FUSED DEPOSITION TECHNOLOGY APPLIED TO THERMOPLASTIC MATRIX PLACEMENT AND WETOUT IN FILAMENT WINDING

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ABSTRACT

Filament winding is a well-accepted method of fiber placement in the production of fiber reinforced composites. As thermoplastic polymers have been considered as composite matrix candidates, there have also been processing developments to enable filament winding of thermoplastic matrix composites. The generally higher process viscosity of thermoplastics has posed a substantial difficulty and wetout concerns have often resulted in interesting processing solutions, including hot head filament winding of prepreg tapes and of commingled tow. The advent of accessible 3D printing technologies, and specifically of the readily available fused deposition systems, has resulted in an alternative approach to the deposition of thermoplastic matrix material candidates. In this effort, a laboratory-scale test bed has been developed which functions as a filament winder, but incorporates two independent fused deposition hot-end printheads. While only work with a single printhead will be described in this article, the purpose of dual printheads is to be able to incorporate details such as integral cores and additional structural details which require thermoplastics of differing process temperatures. Further, by discretely placing matrix material, non-geodesic winding, enabling complex fiber paths, is possible. The current study investigates the effect of processing parameters on the ability to wetout dry glass fiber with PET using a 3D printhead (hot-end) consistent with fused deposition. Specimens are produced by filament winding using the fused deposition head to supply the PET matrix to dry glass fiber and by filament winding commercially available glass fiber/PET commingled tow, for direct properties comparison. The resulting composites are compared visually, through metallographic inspection, and by measurement of short beam shear performance. The resulting dry fiber – fused deposition composites demonstrate performance comparable to, or better than, those of the filament wound commingled tow composites processed under similar conditions.

1 INTRODUCTION

Fiber reinforced materials are composed of a reinforcing fiber and a matrix material. The matrix material is most commonly a thermosetting polymer, but an increasing number of applications are making use of continuous fiber reinforced thermoplastic polymers [1,2,3]. Most typically, the fiber angle and content is determined within the design to optimize mechanical properties and the matrix material is then added. The fraction of matrix material is generally uniform throughout the composite and most commonly flows, in a low viscosity state, wetting out the reinforcing fiber, during the process. Thus, some form of mold or die is typically required to contain the low viscosity matrix material. This results in the need for significant amounts of tooling to generate the general shapes and local features. The resulting properties of the matrix material are usually uniform and isotropic.

Continuous fiber reinforced composites are manufactured in many ways. One manufacturing sub-category involves automated fiber placement. Processes that rely on automated fiber placement include; (i) filament winding, (ii) tape laying and (iii) braiding. Filament winding is a process that allows reinforcing fiber to be wrapped around a rotating surface of revolution (mandrel), which defines the inner shape of the resulting composite. Tape laying relies on pre-impregnated (prepreg) unidirectional fiber tape which is rolled down onto a reasonably flat surface and held in place through the "tack" of the prepreg. Additionally, braiding can be considered a fiber placement-based manufacturing technique, but has limited flexibility of automation compared to filament winding.

In filament winding, when liquid resin is used to wet the fiber tow, a geodesic pattern (the shortest path between two points) is most commonly developed to maintain the fiber position. When a prepreg tow is used, it is possible to rely on the tack of the material to enable patterns which are not geodesic; however, there are fiber position limitations based on the amount of tack [4,5]. Further, since these prepreg thermosets drop in viscosity when subjected to the cure process, the corresponding loss of tack can result in unintended repositioning of non-geodesic patterns. When the fiber tow includes a thermoplastic matrix material a "hot-head" may be used in filament winding [6,7,8]. This local melting and resolidification of the thermoplastic matrix material can be used to facilitate non-geodesic patterns, and depending on specifics of the final processing, this can result in retention, or loss, of the non-geodesic pattern. Hot head filament winding of prepreg tapes [1] and of commingled tow [2] have been just two of the approaches implemented for creating filament wound thermoplastic matrix composites. While the thickness of the filament wound part can be readily changed from one region to another along the length of the mandrel, this is the result of additional fiber, not matrix material. Additional fiber must be applied uniformly around the circumference of the mandrel, unless a process based on prepreg tack or thermoplastic melting can generate a non-geodesic pattern, and since this additional fiber remains in the plane of the laminate – a 2D reinforcement results. Thus, while the current state-of-the-art in fiber reinforced composites processing, based on automated fiber placement, allows significant control of in-plane fiber angle uniformly through the composite, location changes in angle/path are difficult to achieve. Further, current processing does not facilitate the purposeful incorporation of changing matrix concentrations, nor do the processes enable local fiber placement out-of-plane.

Additive manufacture, based on concepts of 3D printing, has become very popular. Currently there are significant efforts directed toward the types of materials that can be printed, or built-up, in this manner [9]. One of the main reasons for continuing material development in this technology area is that the resulting components have limited mechanical and physical properties [10,11]. Some of these limitations result from the process of depositing the material through 3D printing, but other limitations are inherent to the materials being used. There have been recent attempts to incorporate nano-reinforcements into the materials (often polymers) that are being printed to improve the properties [12]. However, while this approach has the potential to result in reasonable property gains, the resulting properties will most likely remain isotropic. Further, even for the nanofiber-filled polymers, these gains will be minor, compared to the gains that have been realized by modern continuous fiber reinforced composites technology.

The research described in the following sections involves the development of a laboratory-scale manufacturing demonstration platform combining continuous fiber placement, based on filament winding technology, with discrete thermoplastic matrix material placement using fused deposition printheads. The demonstration platform has been assembled to investigate the potential to:

- locally vary the amount of matrix material,
- locally vary the type of matrix material,
- incorporate local reinforcement features into a composite component,
- locally vary the in-plane fiber path and overcome the limitation of geodesic patterning,
- locally adjust the fiber path, out of the plane of the majority of the reinforcement, and
- generate complex fiber reinforced composite structures with minimal tooling.

Preliminary to the demonstration of the preceding concepts using multiple printheads, it is necessary to evaluate the potential to process a thermoplastic matrix material using the fused deposition system to fully wetout a dry fiber reinforcement as it is placed via filament winding, and thus create a structural, continuous fiber reinforced composite.

1.1 Concept, Process and Hardware Implementation

The concepts described in the previous section, that result from combining technologies related to automated placement of continuous reinforcing fiber and matrix deposition, using 3D printing, can be implemented in many ways, to process a variety of styles of composite components. Fiber tows and tape can be positioned by processes such as filament winding, tape laying and braiding, all of which fall under the general category of “fiber placement”. Filament winding has been chosen for this study for a number of reasons, including the ability to readily utilize dry single tow reinforcement and the potential for improved consolidation of the composite using the fiber tensioning inherent in the process. 3D printing is typically accomplished by the preprogramed motion of some form of printhead, or deposition source. The speed and resolution of the deposition of the material is based on specific details of each process. Methods of depositing polymeric materials include thermoplastic extruders and liquid resin spray heads (much like inkjet print cartridges). Metals can be deposited by direct melt technologies and by melt spray, while ceramics, to-date, have been printed in the green state, sometimes with a polymeric binder. For the 3D printed ceramics, and some of the metals, significant post-processing via applied pressure and sintering is required to complete the process.

Polymeric materials are by far the most common family of materials used in 3D printing, and are also the most common form of fiber reinforced composite matrix material. While thermoplastics printed using fused deposition extruder heads make up the low cost, hobbyist segment of the 3D printing arena, they tend to be limited by the performance level of the thermoplastic used and in the rates of deposition. However, this style of extruder head can be readily incorporated into fiber placement equipment. Conversely, liquid thermosetting polymer printheads result in the deposition of material that must cure. This means that some source to aid the cure most likely would need to be incorporated, along with the liquid resin printhead itself. Curing of the 3D printed liquid thermoset could be localized and accelerated by techniques including a directed heat source or, in the case of UV curable resins, by a focused UV source. In any of these cases, fiber wetout must be accomplished to generate a fiber reinforced composite of the quality currently expected in industry.

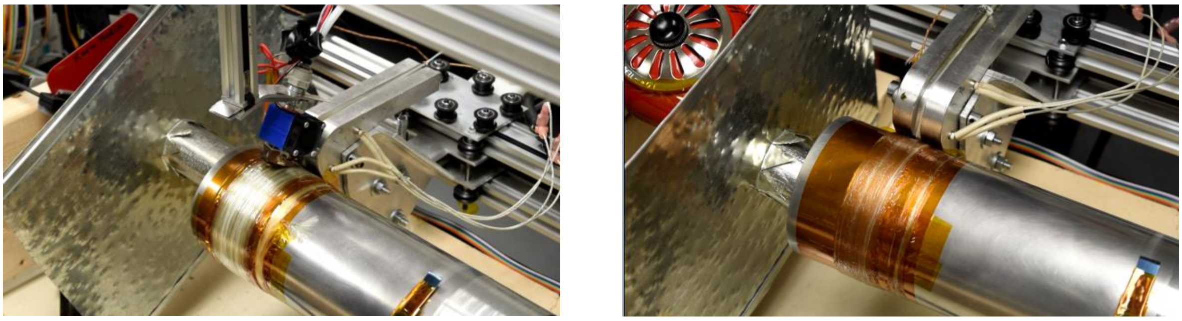
While relatively simple operations may be possible by adding a 3D printhead to the existing carriage of a fiber placement machine, only a small fraction of the concepts presented in the previous section could be realized. To fully realize the potential of combining fiber placement and 3D printing, one or more fiber placement heads, and multiple 3D printheads will need to move independently. Multiple printheads may be applied to increase the matrix deposition rates, or to allow multiple matrix materials to be deposited in parallel. Hybrid schemes may also be advantageous in increasing the production rate, including the tacking, scaffolding and positioning continuous fiber by 3D matrix printing, but rather than fully densify the composite in this way, a secondary liquid resin infusion process may be included.

The current effort focuses on the application of a thermoplastic material extruder, or the fused deposition system, on an independently controlled gantry mounted on a specially configured filament winder, as a source for the thermoplastic matrix material. Prior to attempting to demonstrate more complex fiber positioning, it has been determined that a study of the thermoplastic matrix processing and wetout parameters is necessary. Conventional process parameters for 3D printing with a fused deposition hot-end involve relatively low temperatures to ensure that the thermoplastic does not flow, but rather that the discrete “droplet” fuses to the previously deposited material. The idea is to limit the amount of material placed, and the resulting flow, to maintain relatively high geometric fidelity. However, for this study, the rate of deposition is higher, and rather than positional fidelity, the focus is fiber wetout. PET is chosen as the thermoplastic polymer matrix material. Filament wound hoops are prepared from both commercially available glass fiber/PET commingled tow and also from dry, continuous glass fiber wet out with PET deposited from a hot-end extruder. The effects of process temperature are compared for the two methods and the relative quality of the composites are evaluated to investigate the potential of such a hybrid fiber placement/fused deposition system.

2 EXPERIMENTAL

2.1 Filament Winding/3D Printing Apparatus

The apparatus is a custom-designed, laboratory-scale filament winder based on stepper motor drives and the associated controls. In addition, a modified commercial fused deposition modeling hot-end is moved in 3-space on a separately controlled stepper motor-based gantry system. The hot-end and fiber payout eye are coordinated within the control system. The hot-end, shown in figure 1(a), is the E3D-v5 3mm Bowden commercial printhead, and is capable of temperatures up to 400°C. The nozzle diameter has been increased to approximately 2.8mm. In the current evolution of this system, the hollow aluminium mandrel – nominally 100mm in diameter – is driven from one end in a cantilevered fashion, allowing a hot air source to be used to heat the mandrel interior to temperatures exceeding 250°C. Polyimide film is wrapped around the aluminium mandrel to serve as a release film. Rather than a simple payout eye, the reinforcement is positioned using a heated pressure foot that provides fiber positioning and is used to provide heat through contact with the reinforcement as it passes over the pressure foot. The pressure foot is articulated to provide user controlled pressure to the composite surface, and is designed to help spread the tow to a consistent width of approximately 9mm. This system, without the addition of the hot-end, as shown in figure 1(b), is used for the generation of the composite samples using the commingled tow precursor material.



(a) (b)

Figure 1: Filament Winding System; (a) with fused deposition hot-end in place, and (b) configured for placement of commingled tow.

To produce the composite using continuous dry glass fiber reinforcement and deposited thermoplastic matrix material, the fused deposition hot-end is used. During application of the PET matrix using the hot-end, the PET is deposited slightly in advance of dry fiber contact with the mandrel, allowing the tensioned fiber to be pulled into the hot PET with the goal of improved fiber wetout. The pressure from the hot pressure foot is also utilized to improve wetout.

The test system allows material positioning variables to be controlled, as well as several temperatures for process control. The position-based variables that can be controlled in the system include the relative speeds of the rotating mandrel, the hot-end and the fiber payout system. Temperatures of the mandrel, hot pressure foot and the hot-end extruder can be measured and controlled independently. Fiber tow tension is also a controlled parameter, which has an effect on the wetout and consolidation of the composite.

2.2 Materials

The commingled glass fiber/PET, RPET70N184, provided by TwinTex, is used as the baseline material, against which processing parameters and composite properties from the fused deposition system are compared. The dry glass fiber, provided by PPG, is Tufrov 4588, with a finish designed for thermoplastic matrix materials. Both reinforcements are nominally a 3K tow size; however, since the RPET70N184 is a commingled product with 70% glass fiber by weight, it is 370 m/kg, versus the 453 m/kg for the Tufrov 4588. The PET for the fused deposition printhead is obtained in a nominal 3mm diameter, continuous extruded form.

2.3 Specimen Preparation

Four trial filament wound rings are compared, two produced from commingled tow and two from dry fiber and extruded PET. The fibers are wound as hoops, resulting in effectively unidirectional fiber reinforced samples. Processing temperatures and speeds were held constant for pairs of commingled tow and printed composites. Two process temperatures, considered bounding conditions, were evaluated. These temperatures were held equal in the heated mandrel, the pressure foot, and for the composites with the printed PET matrix, the hot-end printhead. The lower processing temperature was selected to be 190°C while the upper processing temperature was 220°C. The mandrel speed was held constant for all trials at 0.82 rpm. This resulted in a material placement rate of approximately 0.042 kg/hr for the composite based on the commingled material and a rate of 0.057 kg/hr for the composite produced by discrete matrix printing. 100mm diameter hoop wound rings were prepared. Nominal thickness was controlled at 3mm and the rings were wound to a length of approximately 50mm in a total process time of approximately 1.0 hr/ring.

2.4 Test Procedures

Short Beam Shear (SBS) specimens were cut from these rings, such that the reinforcing fiber was in the lengthwise direction, and tested in accordance with ASTM D 2344-11 [13]. For such a large radius of curvature, the ASTM Standard allows the use of conventional loading pins, 3.18 mm for the support pins and 6.35 mm for the mid-span loading nose. Nominal SBS specimen dimensions were 17 mm long and 2.9 mm thick, with a width of 5.7 mm. The test span was 12 mm. The loading rate was the ASTM specified value of 1.25 mm/min. Five specimens of each condition were rough cut using a diamond wafering blade and then finished using abrasive grit paper on a flat surface.

Quantitative volume fraction evaluation was performed using a procedure in accordance with ASTM D2584-13 [14]. Glass fiber/PET specimens from each of the four (4) groups were weighed and measured to determine the composite density. The PET matrix was then removed at high temperature in air, leaving the glass reinforcing fibers, which were then weighed. Known densities of the glass fiber and of the PET matrix were applied to determine the fiber volume fraction. Specimen uniformity was also evaluated through visual comparison and using a limited amount of optical microscopy to verify fiber distribution and volume fraction.

3 RESULTS AND DISCUSSION

Specimens were produced by processing glass fiber/PET commingled tow and by utilizing continuous dry glass fiber tow and a fused deposition hot-end to place the PET matrix material. Completed rings were examined and then sectioned in preparation for Short Beam Shear testing to evaluate the mechanical performance related to processing.

3.1 Visual Evaluation

The four specimens produced, two of the commingled material and two of the dry fiber/printed matrix material, each at the temperatures of 190°C and 220°C, are shown in figure 2 for visual comparison of the outer surfaces. It is noted that fine bubbles appear in both sets of specimens and seem to be concentrated near the mandrel surface, as seen in figure 3. There is a slight color difference in the PET at 220°C versus 190°C, the higher temperature showing a more golden color. A similar color shift is seen in the 220°C processed dry fiber-fused deposition tube as in the commingled tube processed at this same temperature. Not surprisingly, the temperature requirements for flow and wetout are somewhat different for the two processes, as demonstrated by the fully wetout fiber at both temperatures with the commingled tow, while the dry fiber – fused deposition sample at the lower temperature (190°C) shows a lack of translucency, concentrated near the outer surface, suggesting imperfect wetout, at least in this region. At 220°C, the dry fiber – fused deposition PET composite shows better wetout, except at the very outer surface.

The tubes shown in figures 2 and 3 do demonstrate good fiber placement uniformity and, in general, good wetout. In each case, the images show that there is more PET flow at 220°C than at 190°C, which is as expected. In these preliminary trials, it was more difficult controlling the amount of excess PET in the composites produced using the fused deposition system. This is obvious in the excess neat PET adjacent to the fiber reinforced area. Development continues in the areas of printhead positioning and nozzle size and geometry, but these are not topics of the current article.

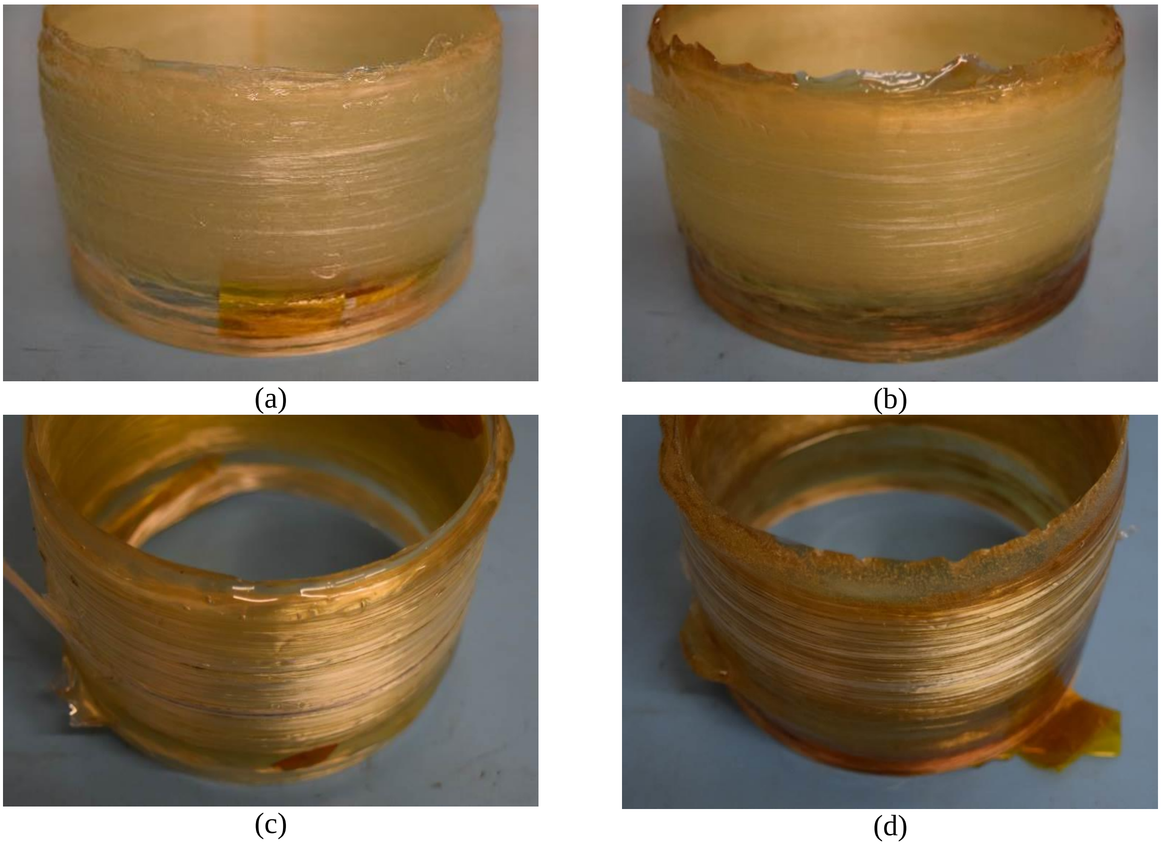


Figure 2: Outer surface visual comparison: (a) Commingled Tow @ 190°C, (b) Commingled Tow @ 220°C, (c) Dry Fiber–Fused Deposition @ 190°C, and (d) Dry Fiber–Fused Deposition @ 220°C.

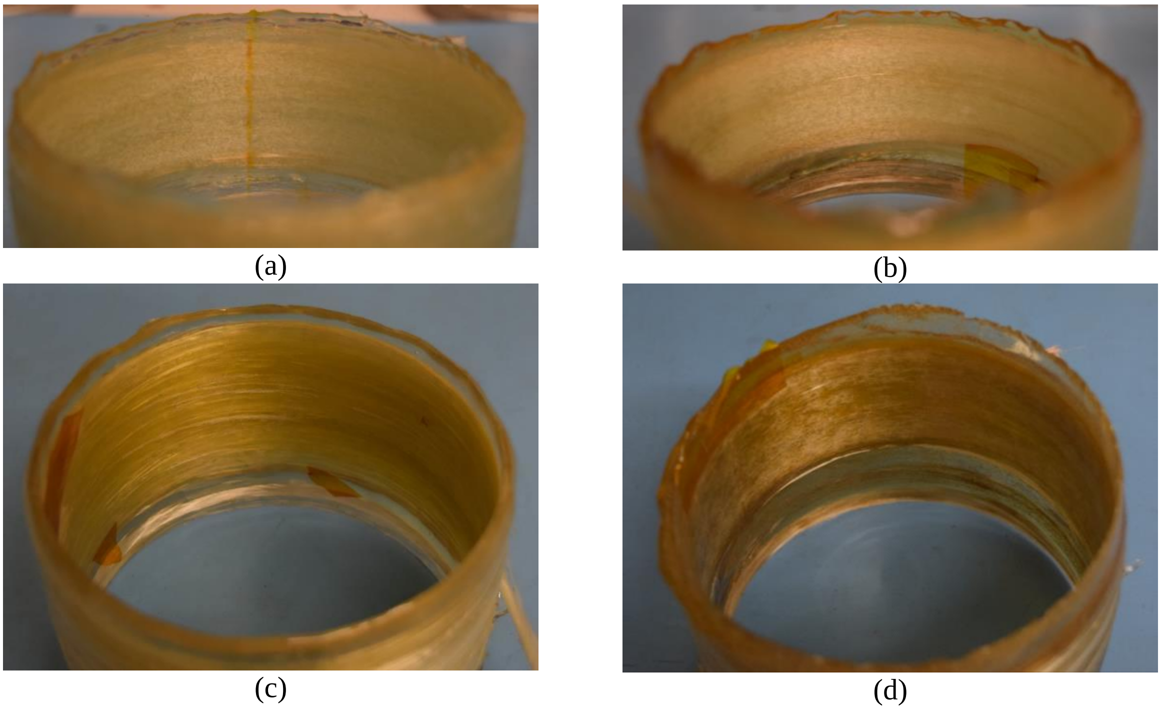
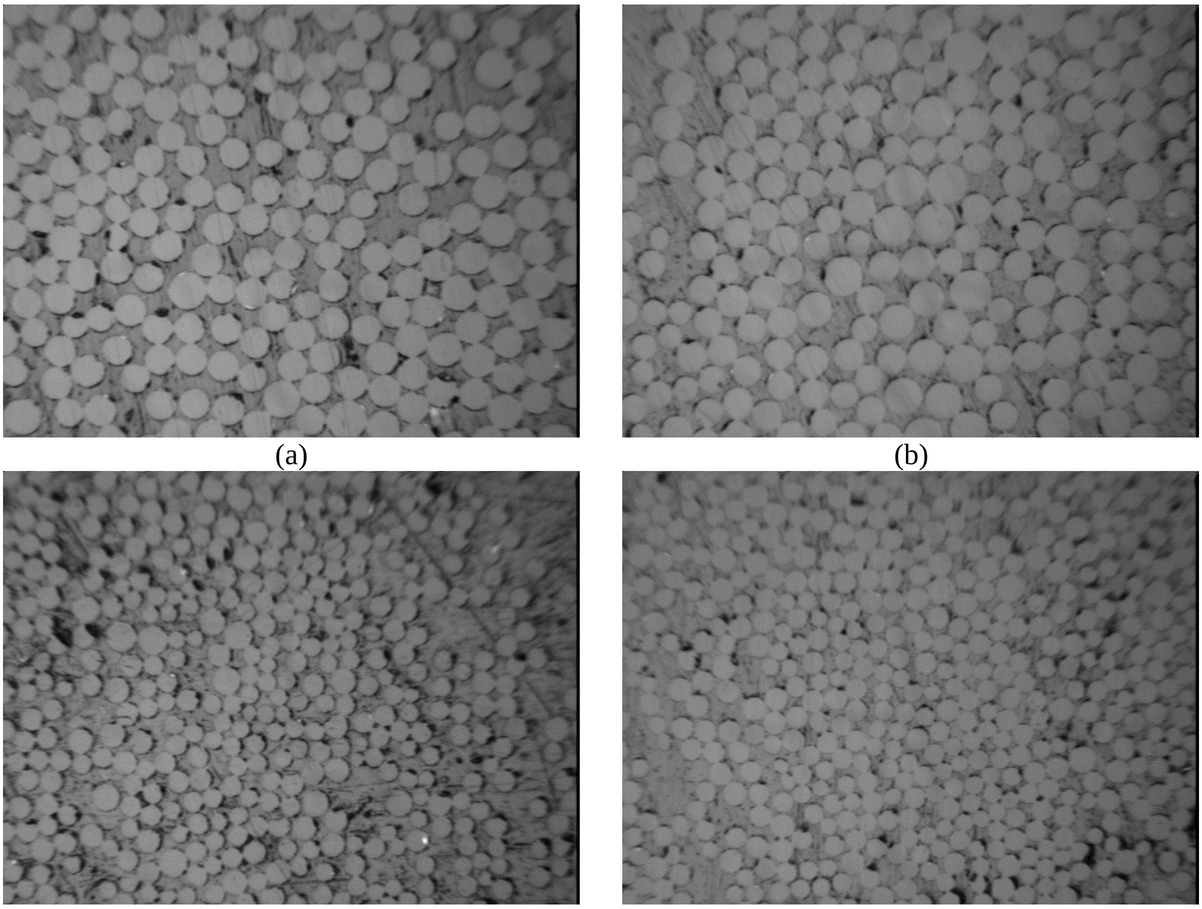


Figure 3: Inner surface visual comparison: (a) Commingled Tow @ 190°C, (b) Commingled Tow @ 220°C, (c) Dry Fiber–Fused Deposition @ 190°C, and (d) Dry Fiber–Fused Deposition @ 220°C.

3.2 Metallographic Evaluation

Specimens were cast in acrylic metallographic mounting compound and ground and polished for microscope evaluation. Representative micrographs of the four process conditions are shown in figure 4. While comparable fiber and matrix materials were chosen, it is obvious from the metallographic images that the glass fibers provided by PPG are of smaller diameter than those in the commingled tow. Black spots on the micrographs are polishing debris related to the challenges involved in preparing metallographic specimens with such thermoplastic matrix materials. These micrographs were used to confirm volume fractions determined through a burn-out measurement. In both the commingled tow composite and that produced using dry fiber and the fused deposition system, the fiber distribution is reasonably uniform and PET matrix seems to wetout all the fibers. The fiber bundles seem reasonably consistent from one specimen to the next, suggesting that the pressure foot is adequately, and consistently spreading the tow.



(a) (b) (c) (d)

Figure 4: Metallographic comparison @ 200X: (a) Commingled Tow @ 190°C, (b) Commingled Tow @ 220°C, (c) Dry Fiber–Fused Deposition @ 190°C, and (d) Dry Fiber–Fused Deposition @ 220°C.

3.3 Mechanical Evaluation

Short Beam Shear testing was used as a quantitative screening tool to determine whether a composite could be prepared, from dry fiber – fused deposition PET, which compared favorably to a similar composite produced using a commercially available glass fiber/PET commingled tow. Short Beam Shear testing, following ASTM D2344-11 [13], was chosen as it is relatively easily implemented and because it gives good information related to interlaminar properties, which are expected to be strongly related to the quality of wetout in the processes being investigated. All short beam shear failures observed can be described as “inelastic”, as shown in figure 5. As described by ASTM, this mode of failure displays significant permanent deformation without fracture. Specimens showed an elastic range on the load/displacement profile, followed by yielding, and then maintained that load, or increased somewhat, as loading continued. Peak load values from the tests were used, as specified in the ASTM standard, to determine the SBS strength.

(a) (b) (c)

Figure 5: Representative Short Beam Shear Specimen (a) as prepared, (b) immediately after initial yield point, and (c) after peak loading.

The resulting short beam shear strengths are consistently much higher for the dry fiber – fused deposition samples than for the corresponding specimens produced from commingled tow. As the results of Table 1 show, the volume fractions attained are comparable for the two processes, with the lower process temperature resulting in a higher volume fraction in both processes. It is noted that at 220°C, both processes resulted in virtually identical fiber volume fractions of approximately 59%. For the 190°C processing, the volume fractions are 4% higher for the commingled tow and 5% higher for the dry fiber – fused deposition material.

Specimen	**Vf (%)**	**SBS (MPa)**
Commingled Tow – 190°C	62.8 ± 5.2	38.2 ± 1.0
Commingled Tow – 220°C	59.2 ± 3.6	34.9 ± 1.1
Dry Fiber - Fused Deposition – 190°C	64.1 ± 8.2	51.3 ± 0.8
Dry Fiber – Fused Deposition – 220°C	59.2 ± 2.1	55.3 ± 1.4

Table 1: Properties Comparison

3.4 Discussion

The goal of this preliminary study was to determine whether the dry fiber – fused deposition process could achieve similar fiber volume fractions and short beam shear strengths as those found for a commercially available commingled tow material. While the glass fiber reinforcement and PET matrix thermoplastic were chosen to be able to be directly compared, it is clear from the micrographs that the glass fibers are of different diameters. The smaller diameter fibers of the dry fiber – fused deposition samples could be partially responsible for differences in short beam shear strengths. Further, since the fiber sizing for thermoplastic matrix materials remains proprietary, it was not possible to ensure that the fiber/matrix interfacial strengths of the two composites would be identical. Higher measured short beam shear strengths would also be consistent with higher interfacial strength. Thus, these results suggest that wetout and interlaminar properties can be generated with the dry fiber/printed PET processing which are, at least, competitive with those of more conventional thermoplastic composite processes.

4 CONCLUSIONS

Based on this preliminary bounding study, investigating continuous glass fiber/PET composites produced by fused deposition and composites produced from commingled tow, it seems that the incorporation of a fused deposition hot-end on a dry fiber filament winding system can generate thermoplastic matrix composites of quality comparable to that of commingled tow-based composites. While further processing details must clearly be assessed, the results of this effort show the potential for this processing approach. Future activities are planned to evaluate the effects of fiber tensioning, deposition rate and process temperatures. These trials are planned in parallel with more complex fiber positioning studies.

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