GEOMETRIC CHARACTERIZATION AND SIEVING OF UNIDIRECTIONAL CARBON-FIBRE/PEEK PREPREG TRIM WASTE

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ABSTRACT

During the manufacture of unidirectional thermoplastic prepregs, the material edges are often trimmed as they feature unacceptable variations in thickness and resin content. This tape edge trim, or TET, can be chopped into smaller pieces before exiting the prepregging line to facilitate disposal. Interestingly, this process produces a material that strongly resembles strand-based compression moulding compounds referred to in the literature as randomly orientated strands, flakes or platelets. However, the chopping operation employed produces TET strands with a broad range of geometries (e.g., length, width, shape) making direct reuse by compression moulding likely to produce components with uncertain mechanical properties. In this study, two different types of sieving systems were used to sort carbon fibre TET strands recovered from the aerospace material supplier Teijin Carbon America, Inc. into batches with more consistent geometries. An optical analysis tool coded in Python was developed and used to measure strand length, width, area, and aspect ratio from pictured TET strands both prior to and following sieving. Different combinations of initial batch mass and sieving time were explored and the governing parameter for sieving was determined to be the strand width. Sieving that involved vertical agitation was found to result in less strand damage and overall efficient sorting, while sieving that involved in-plane circular agitation resulted in the formation of strand aggregates which hindered the movement of smaller strands through subsequent sieves.

1 INTRODUCTION

1.1 Thermoplastic Prepreg Waste

Manufacturing of unidirectional thermoplastic prepregs involves the impregnation of dry fibre tows with molten polymer at elevated temperature and pressure, often by passing through heated rollers. Following this process, the material at the tape edge can exhibit unacceptable variations in both thickness and resin content and is, therefore, trimmed prior to tape rolling. This edge waste is referred to here as tape edge trim (TET), and it may be collected in either roll form, or as TET strands after passing through a chopping system. An example of TET strands that were collected from the prepregging line of the aerospace material supplier Teijin Carbon America Inc. is shown in Figure 1. Despite not satisfying the quality requirements needed for primary aerospace structures, the TET pictured below consists of high-performance constituent materials such as standard or intermediate modulus Tenax® carbon fibre, as well as a variety of thermoplastic polymer systems (*e.g.*, PEEK, PEKK, PPS, PAEK, PEI). To dispose of this manufacturing waste through traditional means such as landfilling or incineration is to lose a high-value material with little contamination, while also contributing to the already overwhelming problem of plastic pollution. Furthermore, the aforementioned TET strands strongly resemble a number of commercially available bulk compression moulding compounds such as Toray's Cetex® MC1200 [1]. However, the chopping operation employed produces strands with a broad range of geometries (e.g., length, width, shape) making direct reuse by compression moulding likely to produce components with uncertain mechanical properties.

Figure 1. TET waste from Teijin Carbon America Inc. which has been chopped into strands following polymer impregnation.

1.2 Objectives

The irregular size and shape of TET strands represents an obstacle to their direct reuse as a bulk compression moulding compound, as many in the literature have shown that the size of prepreg strands can have a large impact on the mechanical performance of compression moulded coupons [2]. It is also likely that having strands of various sizes within the same compound may increase mechanical property variability, making certification more challenging. The objective of this paper is to test the ability of two different vibrational sieving systems to sort TET strands into batches with more consistent geometric characteristics.

2 MATERIALS

The TET strands studied here were generated during the manufacture of Teijin's Tenax®-E TPUD PEEK-HTS45 P12 12K-UD-145 unidirectional prepreg, which is designed to be processed using a variety of methods (e.g., press forming, filament winding, automated fibre placement). The system consists of the standard modulus Tenax®-E HTS45 carbon fibre arranged in 12K tows and impregnated with a polyetheretherketone (PEEK) matrix. The prepreg areal weight and matrix content by weight are specified as 220 g-m^{-2} and 34 %, respectively [3]; however, it is possible that the TET strands to not meet these specifications. For the remainder of this paper, this material will be referred to as HTS45-PEEK TET strands.

3 METHODOLOGY

3.1 Sieving Machines

Two different industrial vibrating sieve shakers were used to sort the aforementioned TET strands. The first is a Model B Ro-Tap® sieve shaker from Tyler Industrial Products which uses in-plane circular motion to agitate the sieve contents (Figure 2a). The Model B Ro-Tap® used in this investigation was equipped with U.S. standard sieves from Dual Manufacturing Co. which measured 200 mm in diameter and 50 mm in height. The second sieve shaker employed to sort TET strands is a TS-1 Gilson testing screen system from Gilson Company, Inc. (Figure 2b). The TS-1 system includes sieves measuring 451 mm x 667 mm x 67 mm (width x depth x height) and uses a linear vertical motion to agitate the sieve contents. A combination of six progressively finer steel wire mesh sieves, like those depicted in Figure 2c and Figure 2d, were used for all of the trials. The exact progression of sieve square cell size was: 28 mm, 20 mm, 14 mm, 10 mm, 5 mm and 2.5 mm.

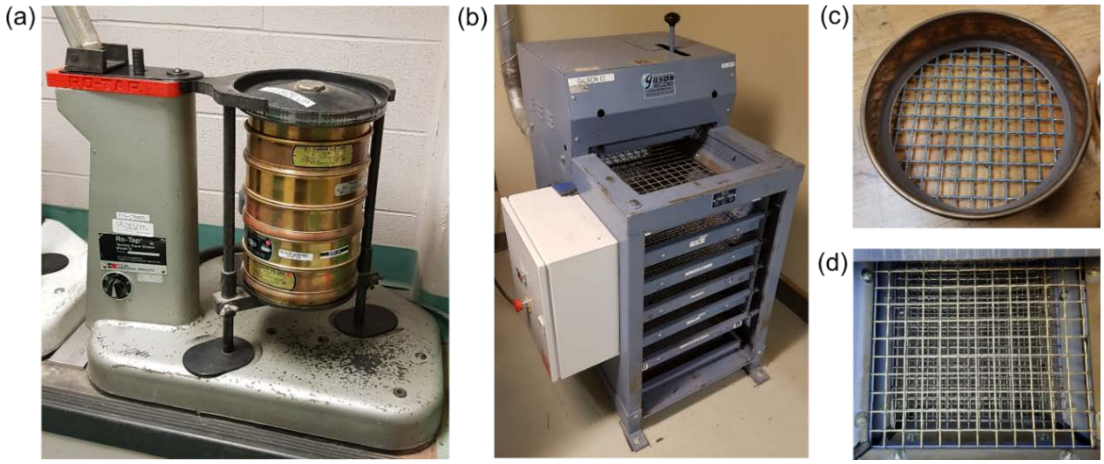


Figure 2. (a) Model B Ro-Tap sieve shaker with U.S. standard sieves; (b) TS-1 Gilson Testing Screen; (c) & (d) wire mesh sieves with square cells used during the TET strand sieving trials.

3.2 Photography & Optical Analysis

Photographs of TET strands were taken using a Canon Rebel T1i DSLR camera with a Canon EF-S 18-55 mm zoom lens. The camera was mounted on a tripod and controlled using a laptop with digiCamControl software (Figure 3a) to minimize vibrations and improve picture repeatability. Each photograph was taken with the zoom lens set to an approximate focal length of 35 mm, an aperture of f/10, a shutter speed of 0.5 s, and an ISO of 100. Figure 3b shows an example of as received TET strands that were photographed against a white background and next to a physical reference scale.

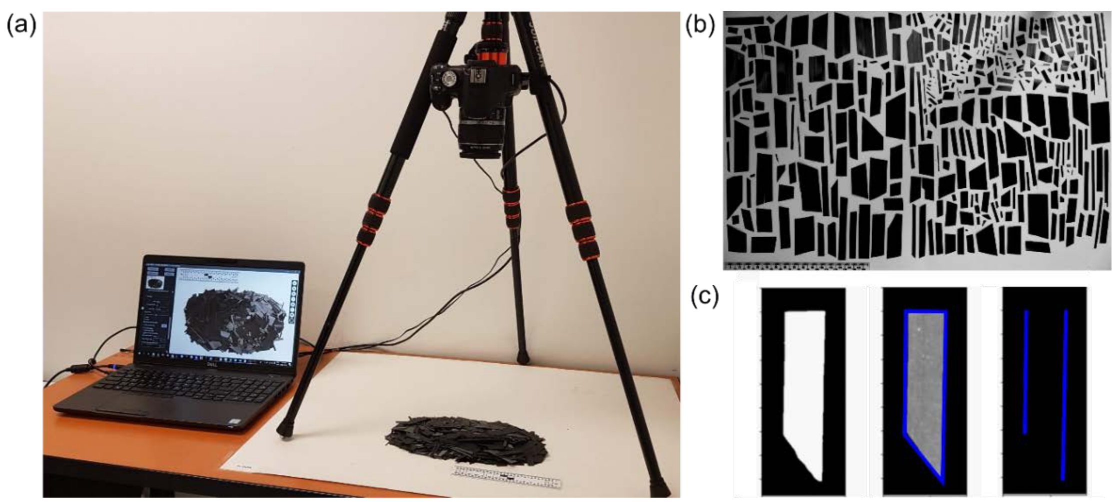


Figure 3. (a) Photo setup used to image TET strands; (b) as-received strands photographed against a white background; (c) visual output of the image analysis Python code including thresholding, polygon fitting, and parallel line detection.

The images collected during this study were processed using an image analysis code written in Python which will be made public via GitHub at a later date. The code performs the following steps in order to obtain information regarding strand geometry:

1. Display imported image and prompt user to define the image scale by drawing a line segment along the physical reference scale visible in each image.
2. Prompt user to crop the imported image so that only the strands are visible.

3. Perform image thresholding based on Otsu's method.
4. Detect objects (strands) and assign each object a number.
5. Perform a polygon best fit for all of the objects detected.
6. Identify the two parallel sides of the fit polygon and use their orientation as the strand fibre direction[1].
7. Calculate the strand length, width and area, as well as the overall batch fibre length distribution.
8. Export collected data to a .csv file.

3.3 Baseline Strand Characterization

As-received HTS45-PEEK TET strands were characterized using the image analysis method described in the previous section to establish baseline values for strand length, width and aspect ratio. Six (6) images with a combined total of 1503 strands were analyzed.

3.4 Circular-Motion Sieving

3.4.1 Material Preparation

For each sieving test performed on the Model B Rio-Tap sieve shaker, batches of HTS45-PEEK TET strands were prepared as follows: first, a large quantity of strands was spread over a working surface (Figure 4a); next, smaller quantities were taken from different locations to avoid preferential selection and placed in a steel bowl to be weighed using a digital scale (Figure 4b); lastly, the weighed strands were placed in the coarsest sieve (28 mm) at the top of the sieve stack and loaded into the sieve shaker (Figure 4c).

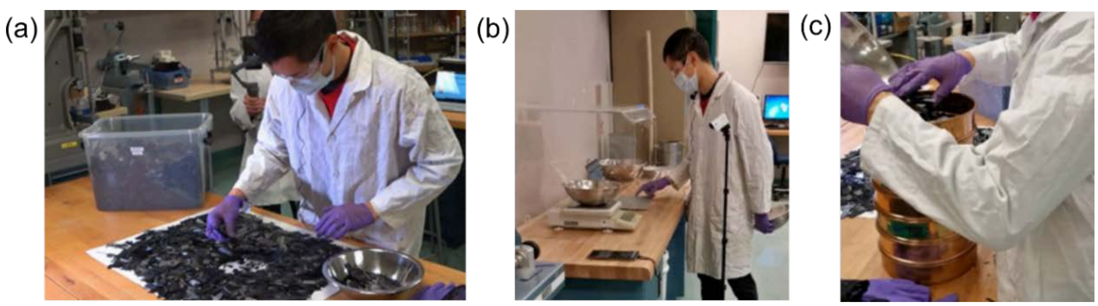


Figure 4. Pictures showing different stages of material preparation prior to circular-motion sieving trials.

3.4.2 Effect of Sieving Time and Batch Mass

Trials were carried out according to the test plan shown in Table 1 to evaluate the effect of sieving time and batch mass on the separation of TET strands using the Model B Ro-Tap. Batch masses of 30 g and 100 g represent the quantities of strands needed to simply cover the sieve surface and completely fill the sieve, respectively. For each of the configurations presented in Table 1, three repetitions were performed. The material collected from each sieve after sieving was weighed and analyzed according to the image analysis method described in Section 3.2.

Table 1. Experimental test plan designed to study the effect of sieving time and batch mass on strand sieving.

Batch Mass (g)	100			30		
Sieving Time (min)	7	10	13	7	10	13
Repetitions	3					

[1] This method works for most of the strands studied, as most edges are cleanly broken along the fibre direction creating to parallel edges. For strands that are very nearly rectangular, the light intensity gradient which is highly variable along the matrix direction is used to determine the fibre direction.

3.4.3 Aggregate Formation

After many of the initial sieving trials, strands were found to have clumped together into aggregates in the top three sieves; namely, those with 28 mm, 20 mm and 14 mm square mesh cell sizes. Some examples of the aggregates observed are shown in Figure 5. Upon visual inspection, it was hypothesized that the formation of these aggregates may have entrapped a number of smaller strands, thus limiting their ability to pass into finer sieves.

Figure 5. TET strand aggregates found in a number of different sieves following circular sieving trials.

A second experimental plan, shown in Table 2, was implemented to study the effect of initial batch mass on the frequency and size of aggregate formation. Sieving time was fixed at 13 minutes and five repetitions were performed for each test configuration. Aggregates were collected from the 28 mm, 20 mm, and 14 mm sieves after each test and weighed. Each aggregate was subsequently deconstructed and the resulting loose strands analyzed according to the method described in Section 3.2. The percentage of strands that should have passed down to finer sieves was quantified by strand area, as it is proportional to strand mass assuming a consistent areal weight.

Table 2. Aggregate formation test plan.

Batch Mass (g)	5	10	20	30	100
Sieving Time (min)	13				
Repetitions	5				

3.5 Linear Vertical Motion Sieving

Sieving trials similar to those described above were also carried out on the Gilson TS-1 to see if using a sieve shaker that employs linear vertical motion would reduce the amount of aggregates formed, or result in more effective TET strand separation. Given the larger scale of the TS-1 and the limited supply of TET strands, batches of 1000 g were tested and only one sieving time of 10 minutes was explored. A total of 14 trials were conducted and the subsequent materials weighed. Unlike the Model B Ro-Tap®, it is possible to operate the TS-1 with or without enclosing panels. It was, therefore, possible to observe the sieving visually using a Chronos 2.1-HD High Speed Camera from Kron Technologies. Recordings were made at 1000 fps to provide insight into the sieving mechanisms.

4 RESULTS & DISCUSSION

4.1 Baseline Strand Characteristics

The length, width and aspect ratio distributions of as-received HTS45-PEEK TET strands obtained through image analysis is presented graphically in Figure 6 as a box and whisker plot. Table 3 summarizes key elements from each distribution such as the mean, median, interquartile range (IQR), minimum and maximum. The minimum and maximum whiskers are defined by the first data point present within the outlier bound of quartile 1 minus 1.5*IQR and quartile 3 plus 1.5*IQR, respectively. The strands measured feature very similar length and width distributions;

however, most of the strands are either longer in the fibre direction, or very nearly square. This is supported by the data found within the lower quartile and the maximum, which represents 75 % of all the data, having aspect ratios of 0.91 – 2.23. IQRs of 8.4 mm – 27.3 mm for strand length and 8.0 mm – 23.4 mm for strand width provide baselines for the dispersion of each parameter, which can be compared with data collected from batches of sieved strands in later sections.

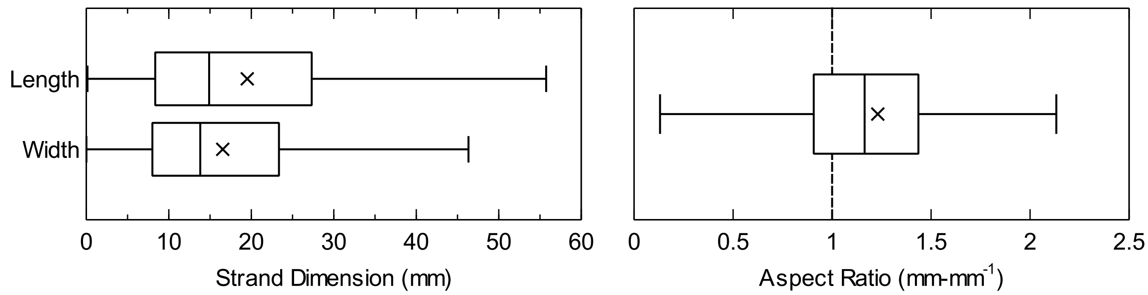


Figure 6. Box and whisker plot showing the distribution of: (a) strand length and width and; (b) strand aspect ratio.

Table 3. Key elements taken from the distributions shown in Figure 6.

	Mean, "x"	**Median, "|"**	**IQR (50 %)**	**Min**	**Max**
Length	19.5 mm	14.9 mm	8.4 – 27.3 mm	0.1 mm	55.8 mm
Width	16.5 mm	13.8 mm	8.0 – 23.4 mm	0.0 mm	46.4 mm
Aspect Ratio	1.23	1.16	0.91 – 1.44	0.11	2.23

4.2 Horizontal-Circular Motion Sieving

4.2.1 Batch Mass & Sieving Time

The masses of HTS45-PEEK TET strands recovered from the Model B Ro-Tap® sieve shaker following the trials outline in Table 1 are shown graphically in Figure 7 and Figure 8. Figure 7 groups the mass distribution data by "batch mass" and clearly shows that the quantity of strands recovered from the top two to three sieves (28 mm – 14 mm) decreases with sieving time, while the quantity of strands recovered from the bottom two to three sieves (5 mm – Bottom) increases. This indicates a progression of sieving with time and shows that neither 7 nor 10 minutes is enough time for strands to complete their journey through the sieve shaker.

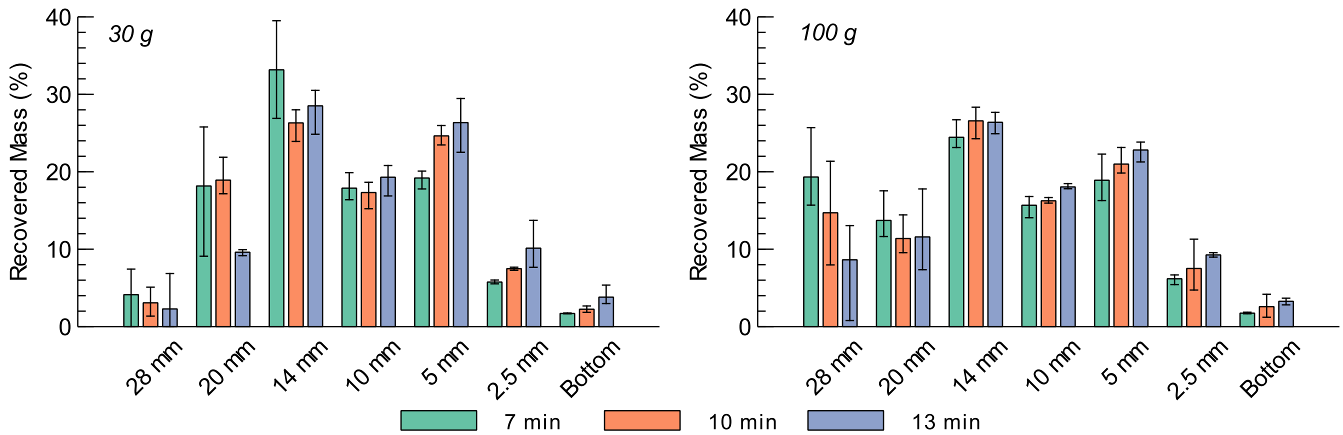


Figure 7. Mass distribution of recovered TET strands organized by batch mass.

Figure 8 groups the mass distribution data by "sieving time" and shows convergence between the 30 g and 100 g batches, as the 13-minute sieving time distributions look quite similar. Furthermore, most of the TET strands were found to have settled in the 5 mm – 14 mm sieves after 13 min, with 74 % settling there for the 30 g batches and 67 % settling there for the 100 g batches. It seems possible that the mass distribution of the 100 g batches would continue to evolve given longer sieving times. That being said, there was evidence of more strand damage after 13 minutes which may represent a limiting factor for this type of sieving system (i.e., circular motion sieving).

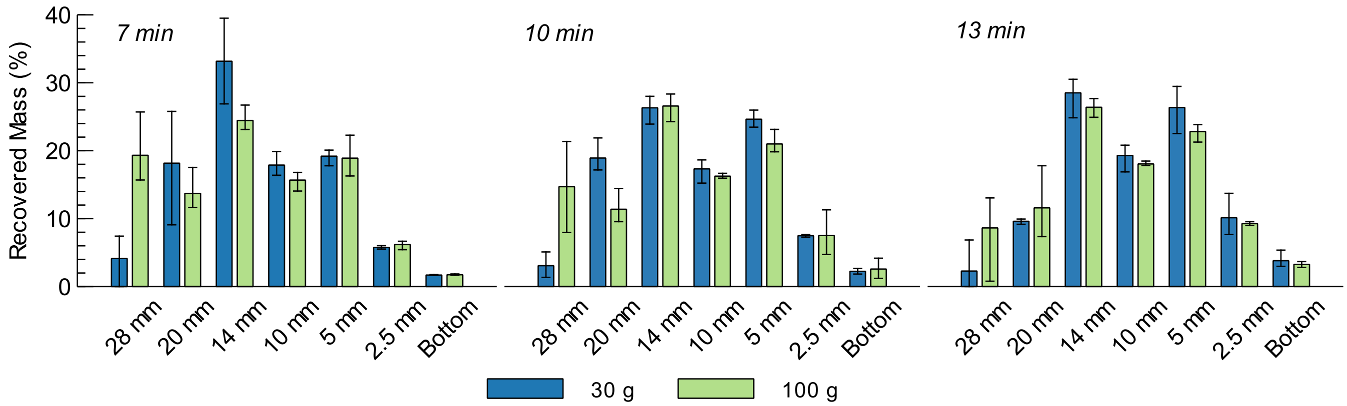


Figure 8. Mass distributions of recovered TET strands organized by sieving time.

4.2.2 Governing Parameters

The results of the image analysis carried out on HTS45-PEEK TET strands following 13-minute-long sieving trials are shown graphically in Figure 9 as box and whisker plots. The same method was used to define the plot's key statistical elements as in Section 4.1. However, strand area is shown here in lieu of strand aspect ratio, as it was thought to be a more pertinent parameter in governing sieving. In addition, the strand geometric characteristic distributions are shown relative to the corresponding sieve cell sizes which are represented by translucent cyan rectangles or diamonds. For the strand length and width, cell size ranges are defined by the square cell side length on the low end, and the cell diagonal dimension on the high end. For the strand area, cell sizes are defined by the area of a given cell.

The data presented shows that the TET strands have been separated based on their size as a result of sieving, as both the mean and median values decrease consistently with decreasing sieve cell size. Furthermore, comparison of the geometric distributions of strands found in a given sieve with the cell size range of the sieve immediately above reveals that strand width is likely responsible for governing the movement of strands through the system. The vast majority of the strands found in a given sieve have greater length and area than the sieve immediately above, while the opposite is true of strand width, which is found to be consistently smaller than or equal to the cell size of the sieve immediately above. For example, the strands found in the 10 mm sieve of the 100 g batch trials feature a mean strand length of 29.9 mm and a median strand length of 24.9 mm (see Figure $9b_1$). Assuming strands did not undergo significant bending or twisting during sieving, it is not possible that these strands passed through the 14 mm sieve which has a cell size range of 14 mm – 19.8 mm. The same can be said for strand area, as the strands found in the 10 mm sieve feature a mean and median area of 298.0 mm^2 and 282.6 mm^2, respectively, compared to the cell area of 196 mm^2 for the 14 mm sieve (Figure $9b_3$). It is, instead, plausible that these strands passed through the 14 mm sieve by aligning themselves width-wise with the mesh, as the measured mean and median strand width are 11.3 mm and 11.5 mm, respectively (Figure $9b_2$).

Finally, the width distribution of the strands recovered from the 28 mm sieve were found to be smaller than both the 28 mm cell size, as well as the strands in the sieve below. This may be correlated with the presence of aggregates consistently found in this sieve and is discussed in the next section.

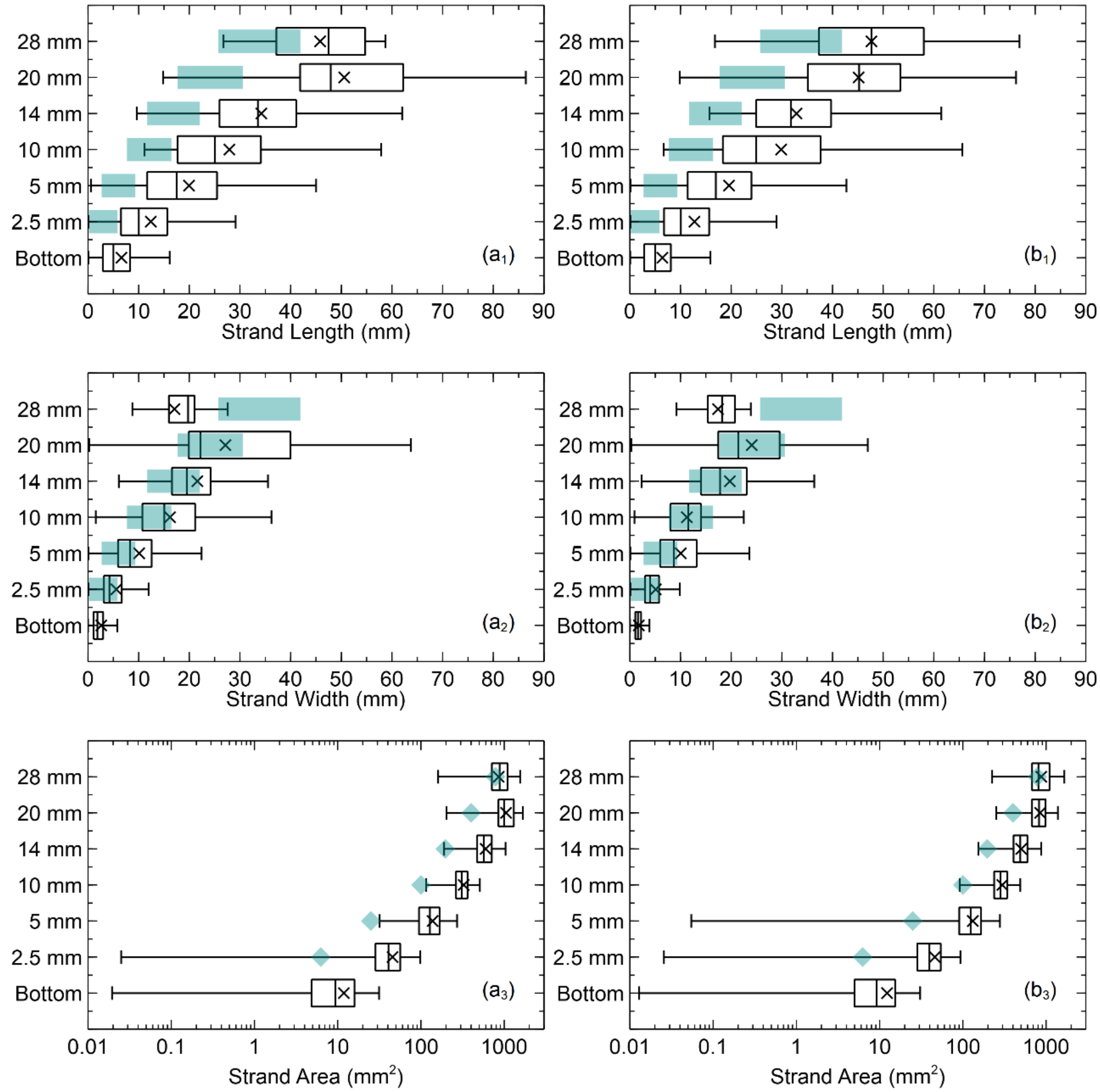


Figure 9. Strand geometric characteristic distributions obtained from image analysis of strands passed through the Model Ro-Tap® sieve shaker for 13 minutes and 30 g or 100 g batches.

4.2.3 Aggregate Formation

Figure 10a shows the mass of aggregates that were recovered from the top three sieves relative to the batch mass. These results show that aggregates of similar sizes were consistently formed during the 10 g, 20 g, and 30 g trials. The distribution of aggregate mass among the sieves was consistent with the 13-minute-long trials presented in Figure 8 of Section 4.2.1, where the most material settled within the 14 mm sieve, followed by the 20 mm sieve and, lastly, the 28 mm sieve. The size of aggregates found in the 28 mm sieve increased when a batch mass of 100 g was used. Conversely, the size and frequency of aggregates formed decreased when a batch mass of only 5 g was used. Figure 10b shows the corresponding percent area of strands that were hindered from passing into finer sieves despite having sufficiently small widths. There is a noticeable increase in out-of-place strands that coincides with the increase in aggregate size at the 100 g batch mass, confirming the hypothesis that aggregate formation hinders the movement of smaller strands.

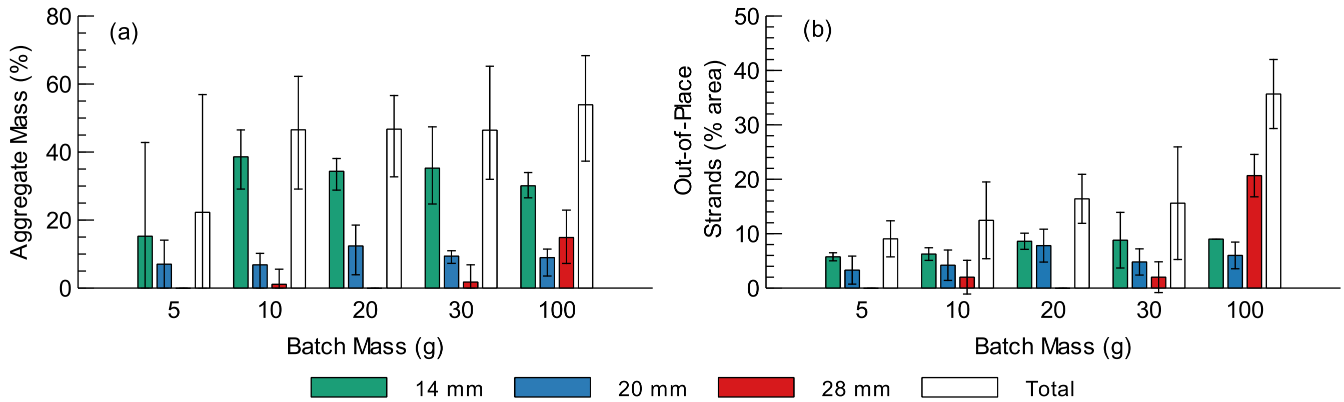
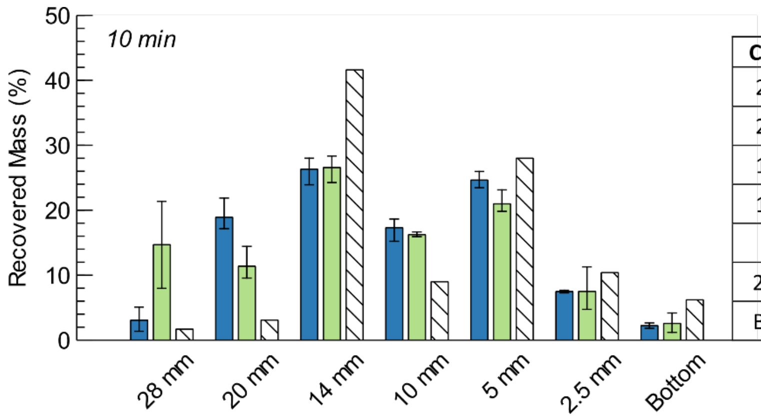


Figure 10. The (a) percent mass of aggregates and (b) percent area of out-of-place strands found in the top three sieves.

4.3 Linear-Vertical Motion Sieving

The sieving trials carried out on the Gilson TS-1 provide insight into the possible differences between sieving based on a horizontal-circular motion versus a linear-vertical motion. There were no aggregates observed while recovering the 14 batches and nearly 14 kg of TS1-sieved strands, nor was there evidence of significant strand damage. The mass distribution data shown in Figure 11 indicates that, after only 10 minutes, the TS1 was more effective at passing HTS45-PEEK TET strands through the sequence of sieves. More than twice the amount of material made its way passed the first two sieves showing that the strand width discrepancies seen in Figure 9a$_2$ and b$_2$ were likely caused by the aggregate formation discussed in the previous section.



Cell Size	Circ. (30 g)	Circ. (100 g)	Lin. Vert. (1000 g)
28 mm	3.1 %	14.7 %	1.7 %
20 mm	18.9 %	11.4 %	3.1 %
14 mm	26.3 %	26.6 %	41.6 %
10 mm	17.3 %	16.3 %	9.0 %
5 mm	24.6 %	21.0 %	28.0 %
2.5 mm	7.5 %	7.5 %	10.4 %
Bottom	2.2 %	2.6 %	6.2 %

Figure 11. Mass distributions of recovered TET strands from both horizontal-circular and linear-vertical motion sieving.

Several of the high-speed video recordings taken during linear-vertical sieving showed strands moving along erratic translational and rotational paths, while being repeatedly tossed upward by the motion of the sieve. Strand collisions made the observed strands movements difficult to track for long periods. However, many instances of strands passing through the sieve mesh were captured. Figure 12 shows a strand, outlined in pink and with a marked reference corner, passing through the 28 mm sieve after approximately 2 minutes of sieving time had elapsed. Interestingly, this strand has a length greater than the cell size and only passes through the mesh once it has aligned itself width-wise, reinforcing the observations made in Section 4.2.2.

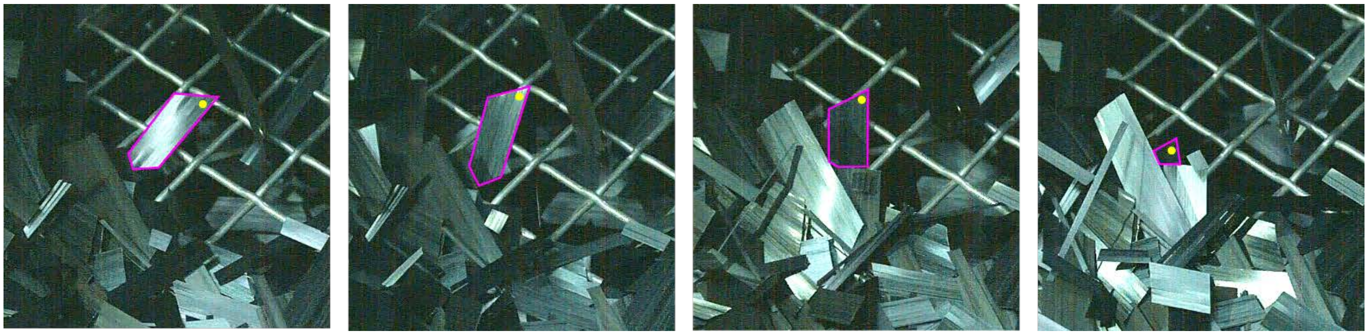


Figure 12. A representative observation of a TET strand passing through the sieve mesh after becoming aligned with its width, captured using a high-speed camera.

5 CONCLUSIONS

As-received HTS45-PEEK TET stands that were recovered from the prepregging line of Teijin Carbon America, Inc. were shown to have a broad range of geometric characteristics (e.g., lengths, widths, aspect ratio) making them uncertain candidates for direct compression moulding as a means of recycling. Horizontal-circular sieving was shown to be an effective way to separate these strands based on their width; however, the formation of strand aggregates hindered sieving as the process was scaled to larger batches. Linear-vertical motion sieving was also attempted and strand sieving observed visually using a high-speed camera. By comparison, the mass distributions measured suggest that linear-vertical sieving is more effective at separating strands given the same amount of time. Furthermore, no aggregates were formed using the linear-vertical approach, which suggests that scaling to industrial volumes of TET waste may be more easily achieved. From the preliminary work presented in which the Gilson TS-1 was able to process about 1 kg of TET waste in 10 minutes, a similar system may be able to process up to 1100 kg per year, assuming a 35-hour work week and 52 weeks in a year.

6 ACKNOWLEDGEMENTS

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