Composites Part A 112 (2018) 263–270

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Automatic glass fiber length measurement for discontinuous fiber-reinforced composites

Ruggero Giusti[a], Filippo Zanini[b], Giovanni Lucchetta[a,*]

[a] Department of Industrial Engineering, University of Padova, Via Gradenigo 6/A, 35131 Padova, Italy
[b] Department of Management and Engineering, University of Padova, Str. S. Nicola 3, 36100 Vicenza, Italy

ARTICLE INFO

Keywords:
Long-glass fiber
Fiber length measurement
Injection molding
Fiber breakage

ABSTRACT

Severe fiber breakage occurs in injection molding, affecting the mechanical performance of discontinuous fiber-reinforced composites. Accurate measurement of the residual fiber length distribution is crucial to experimentally investigate the physics of fiber breakage. This work proposes an automatic glass fiber length measurement method, based on the algorithm CT-FIRE for individual fiber detection. The main parameters of the algorithm were optimized to minimize the average systematic error between measurements performed with CT-FIRE and with a high-accuracy CMM. An approach to the evaluation of the measurement uncertainty based on substitution measurements was proposed and verified for a large size sample. For the scanner used in this study the uncertainty was 0.651 mm.

Eventually, the developed automatic measurement method was used to investigate fiber breakage during plastication of long glass fiber-reinforced PP. The results obtained using the optimized algorithm parameters showed that significant breakage is due to the presence of the dynamic mixer.

1. Introduction

Discontinuous fiber-reinforced thermoplastic composites are increasingly used in industry when enhanced mechanical properties and lightweight are required [1]. Moreover, they can be easily formed into complex-shaped structures by using conventional molding processes, such as compression and injection molding. The latter is one of the most widely used manufacturing technologies for mass production of plastic parts, due to its high automation level, high efficiency and process versatility. Although long fibers would be necessary to achieve good mechanical properties [2,3], severe fiber breakage often occurs in injection molding, due to the high shear stresses generated during the process [4,5], which affect the mechanical performance of the molded parts [6]. Fibers breakage results in decreased tensile strength and impact resistance both for long [7] and short fiber-reinforced thermoplastics [8].

In injection molding, several factors contribute to the final fibers length, such as mold geometry, fiber content and processing conditions [9]. In order to achieve the desirable performance in the final molded product, the manufacturing process has to be optimized by establishing a correlation of the processing parameters with the fiber characteristics [10,11]. In particular, several studies have reported that the majority of fiber breakage is associated with the plasticating phase [12–16]. Turkovich and Erwin found that most fiber length breakage occurs in the compression zone of the screw, with marginal degradation in the feed zone [12]. Bailey and Kraft noticed that fibers with an initial length of 10 mm in a Polyamide matrix are reduced to an average length of 1 mm in the part, with an average length of 1.6 mm at the outlet of the nozzle [13]. This result was also confirmed by Lafranche et al. for long glass fiber-reinforced Polyamide 6 [14] and by Vu-Khanh et al. for a PBT-PET blend [15].

In order to reduce the fiber breakage Inoue et al. proposed a low-shear screw design, which mainly differs from a standard three-zone screw by having a variable pitch [16]. With regards to the plasticating process parameters, Rohde et al. reported that increasing the back pressure from 50 to 80 bar reduced the residual fiber length in the molded part by approximately 30% [5]. However, the screw speed rather than back pressure was identified by Lafranche et al. as the process parameter that mostly affects fibers breakage [14].

All these studies rely on the accurate measurement of the residual fiber length distribution to experimentally investigate the physics of fiber breakage. However, their results are often not comparable because they were obtained by a wide variety of measurement approaches, with substantial differences in key aspects of the measurement techniques and the execution of the actual measurements [17].

Most of the measurement approaches can be divided into four main

* Corresponding author.
E-mail address: giovanni.lucchetta@unipd.it (G. Lucchetta).

https://doi.org/10.1016/j.compositesa.2018.06.016
Received 28 August 2017; Received in revised form 31 May 2018; Accepted 10 June 2018

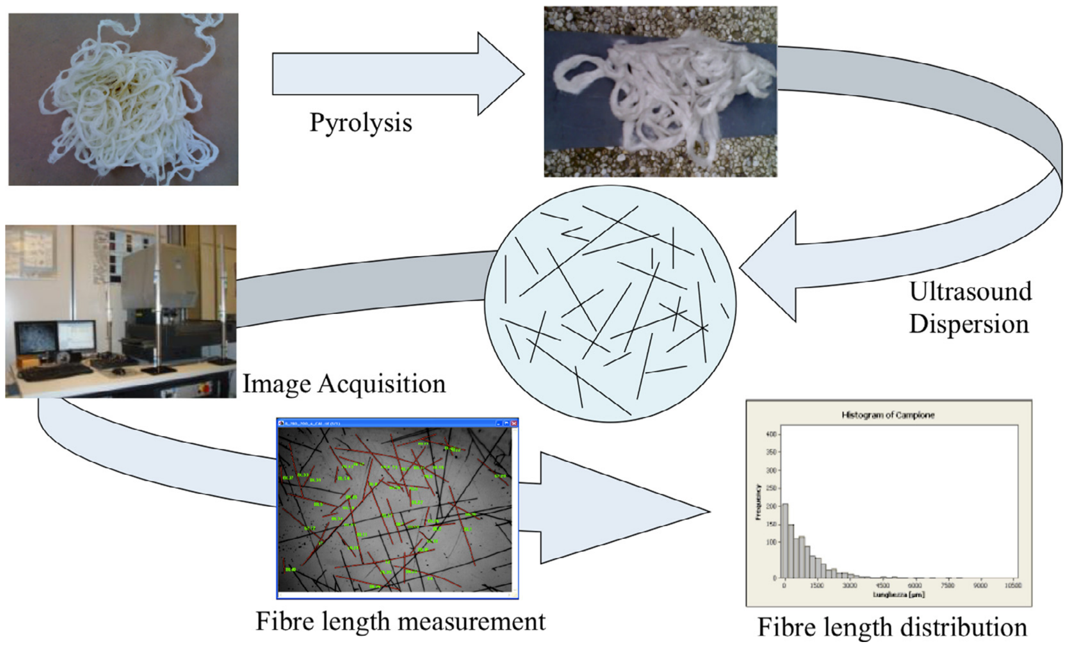

Fig. 1. Main steps of the fiber length measurement technique. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

steps (Fig. 1), which are partly reported in the ISO:22314 standard for fiber length measurements of short fiber-filled materials [18]. First a sample is extracted from the part and the polymer matrix is pyrolyzed by means of a high temperature oven. The sample must be sufficiently large to avoid considering the fibers broken during the extraction. A subset of the fibers, selected at the center of the sample, is then dispersed in an ultrasonic bath. The sample is then put under a microscope or a document scanner and digital images are acquired at a suitable magnification. Finally, the fibers are measured using image processing software either manually (by measuring the distance between fibers endpoints) [6,14,16,18,19] or using image-processing algorithms [17,20,21].

Manual fibers detection is a cumbersome task since to get an accurate fiber length distribution at least 1000 fibers for each sample must be measured [20]. Moreover, it is a critical task since it is often carried out by looking for specific areas within the sample, in which it is possible to capture a high number of fibers entirely contained in the size of the image and possibly not too tangled to facilitate the detection. In this manner, however, the fiber length distribution is biased by the operator [19].

Another critical aspect of fiber detection is related to the presence of fibers intersecting the boundaries of the image, whose length is clearly distorted. Since the probability of intersecting the image boundaries is higher for longer fibers than for shorter ones, the measurement of such samples is affected by an underestimation of average fiber length [19]. To overcome this problem an optical acquisition system with a large field of view should be used, such as a high-resolution document scanner.

The analysis of the measurement techniques used in recently published studies shows that repeated measurements are rarely performed or reported [17]. Furthermore, no study provided the measurement uncertainty related to the fiber length distribution.

This work first proposes an automatic measurement technique. Second, it presents an approach to the evaluation of the measurement uncertainty. Eventually, the developed measurement technique is tested and applied to a study of fiber breakage in the plastication phase of the injection molding process. In this case study, the effects of a mixing screw on fiber breakage during plastication is investigated and quantified for long glass fiber-reinforced polypropylene (PP).

2. Automatic fiber length measurement technique

2.1. Image acquisition

The method developed for the automatic measurement involves the use of a document scanner (EPSON, AcuLaser CX11) that has a maximum resolution of 600 dpi. To avoid measuring fibers that cross the field of vision, a rubber grid (or template) is used, having dimensions of 220 mm × 310 mm with 35 square holes of 20 mm side and 20 mm pitch (Fig. 2).

The rubber grid is positioned and aligned on an equal size glass sheet. The deposition of the sample fibers on the grid takes place by manually dispersing them homogenously on the entire surface. This operation is the only one that requires operator sensitivity and a certain initial training. Some fibers will fall into the empty spaces, some others on the grid. After performing these steps, the rubber grid is slowly removed, in order to avoid any action that could affect the original position on the glass fibers. Some of the fibers, located on the edge of the grid, will fall on the glass, occupying the surrounding space, which remains inside squares of 35 mm side. The glass with the fibers is then placed on the scanner and covered with a black box, to isolate it from

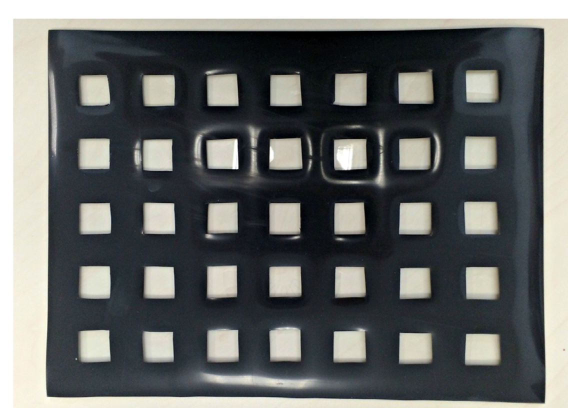

Fig. 2. Rubber grid used to avoid measuring fibers that crossed the field of vision.