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Review

Mathematical simulation of pultrusion processes: A review

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ABSTRACT

A review of computational modelling and simulation of pultrusion processes is presented including such aspects as: resin flow and pressure distribution in a forming die; impregnation of reinforcing fibers; heat transfer and resin reaction; pulling force, stresses and strains development; methods for numerical optimization of the process. Development of models provides deeper knowledge concerning the mechanisms behind the process as well as the influence of constituent materials' properties and manufacturing parameters. Consequently, accelerated development of pultrusion process, allowing for the manufacturing of geometrically complex profiles is promoted.

1. Introduction

"Pultrusion" is a portmanteau term derived from words "pull" and "extrusion". The significant contribution to the development of pultrusion as a viable manufacturing process was made by Sir Brandt Goldsworthy who is often regarded as the "father" of pultrusion [1]. Back in the 1950s early pultrusion machines had vertical design and were often of an intermittent pull type. Lately, in the 1960s, pushed by the growing demand for pultrusion products, the industry started to invest in the process development, giving an opportunity to improve production equipment and to broaden the range of reinforcement types and resin systems used. Over the last 70 years, pultrusion has come a long way and is now one of the more efficient processes of fabricating composite profiles with constant cross-section, meeting close dimensional tolerances [2–4]. The process allows fabrication of pultruded profiles of virtually unlimited length, with higher flexibility and tensile strength compared to those fabricated with any other reactive polymer process [5,6].

Pultrusion products feature excellent mechanical, chemical, and structural performance and are used in various industries [3,5,7–10], such as architecture, transportation, construction, agriculture, chemical engineering, aircraft and aerospace. Examples of various pultrusion applications are shown in Table 1. A list of successful applications has also been posted on the website of the Pultrusion Industry Council of the American Composites Manufacturers Association (ACMA) [11]. Another organization promoting the interests of pultrusion industry is the European Pultrusion Technology Association (EPTA) [12].

During pultrusion, fiber reinforcement in a form of tapes, woven fabrics and/or mats is impregnated in a bath with resin of suitable viscosity. Then, the impregnated reinforcement is fed into a preformer where the excess resin is removed and reinforcement pack acquires the desired shape. Preformed reinforcement pack is pulled through the heated die block where the curing process takes place. Usually, several heating zones with different temperatures are installed along the die block, depending on the type of resin, the pulling speed, and the length of the block. After the die exit a cured pultrusion is pulled by a puller unit and cut to segments of desired length (Fig. 1).

The average processing speed is 1 m/min for thermoset and up to 60 m/min for thermoplastic matrices. The processing speed must be chosen wisely as, among other things, it affects fiber wetting and resin cure and, thus, the reproducibility of physical and mechanical properties of fabricated composite profile.

The die section is shown in Fig. 2. Compacted reinforcement/resin pack heats up as it passes through the heated die block. As the temperature reaches the gel point, an exothermic reaction is initiated and the resin starts curing. Certain modifications of the pultrusion process exist, where resin is injected in an upstream chamber or directly into the die block (Fig. 3). Processing speed is dictated by rate of reaction. Processing speed and the die length (0.9 to 1.5 m) determine the time during which material stays within the die block. Processing speed is chosen by tracking the position of chemical reaction within a die block and observing the quality of finished product.

Various forms of reinforcement can be used in a pultrusion process. Continuous roving provides longitudinal strength, while mat and fabric reinforcement provide transverse strength. Mostly, pultruded profiles are fabricated with continuous-strand mats or other forms of transverse

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Table 1
Typical applications for pultruded profiles [3].

	Required properties	Examples
Construction	Light weight, high strength, fatigue resistance, ease of installation, fire performance, easy maintenance	Flooring and walling systems, fences, bridges
Applications in adverse environment	Excellent corrosion resistance, Suitable for a wide range of environments	Walkways, ladders, staging, fencing, stairs
Electrical applications	Insulating properties	Cable tray support members, ladders, transmission poles, towers
Marine	Corrosion resistance	Wastewater treatment plants
Transportation	Light weight, electrical and environmental resistance. costeffective	Railways, vehicle body panels
Sport and Leisure	Light weight, easy installation, corrosion resistance	Hockey sticks, ski poles, golf clubs, arrows, kites, sail mats, etc

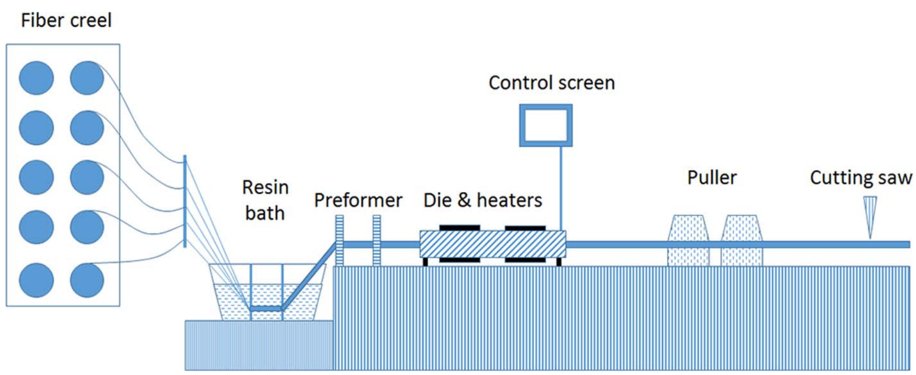

Fig. 1. The schematic representation of the conventional pultrusion process.

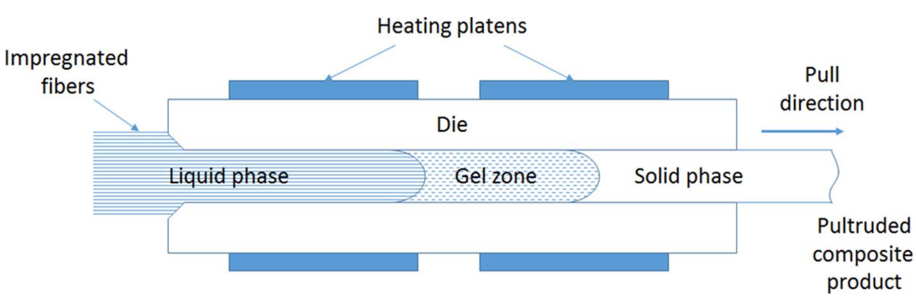

Fig. 2. Composite profile and heating sections of the conventional pultrusion die.

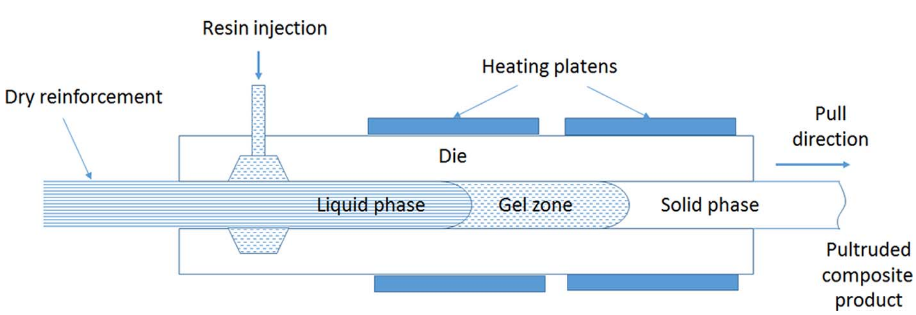

Fig. 3. Resin injection die.

reinforcement, as these reinforcement forms allow fabrication of composites with more even distribution of properties. Fig. 4 shows typical reinforcement structure of pultrusion profile. Table 2 shows properties of pultruded composite fabricated with glass fiber reinforcement and thermoset resin. Tables 3 and 4 list properties of glass- and carbon fiber reinforced pultruded composites based on thermoplastic resins. The following abbreviations are used in both Tables: PP-polypropylene, PMMA-poly (methyl methacrylate), PU-polyurethane, NY6-nylon 6, PPS-polyphenylene sulfide, UP-unsaturated polyester, PH-phenolic resin and ABS-acrylobutadiene styrene.

Glass fiber is the most popular reinforcement for composite materials in a broad range of applications, due to its good mechanical properties and high affordability. However, handling of glass fibers may involve health risks. The use of natural alternatives such as flax fibers can alleviate these problems [14].

In order to obtain a composite with a highest mechanical performance, reinforcements must be fully impregnated with resin. Dry fibers and captured air bubbles resulting from poor impregnation may severely degrade the performance of composite in many respects. The choice of resin is based on process requirements and the proposed end-use of the product, and depends on viscosity, reactivity, working time, curing conditions, dimensional shrinkage, structural performance, chemical resistance, safety and environmental aspects and other factors. Typical resin formulations are composed of several components, based upon the required performance of the product and cost considerations, as shown in Table 5. A good fiber wetting out should be