observations on polished samples provide two-dimensional sections of the fibers; simple geometrical calculations allow then to generate the fiber orientation [6,17,24,25]. Despite low equipment cost associated with these methods, they are destructive and time consuming and hence only small volumes can be analyzed. More importantly, they often are not capable of accurate extraction of three-dimensional information [19,24–27]. The fiber length distribution can be determined with matrix burn-off techniques, which are again destructive and are prone to significant errors due to degradation of the fibers and altered geometries [28].

To overcome those problems, X-ray micro-computed tomography (micro-CT) recently emerged as a powerful non-destructive tool for three-dimensional fiber microstructure analysis [26]. A number of studies thus far aimed at the characterization of the geometrical parameters of short and long fiber reinforced composites using X-ray micro-CT techniques [19,28–31]. However, the primary focus of those investigations is straight fibers or straight fiber segments. The quantification of the architecture of wavy fibers reinforced composites remains yet a new topic of interest. The use of X-ray micro-CT is especially suitable for the characterization of the steel fiber reinforced polycarbonate samples considered in this study, due to the large difference in X-ray absorption and hence high contrast imaging between the metallic fibers and the polymer matrix.

The geometry of wavy fiber assemblies was studied before in the field of non-woven textile materials. In a series of papers [32–35], Pourdehyhimi et al. investigated different methods of evaluating fiber orientation distribution functions (FODs) of non-woven fabrics using image analysis, including direct fiber tracking, two-dimensional Fourier analysis of images and a flow-field analysis to derive fiber orientation by analyzing local texture information. By applying these methods on simulated structures with well described orientation and further, on real non-woven webs, they concluded that direct tracking is the most accurate technique for extracting fiber orientation distributions. Similar investigations for characterizing FODs of wavy non-woven assemblies using image processing include, among others, Gong and Newton [36], Rawal et al. [37], Masse et al. [38], Xu and Yu [39] who explored Hough transform image analysis algorithms. Nevertheless, all of the mentioned investigations involve two-dimensional techniques based on early concepts developed by Komori and Makishima [40] who considered that FODs of curved fibers can be approximated by those of hypothetical straight segments obtained by subdivision of fibers and replacement of divided parts by straight segments. The main disadvantage of this concept is that the resulting FODs depend on fineness of subdivision of the fibers leading to inaccuracies [32,40]. Those can be especially more significant in the case of three-dimensional wavy fibers. Thus, a technique allowing three-dimensional analysis of complex wavy fibers and an accurate method for the description of the FOD of three-dimensional wavy fibers is needed.

Steel fiber reinforced polycarbonate samples with initial fiber length (pre-injection) of 5 mm are considered for this investigation. In this work, we will be referring to that material as a short random discontinuous fiber reinforced composite system following the definition by Phelps and Tucker III [41] and Tatara [42], among others, who classified long fiber thermoplastics (LFTs) as materials reinforced with fibers longer than 10 mm.

To summarize, the aim of this paper is two-fold: (a) to develop a geometrical model for generation of the random RVE of short wavy steel fiber reinforced composites, (b) validation of the model through X-ray tomography techniques. For the latter purpose, a novel methodology is established for accurate three-dimensional quantitative measurement and analysis of the micro-structural parameters of short wavy steel fiber reinforced thermoplastic samples, which will be used as input for the mathematical model. The generated RVEs are compared qualitatively against real tomography reconstructed volumes. A quantitative comparison is done using a straightness parameter (P_s) outputted from both the simulated and real volumes.

The developed models for generation of random RVEs of short wavy fibers provide a necessary starting point for further predictive methods of modeling of the mechanical behavior of the composite, which take into account its complex internal geometry. A key characteristic of short steel fiber composites is its stochastic nature which presents itself in fiber length, orientation, position in addition to the stochasticity of waviness. For this reason, an accurate statistical description of the "randomness" of generated RVEs is crucial for reliable modeling of the overall composite behavior.

2. Geometrical model

In the present paper the terms "geometry" or "architecture" refer to the local orientation and fiber length distributions, fiber positions and fiber waviness. In the RVE generation algorithm fibers are modeled as solid cylinders with a wavy central line. The geometrical model is based on the following input parameters:

1. Fiber volume fraction V_f.
2. Fiber diameter given as one average value for all fibers (this constraint can be easily waived in further model development, for example, statistics of fiber diameters can be introduced).
3. Fiber length distribution $\psi_L(l)$; the type of the distribution function is not fixed, it can be even, normal, Weibull etc. The type and values of the parameters of the selected fiber length distribution are input, e.g. for a normal distribution the mean and variance parameters are input.
4. Fiber orientation distribution, given as the 2nd order orientation tensor [18], which is used for reconstruction of the orientation function $\psi(\theta, \Phi)$. This constraint also can be waived, with input of an orientation tensor of the 4th order, or approximated orientation function itself. Orientation distributions here are considered as the end-to-end orientation of the wavy fibers.
5. Fiber waviness profile. Fiber waviness is represented by a combination of random harmonic functions:

$$r(s) = A\left(\boldsymbol{r}_1 \sin\left(n_1 \frac{\pi s}{L} + \psi_1\right) + \boldsymbol{r}_2 \sin\left(n_2 \frac{\pi s}{L} + \psi_2\right)\right), \quad (1)$$

where: $r(s)$ is the radial position in relation to a certain axis, s the coordinate along the curved fiber axis, A is average amplitude of fiber waves generated randomly as uniformly distributed on the interval [0, A_{max}], A_{max} is maximum amplitude parameter given by the user. $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are two randomly generated orthogonal unit vectors ($|\boldsymbol{r}_1| = |\boldsymbol{r}_2| = 1$) normal to the axis. $n_{1,2}$ are waviness numbers generated randomly (on log2 scale) as uniformly distributed on the interval $[1, n_{max}]$, n_{max} is the maximum waviness number parameter given by the user. L is the fiber length randomly generated following the FLD given by the user. $\psi_{1,2}$ are phase shifts randomly generated as uniformly distributed on the interval $[0, 2\pi]$.

The geometrical model creates a realization of a random RVE via a hierarchy of modeled objects: