Thermoplastic Pultrusion: A Comparison of Melt and In-Situ Profiles

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1. Abstract

Pultrusion is an efficient method to produce lightweight and strong composite profiles. Thermoset pultrusion has long been established, while thermoplastic pultrusion is being developed as a sustainable alternative due to their reusability and recyclability, as well as for the ability to be formed in post-processing. In-situ thermoplastic pultrusion takes advantage of the low viscosity monomer, while melt pultrusion is particularly challenging because of the relatively high viscosity of the resin. However, melt pultrusion is not constrained to specific polymer types. In this study, glass fiber reinforced polyamide profiles with up to 60 vol% (c. 80 wt%) fiber were successfully manufactured using melt pultrusion. Good profile quality and fiber wet out were achieved. Tensile and flexural testing showed comparable performance to in-situ pultrusion profiles. A design case highlights the lightweighting potential of thermoplastic pultrusion compared to conventional engineering materials.

2. Introduction

Polymer composites are a popular material choice to replace metal for lightweighting in various applications. They are of low density and yet provide good mechanical properties while being able to withstand harsh conditions and environments [1]. Many industries have taken advantage of the many desirable properties that polymer composites possess. For example, fiber-reinforced polymers are well established in the transportation industry, including automotive and aerospace, and are also seeing increased use in sports and leisure [2]. Their high specific strength stemming from the fiber and polymer composition enables their use in many semi-structural applications.

Polymer composites can be manufactured using many different methods. Pultrusion is a manufacturing method that combines polymer and fibers into a continuous profile, usually with a constant cross-section. The pultrusion process has a long history, having been established since the 1950s [3]. It is an efficient process with a relatively simple, highly automated, and cost-effective setup, while being able to produce materials with very high fiber content.

3. Thermoset pultrusion

Conventionally, thermoset polymers are used in the pultrusion process. The process begins with dry fiber spools that are stocked on a rack. The fibers are pulled through eyelets on a set of guide plates to be separated and arranged into the desired architecture. Then, the fibers enter a resin reservoir, usually an open bath that is filled with resin, to be wet out. After that, the wet fibers pass through a set of guide plates that preform the fiber bundles and also squeeze out extra resin. Then, the wet fibers are pulled into a heated die, in which the thermoset resin is cured from liquid to solid, and the cross-section of the final cured part would match the cross-sectional shape of the die cavity. Glass fiber is the most used reinforcement, while other types of synthetic fibers such as carbon and aramid have also seen usage [4]. For the resin system, polyester resin is popular due to its balanced properties and low cost [4]. Vinyl ester and epoxy are also used for their superior properties, but they are more difficult to process and more expensive than polyester [4].

4. Thermoplastic pultrusion

Thermoplastic resins can be used in place of thermoset resins in the pultrusion process. A major advantage that thermoplastics have over thermosets is that thermoplastics are not chemically cross-linked. As such, they can be melted under heat and reshaped into a new shape. This enables thermoplastics to be easily recyclable compared to thermosets. This is especially important in today's climate as sustainability continues to be one of the most focused-on topics in the composite industry.

However, resin viscosity has been a factor that limits the wide adoption of thermoplastic pultrusion. Overall, good fiber wet out is crucial in the pultrusion process to minimize void content and to achieve good mechanical properties in the final part. A low viscosity resin is often preferred since it can penetrate fiber bundles better than high viscosity resins. Most conventional thermoplastic resins possess viscosities that are much higher than thermoset resins. To still be able to achieve good fiber wet out in the thermoplastic pultrusion process, two approaches have been used.

4.1. In-situ pultrusion

Thermoplastic in-situ pultrusion takes advantage of the low-viscosity monomers. This process has been investigated at the Fraunhofer Institute for Chemical Technology (ICT), and the setup is illustrated in Figure 1. The core of this technology is the utilization of the low-viscosity ε-caprolactam, activator, and catalyst to achieve good fiber wet out, as well as the in-situ polymerization process to form the polyamide matrix. Pultrusion profiles with up to 70 vol% fiber content were able to be manufactured and details are provided in Janssen et al [5].

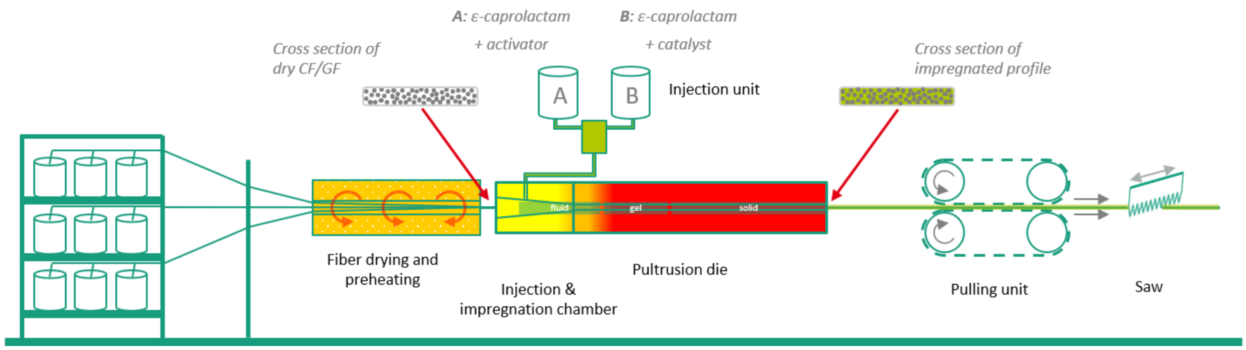

Figure 1. Thermoplastic in-situ pultrusion setup [5].

4.2. Melt pultrusion

The other thermoplastic pultrusion method is melt pultrusion that uses specialty grade low viscosity thermoplastic resins. The rest of this paper focuses on the description of the melt pultrusion process at the Fraunhofer Innovation Platform for Composites Research at Western University (FIP).

5. Materials and methods

5.1. Materials

The resin used for the experiment was XA3604 polyamide by BASF. The reinforcement used for the experiment was StarRov 895 glass fiber by Johns Manville.

5.2. Equipment

The pultrusion machine used for the process was an NLL/C-12TP-14TC-350/80 pultrusion equipment. The extruder used was a TDD65 single screw extruder by USEON with screw diameter of 65 mm and L/D of 30:1.

5.3. Die

The die was custom designed and made at the University of Western Ontario. It was originally designed for a rectangular profile with a cross section of 100 mm × 0.5 mm, and later modified to a cross section of 20 mm × 2 mm.

5.4. Pultrusion process

The pultrusion process was set up using the equipment, die, and materials described above. The setup is shown in Figure 2. Like thermoset pultrusion, the process started with fiber bobbins on a rack with fibers fed through fiber bundle guides for spacing and formation. Then, the fibers passed through the fiber pre-heating units, where the fibers were heated to prevent the polymer melt from freezing too quickly upon touching the fiber surface. The thermoplastic polymer was fed into the extruder that was positioned perpendicular to the pultrusion line. The extruder melted the polymer and pushed the polymer melt into the heated die. The fibers also entered the die and were wet out by the resin inside the die. The materials were then cooled to below melting point of the resin as they traveled along the die and exited as pultruded profile.

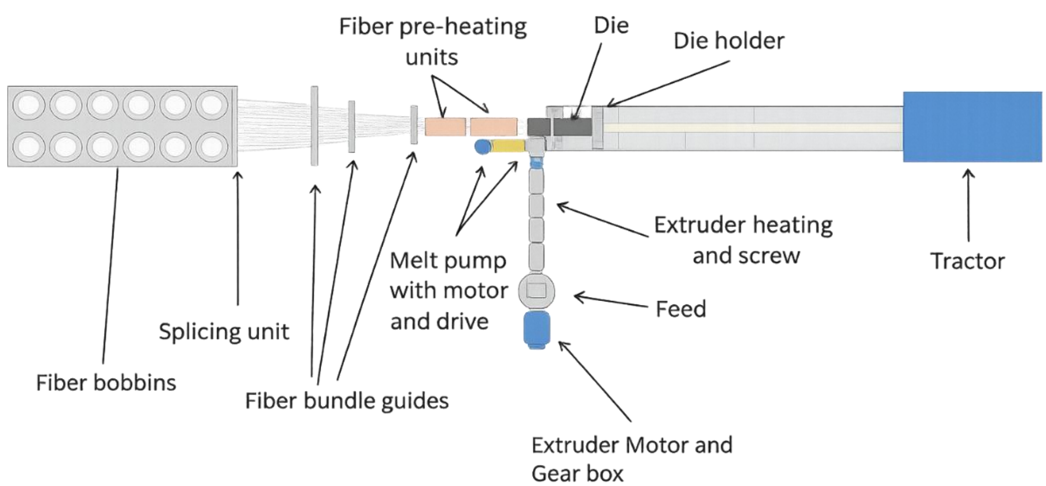

Figure 2. Thermoplastic melt pultrusion setup.

5.5. Tensile and flexural testing

To evaluate the performance, the pultruded profiles from the thermoplastic melt pultrusion process were subjected to tensile and flexural testing following ASTM D3039 and ASTM D790 standards modified to accommodate the pultrusion profile specimens. The tests were conducted with tensile and three-point bending fixtures that were installed in an MTS Criterion C45_105E universal test system with an LPS.105 100 kN load cell.

6. Results and discussion

6.1. Manufacturing of tape

Thermoplastic tape was manufactured first as a proof-of-concept experiment to confirm wetting out of the fiber tows. Tape at 67 vol% fiber content with 100 mm × 0.5 mm cross section was successfully manufactured. A section of the tape was prepared for optical microscopy. The fibers in the tape appeared to be well impregnated with resin as shown in Figure 3 (c).

Figure 3. (a) Thermoplastic tape (67 vol% fiber content with 100 mm × 0.5 mm cross section) from melt pultrusion process exiting the die, (b) manufactured tape, and (c) microscopy of the tape cross section.

6.2. Manufacturing of pultrusion profile

After the proof-of-concept, the die was modified to a 20 mm × 2 mm cross section for the manufacturing of pultrusion profile. Profiles at 60 vol% fiber content (c. 80 wt%) were prepared for property comparison to existing in-situ pultrusion profiles at the same fiber content.

6.3. Tensile and flexural properties

The melt pultrusion profiles (FIP) and the in-situ pultrusion profiles (ICT) were subjected to tensile and flexural testing. The results are shown in Figures 4 to 7. The standard deviation is approximately 5-10% on the tensile and flexural modulus and strength measurements. Properties of other relevant materials, including PA6 [6], 30GF/PA6 [7], E-Glass, Aluminum 6061, and A36 steel are also plotted for comparison.

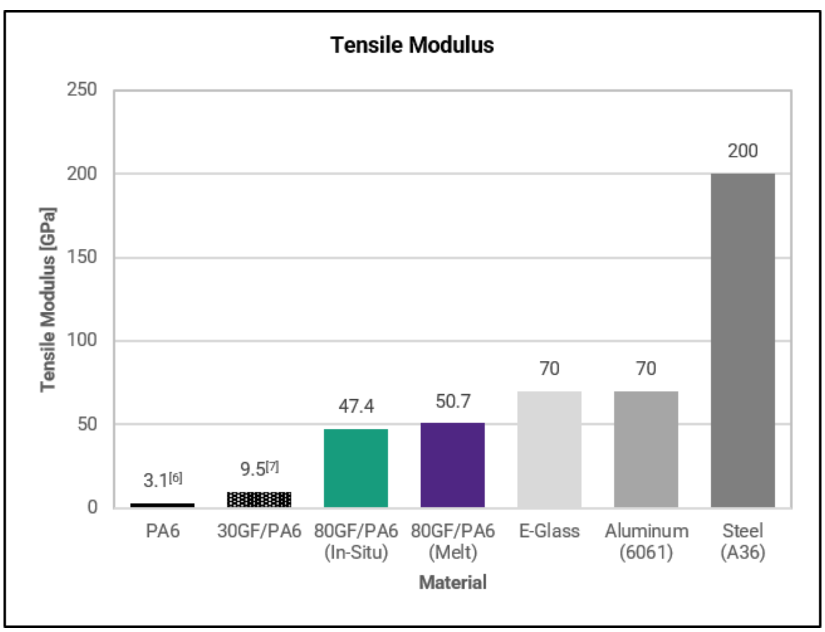

Figure 4. Tensile modulus comparison between pultrusion profiles and other relevant materials.

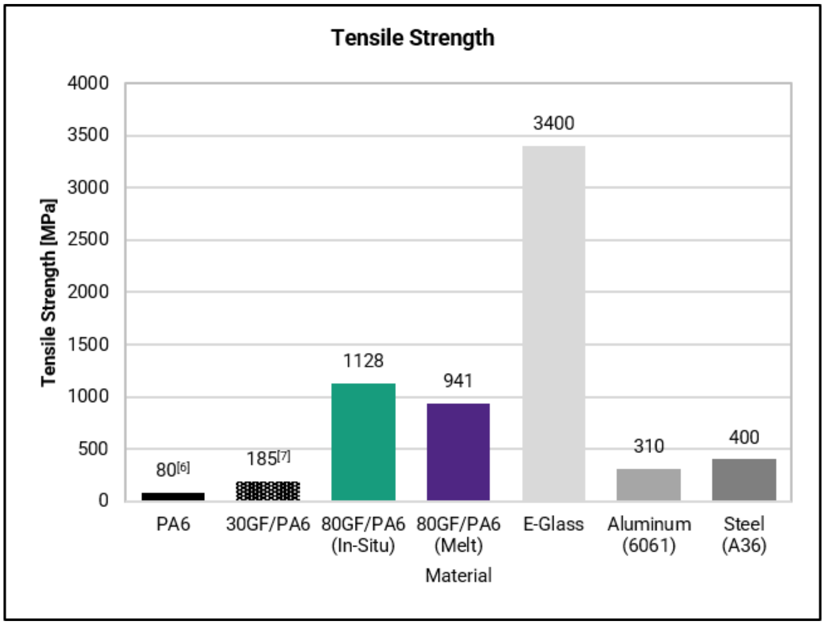

Figure 5. Tensile strength comparison between pultrusion profiles and other relevant materials.

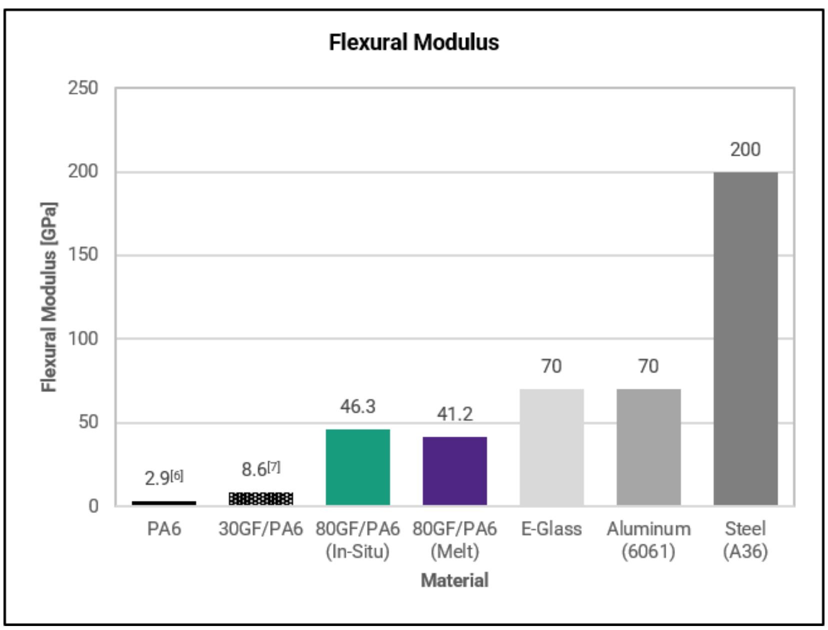

Figure 6. Flexural modulus comparison between pultrusion profiles and other relevant materials.

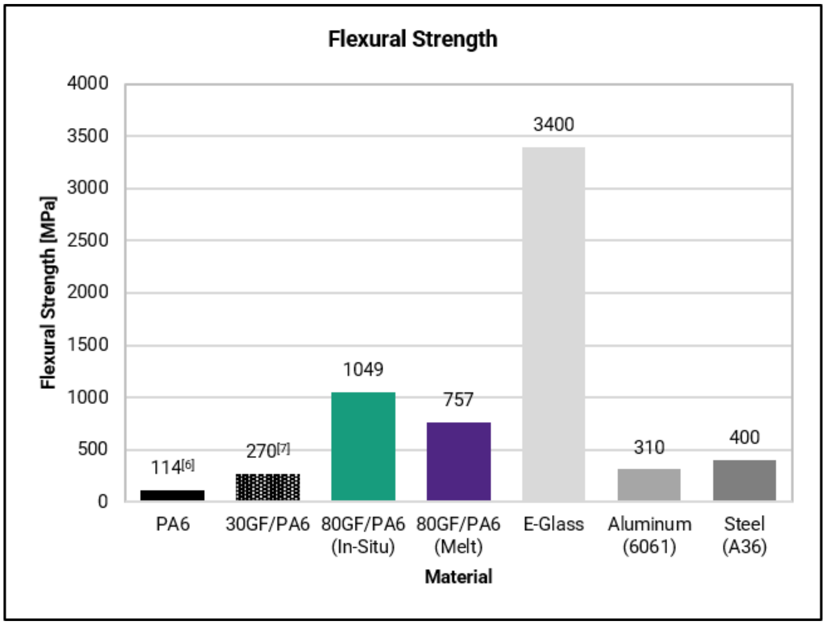

Figure 7. Flexural strength comparison between pultrusion profiles and other relevant materials.

The melt pultrusion profiles performed 7% better than the in-situ pultrusion profiles in tensile modulus, and performed 17%, 11%, and 28% worse in tensile strength, flexural modulus, and flexural strength, respectively. It is hypothesized that the in-situ pultrusion profiles had better fiber wet out and lower void content than the melt pultrusion profiles due to the difference in resin viscosity. However, the differences in properties are not significant, indicating that the melt pultrusion profiles still achieved good wet out and adhesion between resin and fiber. Although this experiment was limited to polyamide resin, the melt pultrusion process is suitable for all types of thermoplastic resins, as long as the viscosity is low enough to achieve good fiber wet out. This enables a broad range of resins to be utilized in the pultrusion process that was previously limited to thermoset resins and select thermoplastic resins suitable for the in-situ process.

7. Design scenario

To illustrate the lightweighting advantage of thermoplastic pultrusion profile in a structural application, a design scenario was carried out as illustrated in Figure 8. A rectangular beam with a 914 mm span and a 101 mm width is subjected to an 8.9 kN load in the middle. The height of the beam to ensure a maximum deflection of 12.7 mm is the variable in question. The calculation of the required beam height is dependent on the modulus of the material that the beam is made of. Table 1 lists a few different materials and the calculated height and weight of the beam accordingly.

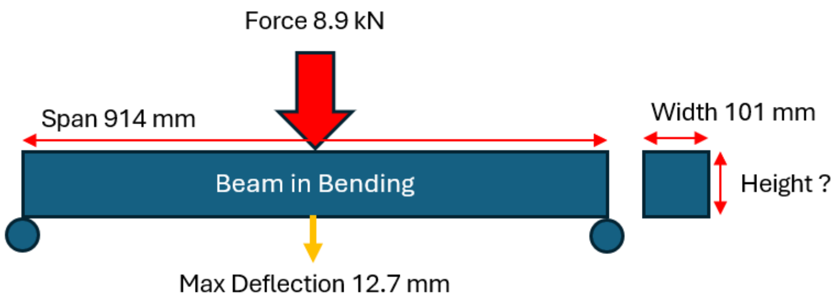

Figure 8. Flexural strength comparison between pultrusion profiles and other relevant materials.

Table 1. Design scenario results with pultrusion profile and relevant materials.

Material	PA6	30GF/PA6	80GF/PA (Melt)	E-Glass	Aluminum (6061)	Steel (A36)
Flex Modulus [MPa]	2.9 [6]	8.6 [7]	41.2	70	70	200
Height [mm]	77	54	32	27	27	19
Density [g/cm^3]	1.11	1.36	2.00	2.60	2.60	7.85
Weight [kg]	8.0	6.8	5.9	6.4	6.4	13.7

Although having a higher density than PA6 and 30GF/PA6, the 80GF/PA melt pultrusion material could satisfy the design requirement at much lower height, and therefore resulting in a lower overall weight of the beam. And although needing a greater height than E-Glass, aluminum 6061, and A36 steel, 80GF/PA melt pultrusion material still came in at a lower weight due to its lower density comparatively.

8. Formability and reusability of thermoplastic pultrusion profiles

Since the thermoplastic matrix can be melted under heat, the forming of thermoplastic pultrusion profiles after they are produced becomes possible. Schukraft et al. have investigated this topic using in-situ pultrusion profiles and bending them under heat and pressure [8]. Another paper that investigates the reusability of thermoplastic pultrusion profiles by Schukraft et al. is also being submitted for review.

9. Conclusion

Thermoplastic melt pultrusion process was successfully used to produce profiles with low viscosity polyamide resin matrix and high glass fiber content. Good fiber impregnation was achieved, and the mechanical properties were comparable to in-situ pultrusion profiles. The results demonstrate the potential of melt pultrusion as a versatile manufacturing process for lightweight structural components.

10. References

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