THE EFFECT OF GLASS FIBER LENGTH ON THE SHORT-TERM AND LONG-TERM BEHAVIOR OF POLYPROPYLENE

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Abstract

The plastics industry is utilizing glass fiber reinforcements within polymer matrices to create composite materials that match the specific properties required for the application. However, the choice of the correct composite material for manufacturing is a complex task for a designer. During processing of the glass fiber reinforced materials, it is expected that fiber attrition will occur. This will reduce the glass fiber length and change the mechanical properties. Typical data sheet property values are measured at one fiber length that is not regularly given with the data. Therefore, although the requirements for the application may be met with data sheet values, the designer has to consider how manufacturing of their part will affect the final properties. Furthermore, the designer must understand how the glass fiber length will affect not only the short-term properties, but the long-term as well. The study in this paper will provide information on how the glass fiber length will affect both the short-term and long-term mechanical properties of polypropylene.

Background

The plastics industry is using reinforcements to create composite materials that make them stronger, lighter and less expensive. By combining fillers or reinforcements with the polymer, the material can be changed to match the specific properties required for the application. This can be performed by adding fillers such as talc or calcium carbonate and reinforcements including glass fibers, carbon fibers, graphite or nanocomposites. These fillers and reinforcements all have distinct attributes, which can be combined with the polymer to create a material suited for its application, offering substantial benefits. One of the reinforcements commonly used in the plastics industry to achieve these goals is glass fibers.

When a load is applied to the composite material, the weaker polymer structure transfers the stress to the glass fibers. These stiff and strong fibers then withstand the loading applied to the composite material. However, to completely transfer the loading from the polymer to the fibers, an adequate fiber length must be retained. This value is referred to as the critical fiber length. The critical fiber length value is dependent on the adhesion between the polymer and glass fiber, in addition to the length [1]. Polypropylene does not readily adhere to glass fibers. Therefore, critical fiber values for polypropylene typically range from 1.3 mm to 3.1 mm for uncoupled polypropylene [2].

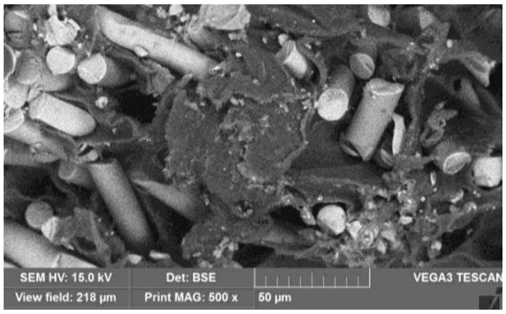

Figure 1: Image showing poor adhesion between the glass fibers and the polymer.

In a poor adhesion case, such as the one shown in Figure 1, the glass fibers are dry and show minimal polymeric material bonded to the glass fibers. This type of interaction will result in the fibers acting as a filler instead of a reinforcement, in which minimal loading, if any, will be transferred to the fibers.

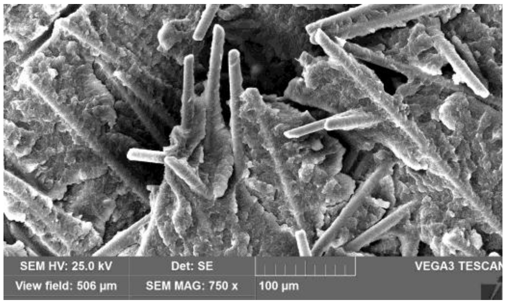

Figure 2: Image showing adhesion between the glass fibers and the polymer.

To promote adhesion and lower the critical fiber length, a coupling agent can be added to the composite material. These coupling agents have the ability to adhere to non-polar molecules such as polypropylene and polar materials such as glass fibers [3]. In the adhesion case shown in Figure 2, a coupling agent was utilized to promote adhesion between the polymer and glass fibers. The adhesion between the polymer and fibers will assist in transferring the loading from the polymer matrix to the glass fibers. This will in turn lower the critical glass fiber length. Based on previous research, if a coupling agent is utilized, it can reduce the critical fiber length to approximately 0.9 mm [2].

When adding reinforcements such as glass fibers to the polymer, there are different sizes of fibers that can be utilized. A broad categorization of fiber lengths is short glass fibers and long glass fibers. Short glass-filled composites typically start with an average fiber length of 0.3 mm to 1.0 mm, while long glass fiber-filled composites normally start with a glass fiber length of 10.0 mm to 14.0 mm [2]. However, the length of these glass fibers within the composite material will become reduced due to the expected manufacturing conditions. The more aggressive the manufacturing conditions are, the higher the fiber attrition will be. Specifically, the glass fiber length will be affected by the screw recovery, mold temperature, melt temperature, injection speed and hold pressure. Furthermore, part and mold designs can have a significant influence over fiber attrition. The part and mold design includes sprue geometry and size, runner geometry and size, gate geometry and size, wall thickness, corners and overall geometry [4].

As previously noted, the length of the glass fiber will affect the loading transferred from the polymer to the fibers. Therefore, any reduction in glass fiber length will influence the mechanical properties. This study will look at how the short-term and long-term mechanical properties are affected by the glass fiber length.

Fiber Length Measurement Technique

The characterization of the fiber length distribution is a cumbersome task since even small samples can be comprised of millions of fibers. A wide variety of measurement approaches exist, but no industry standard has yet been defined. The substantial differences in the measurement concepts and lack of a standard approach raise questions about repeatability as well as comparability of the results, as pointed out in [Goris et al., 2017].

The Polymer Engineering Center (PEC) at the University of Wisconsin-Madison developed a new measurement technique that applies a time-efficient dispersion system and a fully automated image-processing algorithm to measure large amount of fibers without needing manual fiber dispersion or detection. To ensure that the measured fiber length distribution is statistically representative, at least 20,000 fibers were analyzed for each sample. The measurement procedure is described in detail in [Goris et al., 2017].

Materials

The material utilized for the study was RTP 199 x 70815, which is a long glass fiber-filled polypropylene. Initial measurements conducted on the pellets showed a fiber length of 11 mm.

The samples were molded on a Toyo 35 ton injection molding machine. The machine had a 24 mm screw diameter that was not specialized for the molding of long glass fiber-filled materials. ASTM Type I tensile bars were molded. To obtain samples at different fiber lengths, injection molding parameters were varied, which are shown below in Table 1.

Table 1: Injection Molding Parameters

	Back Pressure	Screw RPM	Injection Speed
Sample 1	1.75 MPa	30%	50%
Sample 2	5.27 MPa	30%	50%
Sample 3	8.79 MPa	30%	50%
Sample 4	15.82 MPa	30%	50%
Sample 5	15.82 MPa	70%	50%
Sample 6	1.75 MPa	30%	25%

Fiber Lengths

To evaluate the process parameter effect on the fiber breakage, fiber length measurements were conducted at the gauge length of the long glass fiber-filled polypropylene Type I tensile bars. These measurements of the long glass fiber-filled polypropylene (LGPP) samples, shown in Table 2, were conducted through the use of image processing algorithms. The molding of these specimens resulted in 92% to 95% fiber breakage during molding.

Table 2: Glass Fiber Length

	Number Average Fiber Length	Weight Average Fiber Length
Sample 1	0.767 mm	1.639 mm
Sample 2	0.714 mm	1.471 mm
Sample 3	0.654 mm	1.287 mm
Sample 4	0.571 mm	1.017 mm
Sample 5	0.582 mm	1.121 mm
Sample 6	0.835 mm	1.680 mm

Impact Testing

Impact testing measures the amount of energy absorbed by a material during a high strain-rate fracture. The samples obtained for this study have a weight average fiber length ranging from 1.017 mm to 1.680 mm. Impact testing was performed on Type I tensile specimens in general accordance with ASTM D 4812; “Standard Test Method for Unnotched Cantilever Beam Impact Resistance of Plastics” [6]. All testing was conducted under the same conditions using a cantilever beam impact tester. The samples were obtained from the gauge length of the Type I tensile specimen. Abiding by ASTM standard, a total of eight specimens were tested for each condition. The summary of the results are displayed in Figure 3.

As shown by the error bars, the impact testing resulted in variation when performed. Therefore, there was no measured correlation between the impact energy and fiber length.

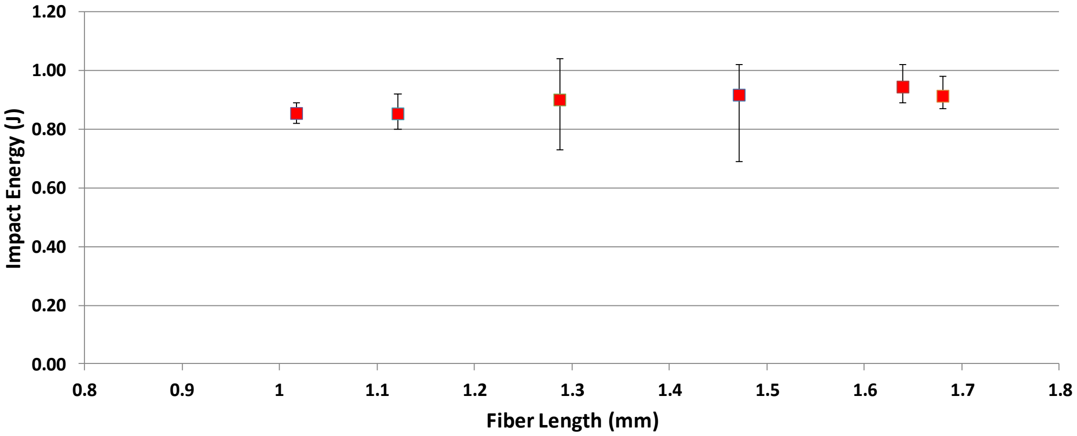

Figure 3: Graph showing the impact energy vs. the fiber length.

Tensile Testing

Tensile tests were performed on samples representing the long glass fiber-filled polypropylene in accordance with ASTM D 638 [7]. All testing was conducted under the same conditions using a universal mechanical tensile tester. A contact extensometer was utilized to measure the strain during testing. Following the failure criteria in the ASTM standard, the speed of testing utilized was 5 mm/min. Per ASTM, five test specimens were evaluated for each condition. The summary of the results are graphically represented in Figures 4 through 6.

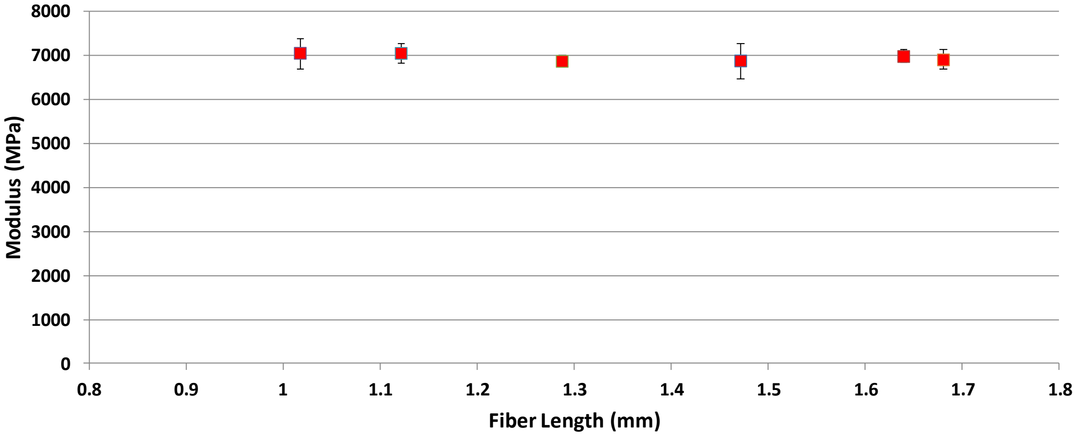

Figure 4: Graph showing the modulus vs. the fiber length.

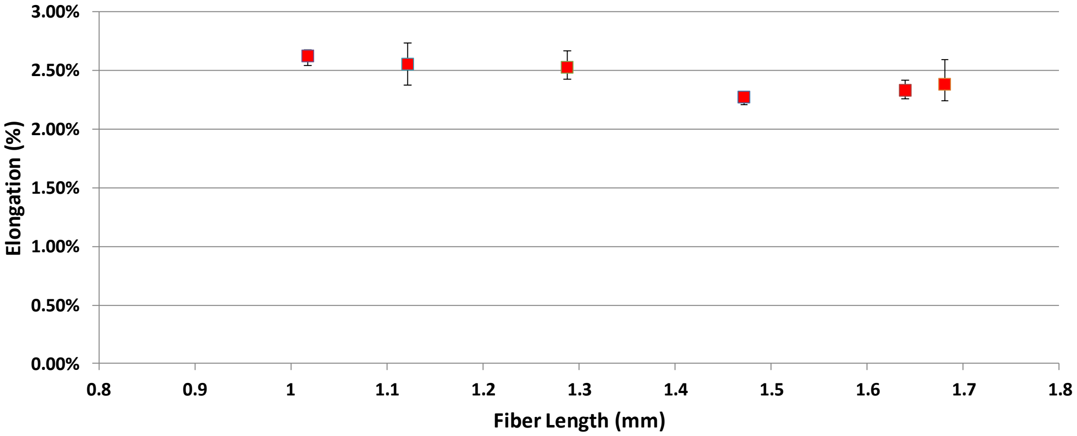

Figure 5: Graph showing the elongation vs. the fiber length.

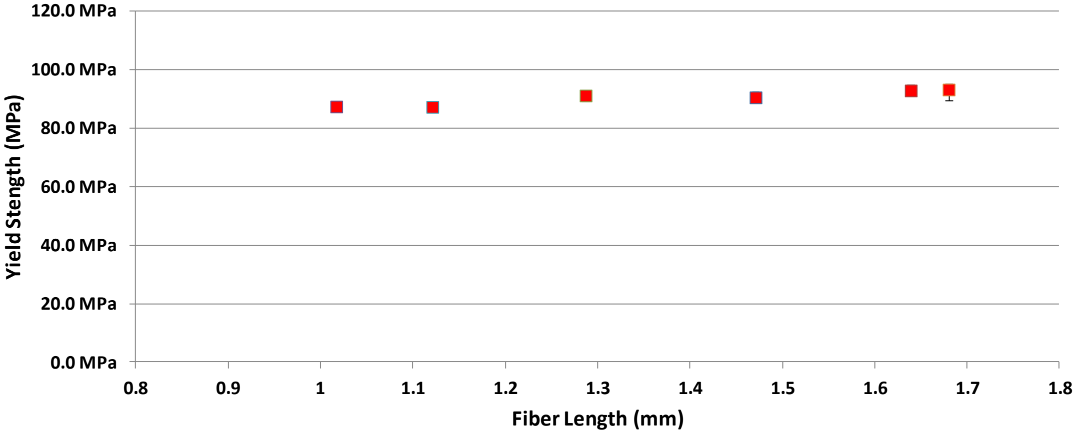

Figure 6: Graph showing the yield strength vs. the fiber length.

A graphical representation of the modulus as a function of fiber length is shown in Figure 4. Based on the data, there was no observable correlation between the fiber length and the modulus of the material.

A graphical representation of elongation vs. fiber length is shown in Figure 5. The data showed no distinct trend when the elongation at break was compared to the fiber length.

A graphical representation of yield strength vs. fiber length is shown in Figure 6. The yield strength of the material showed a slight downward trend with shorter fiber lengths.

Creep Evaluation

Creep is a result of the stress-related disentanglement of polymer chains in a plastic material. Over time, while under constant stress, polymer chains will disentangle and slide past each other. Given sufficient time and loading, disentanglement of the polymer chains will lead to premature micro cracking and creep fracture.

Creep evaluation of the material can be tested in multiple ways. One technique is through manual measurement. This test is conducted by placing a constant load on the specimen and measuring the strain over time. This is a time-consuming task, as six year material predictions, would take six years to complete. In today's industry, this amount of time is not satisfactory because products are being developed and delivered at a fast pace [8]. So there is often not enough time to conduct a manual long-term creep test. This is where the time temperature superposition principle comes in. In plastic materials, time and temperature are correlated. Therefore, testing the creep properties at higher temperatures can be used to predict behavior at longer times.

Type I tensile specimens that were molded from long glass fiber-filled polypropylene were used for the DMA evaluation. All measurements were conducted in the flow direction of the material. Assessment of the creep properties were conducted via dynamic mechanical analysis (DMA) by running multiple determinations for 15 minute time periods at isothermal conditions.

Utilizing the creep data, master curves were generated that extended to 100,000 hours at a reference temperature of 25 ºC (Figure 7).

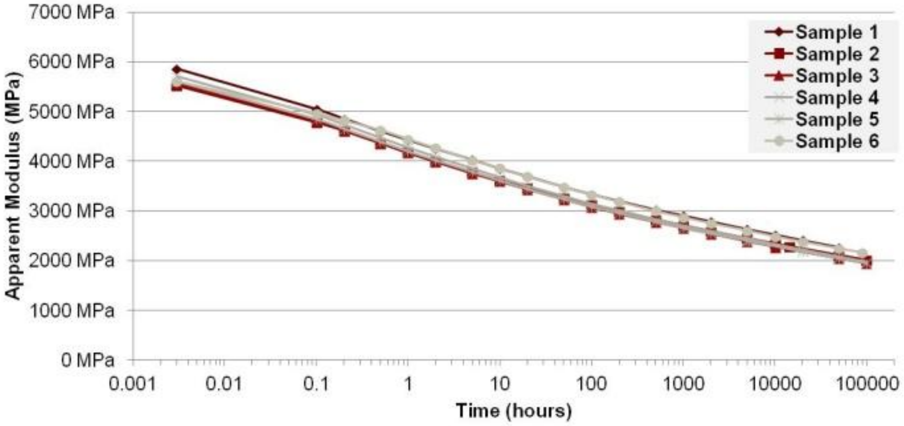

Figure 7: Graph showing the creep master curves for the samples.

Utilizing the creep master curves, along with the short-term data, lifetime predictions were made.

The maximum working stress is dependent upon the timeframe over which, a material is expected to perform. This result indicates that if the stress is maintained, it will result in crack initiation at the corresponding time. The working stress values over milestone times are indicated in Figure 8.

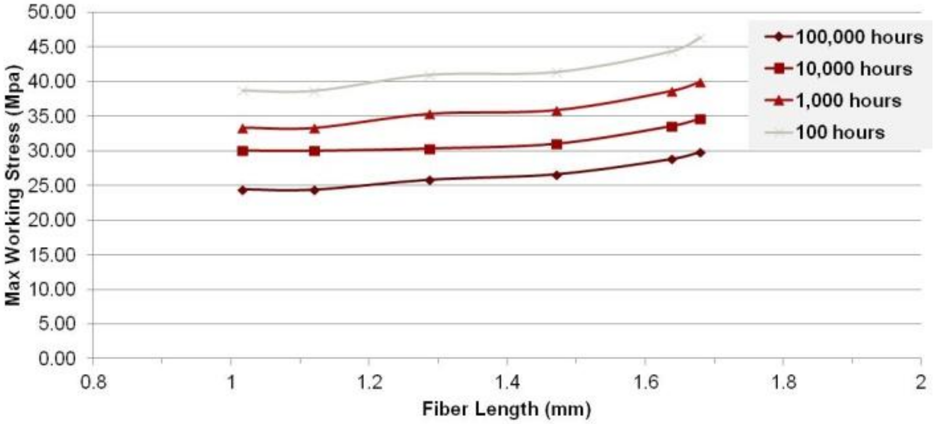

Figure 8: Graph showing the working stress vs. the fiber length.

A graphical representation of the lifetime prediction as a function of fiber length is shown in Figure 9. The loading represented in the lifetime predictions was 30 MPa. It was shown that fiber length has a direct correlation with the lifetime of the product. For example, the specimens with a weight average fiber length of 1.68 mm showed expected life times of approximately 10 years when exposed to 30 MPa of loading. However, the specimens with a weight average fiber length of 1.017 mm were only expected to last a little over one-half a year. Based on the data, the material with the longest weight average fiber length will last 15-17 times longer than the material with the shortest glass fiber length. The difference in fiber length was 0.66 mm.

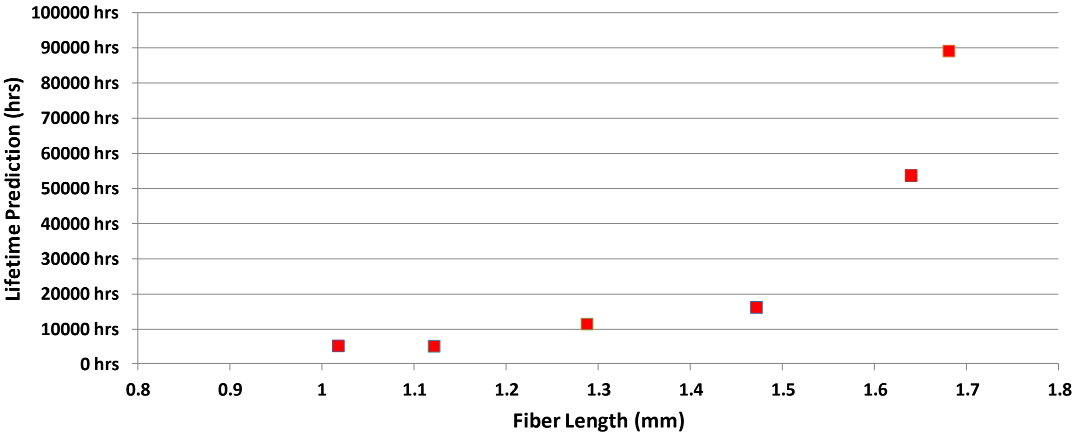

Figure 9: Graph showing the lifetime prediction vs. the fiber length when exposed to 30 MPa.

Summary

The variation in fiber length achieved through the alterations of the injection molding parameters resulted in specimens that had fiber lengths between 1.7 mm and 1.0 mm. The testing of these specimens displayed differences when evaluating the short-term and long-term properties. The testing of the short-term properties showed no distinct effect on mechanical properties. However, the reduction in fiber length had a drastic influence over the long-term properties. Specifically, lifetime predications when exposed to 30 MPa, showed a reduction in the service life by a factor of 15. Therefore, it is the conclusion of this study that the glass fiber length has a significant influence over the long-term behavior of the material.

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