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Cost-efficient, automated, and sustainable composite profile manufacture: A review of the state of the art, innovations, and future of pultrusion technologies

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ABSTRACT

Over the last 70 years, pultrusion has matured into an industry-leading process when it comes to providing high throughput and automated composite manufacture at a competitive price point. In this paper, we review recent innovations that have advanced pultrusion to a versatile manufacturing technology and thereby allowed composite materials to penetrate markets in, e.g., the automotive, construction, aerospace, and wind turbine industries. We accompany our review with discussions on how pultrusion has enabled new innovations within additive manufacturing and sustainable composite manufacturing, and finally, we provide an outlook and suggestions for where we see the potential for research and new industrial applications of pultrusion technology.

1. Introduction

Pultrusion is a continuous, fully automatable, and increasingly popular process that is used to manufacture fibre reinforced composite profiles with a constant cross section (see Fig. 1). As the name implies, pultrusion is a compound word of the terms “pull” and “extrusion”, but as opposed to extrusion processes where the profile is produced by pushing material through a die, a pultrusion process advances the profile by pulling it.

There is a broadening adoption of pultruded profiles and products. This can be motivated by the cost and energy efficiency of the process as well as the repeatable, high material quality even for high fibre volume contents. Pultrusion has been experiencing some of the fastest growth across the European fibre-reinforced polymer composite industry [1], and it is expected that the global pultrusion market ($2 billion) will expand with an annual growth rate of 4.9% [2], far exceeding the near-future global GDP (gross domestic product) growth of 2.3% (in 2023, [3]). With a reported energy intensity of 3.1 MJ/kg, or approximately one-seventh of autoclave moulding[1] [4,5], pultrusion is an industry-leading process in terms of energy efficiency. Together with processes like filament winding and automated fibre placement technologies, pultrusion is a continuous manufacturing process, but it is the only manufacturing technology that allows for endless and uninterrupted composite manufacture [6]. This enables composite manufacture at a very competitive price point, also since pultrusion has a high material efficiency with low waste and no inherent need for disposable items such as vacuum bags and flow mats. Even with the outbreak of COVID-19, and the subsequent disruption of global supply chains, pultruded polyester/glass fibre profiles may today be acquired in bulk from East Asia for as low as roughly $3/kg, close to the price point of the raw materials[2].

While pultrusion was first introduced in early variants in the

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[1] It is important to note that the design freedom of autoclave moulding is unparalleled to pultrusion, which is why this reported energy intensity should be taken as a reference point and not a direct comparison.

[2] This estimate was based on prices of raw materials and pultruded profiles on the e-commerce giants, okorder.com (CNBM International) and alibaba.com (at the time of writing, the 20th of March 2022).

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1950'ies with the work of W. Brandt Goldsworthy in the USA on polyester resins and Ernst Kühne in Switzerland on epoxy resin [6], a lot has happened since the initial concepts 70 years ago. Pultrusion is today a highly versatile process that is compatible with a wide variety of fibre reinforcements and matrix materials, e.g., conventional thermosets and thermoplastics, as well as renewable matrices, reinforced with glass, carbon, aramid, and natural fibres. Many innovations were required to reach its current maturity and flexibility that have facilitated production of, e.g., lightweight parts for the automotive, construction, aerospace, and wind turbine industries. These are reviewed in this paper together with an accompanying discussion on how pultrusion has enabled technological advancements within additive manufacturing and sustainable composite manufacturing. Compared to other review papers about pultrusion (recapitulating mathematical modelling and simulation [7], materials & applications [8], and thermoplastics [9]), we focus on *recent* innovations, their advantages, and how they have enabled applications and penetration of new markets for composite materials. Finally, we also draw on our consortium's extensive experience in pultrusion gained from completing multiple academic and industrial research projects to provide an outlook and suggestions for where we see potential for new pultrusion-related research and industrial application.

The structure of the review paper is organised as follows. Sec. 2 starts by providing an overview of the pultrusion process and the processing steps. Sec. 3 represents the main body of the paper, and starts with a short review of some of the methodical work that has been completed about pultrusion. Subsequently, we review and discuss recent innovations in pultrusion technology, in particular: new production technology (such as microwave and UV-assisted curing, pultrusion of bent profiles, etc., Sec. 3.1), new layup and material-forming technologies (e.g., pull-braiding, hybrid materials, and multi-step pultrusion, Sec. 3.2), advanced intermediate materials for thermoplastic pultrusion (such as bi-component fibres, Sec. 3.3), how pultrusion is an enabler for additive manufacturing (e.g., pultrusion of thermoplastic strands with fibre reinforcements, use of pultrusion technologies for free-form 3D printing, Sec. 3.4), and how pultrusion can facilitate sustainable composite manufacture (low-waste and energy-efficient composite manufacture, utilisation of renewable materials, etc., Sec. 3.5). Finally, in Sec. 4, we summarise conclusions, outlook, and suggestions for where we see the potential for new research and industrial applications.

2. Process overview and material behaviour

2.1. Process overview

Profiles manufactured using pultrusion processes can be processed using several different process concepts that are compatible with thermoset and thermoplastic polymers, produced from both renewable and fossil resources, reinforced with glass, carbon, aramid, and different types of natural fibres. Table 1 presents common material compositions and process configurations that reflect the state-of-the-art and versatility of pultrusion processes. While pultrusion processes vary by design, the process generally includes the following substeps [6]:

- **Preparation of layup:** The raw material is drawn from fibre creels or racks. Depending on the required application of the profile, rovings (tows of individual fibres), mats, and fabrics enter the profile layup, but it can also be pre-preg materials, tapes, commingled fibres, or bi-component fibres, as well as other raw materials where the fibres might be pre-combined with the matrix material. Before entering the pultrusion die, the raw material passes a number of guides that organise and shape the layup into the desired cross-sectional shape and ply plan.
- **Impregnation and heating/cooling:** The organised fibre material is now moved towards the pultrusion die. In resin-injection pultrusion (Figs. 2,3 and 4), injection takes place in the first part of the die. Typically, active heating and cooling are now applied to ensure proper viscosity while controlling the solidification of the profile. In other pultrusion concepts, such as resin-bath pultrusion and open-die pultrusion, the fibre material is pre-impregnated before entering the die, otherwise, the processing steps are identical. A clear advantage of resin-injection pultrusion is the fact that it is a closed-mould process, which limits possible exposure to volatile solvents, etc., from the resin system. Before exiting the die, the outer edges of the profile must be solidified to ensure that the profile remains stable when it is no longer supported by the die walls.
- **Cooling and cutting:** A pulling mechanism advances the process by continuously pulling the solidified profile out of the die to cool down. Finally, the profile is cut into desired lengths.

2.2. Process and material behaviour

Independent of the pultrusion concept, a key ingredient to processing of fibre-reinforced polymer profiles using the pultrusion process is *heat*, and since the rheological behaviour of the matrix material is both time and temperature dependent, tight control of the profile's thermal history is crucial to ensure correct material flow and process quality. Here, we describe the process behaviour of a thermoset resin-injection pultrusion process, and we also discuss how this is different for other materials and pultrusion concepts.

A pultrusion die (Fig. 4) can be designed with or without a tapered section. A taper allows resin saturation to take place at a lower fibre volume fraction, which is a necessity for resin-bath pultrusion where impregnation is started at atmospheric pressure. Collimation, as well as the viscous and mechanical sliding friction, contribute to the pulling force [26,27], but with a tapered die design, the hydrostatic resin pressure during consolidation must be overcome as well (cf., Sec. 6.5.3 in Ref. [10]). For resin-injection pultrusion, the resin system is injected at an elevated pressure allowing for saturation, also in a straight

Fig. 1. Fibre-reinforced, thermoplastic rods with different diameters (left and middle, $\varnothing 10 - 40$ mm), fibre-reinforced, thermoset profiles with complex cross sections (right, $w \times h \approx 60 \times 60$ mm^2, wall thickness 2 mm). All these profiles were manufacturing using the pultrusion process.

pultrusion die. Here, the magnitude of the injection pressure together with the profile-advancing pulling speed is adjusted to achieve sufficient impregnation without resin wastage due to overflow [11,28,29].

Once the fibres are impregnated, the state of the composite profile in a pultrusion process can be derived from the temperature, T, and for a thermosetting polymer, the degree of cure, α, as well. Here, α ranges from 0 to 1, which corresponds to an uncured ($\alpha = 0$) and fully cured matrix material ($\alpha = 1$). A process diagram of a thermosetting resin-injection pultrusion process that was achieved using numerical simulation can be seen in Fig. 5 [11]. This diagram exemplifies how the temperature, degree-of-cure, glass-transition temperature, resin pressure, and viscosity can develop throughout a pultrusion process.

Chemorheology describes the cure and temperature-dependent constitutive behaviour of the matrix material. For a polymer, this behaviour is split into three phases. In the first phase, the viscous phase, the polymer chains are mobile, and the mobility of the polymer chains is characterised by the viscosity of the matrix material. In most thermoset pultrusion processes, impregnation takes place close to or below room temperature, while in some pultrusion concepts, heat is applied to decrease the viscosity and therefore expand the process window suitable for impregnation. For fully polymerised thermoplastics, heat *must* be applied to melt the polymer, otherwise, impregnation cannot take place. Towards gelation, which is the second phase, the viscosity rises as the mobility of the polymer chains decrease. The gelation point is defined as the point where the viscosity rapidly increases, and the matrix starts to support loads without flowing. After gelation, the polymer is in a "rubbery" phase, and as a result of the developed polymer chain structure, straining the polymer introduces a lasting stress state. In loose terms, some may refer to this as the point where the matrix starts to gain "memory" as the response is no longer only viscous but also elastic. For thermosetting polymers, curing is thermally activated (hence the name, "thermoset") and external heat is now normally needed, however for thermoplastic materials, cooling is needed for the polymer to solidify. In the final phase, further cooling is applied, and the temperature reaches the cure-dependent glass-transitioning temperature (which corresponds to vitrification), $T = T_g$. As Fig. 5 illustrates, resin curing can continue upon die-exit. After cooling down, the process is complete.

3. Innovations and research in pultrusion technology

Over the last 50 years, more than 1400 papers have been published in scientific journals and conference proceedings about pultrusion[3], which includes theoretical and experimental studies of various thermoset resin systems [30–40], thermoplastics [20,22,24,41–49], as well as alternative and renewable materials and reinforcements [50–54]. For resin-injection pultrusion, in particular, where analyses of the impregnation flow is essential to ensure saturation [15,38–40,55,56], studies have considered geometrical configurations of the injection chamber [57–61] as well as other process parameters such as the profile-advancing pulling speed [62], resin viscosity [63], and fibre permeability [64]. Using thermo-chemical-mechanical analyses, numerous studies have also looked into process-induced stresses and deformation of thermoset pultrusion [17,65–72]. Clearly, extensive efforts have been invested in advancing the fundamental understanding of the governing physics of pultrusion. These tools today equip engineers to perform the analyses and optimisation of pultrusion processes that are needed to find the most suitable process parameters to reduce costs and defects while maintaining production output and efficiency.

The main limitations of the pultrusion processing window are defined by heat transfer, impregnation, consolidation, die-pultrudate interaction, residual stresses and warpage as well as the alignment and distribution of the reinforcing material in the profile. From the production side, the cost of the overall product remains the main driver for increasing line speeds and the development of new resin formulations, while the need for recyclability and ease of operation puts the focus on thermoplastics in general as well as sustainable and renewable fibre options and bio-based polymers such as PLA. From an application perspective, the limitations in profile geometry as well as the choice of fibres, matrix, and lay-up are the main factors. The following sections (outlined in Fig. 6) address innovations that not only improve the traditional process-related limitations of pultrusion but also extend the application range of pultruded profiles from constant-cross-section profiles to fully functionalised, variable cross-section, multi-material components that keep the advantages of cost-efficient high-quality pultrusion while offering significantly higher design freedom in terms of geometry, material choice and functional integration.

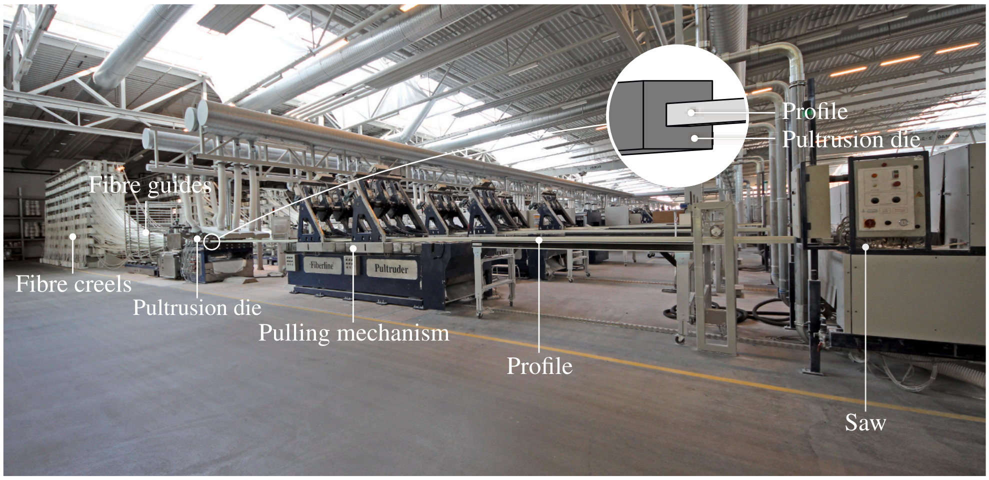

Fig. 2. A state-of-the-art, industrial resin-injection pultrusion line. Here, the material flows from left to right (courtesy of Fiberline Composites A/S). A schematic of the line can be seen in Fig. 3 and a cut-view schematic of the pultrusion die can be seen in Fig. 4. This figure was taken from Sandberg [10].

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[3] This statement is based on a web-of-science search on titles that included "pultrusion" or "pultruded" on the 9th of February 2022.

3.1. Advances in production technology

Reducing energy and time consumption for manufacturing is a common goal for the whole composite material community to increase efficiency and decrease the environmental impacts. Here, energy-efficient, high-quality, and fast manufacturing methods are needed, and in this section, we review advancements in pultrusion production quality to achieve just that.

3.1.1. Alternative curing/heating technologies

In conventional pultrusion processes, a metal die with electrical heating elements is used to cure and consolidate the pultruded profile (Fig. 4). Even though conventional pultrusion processes are considered to be energy efficient, efforts have been made to further advance the efficiency of pultrusion using alternative heating/curing methods [73].

Radiation curing is an alternative for thermal curing, in which the polymerisation of thermosets is induced by ultraviolet (UV) radiation, gamma X-ray, electromagnetic (microwave), or electron beams [74]. UV radiation is less hazardous, has lower energy consumption, and needs lower initial investment cost compared to the others, and therefore this is one of the most promising choices of alternative curing method for the pultrusion process [74]. A critical factor of UV-curing is the opacity of the resin and fibres, which limits the effectiveness of curing composites with carbon reinforcement [75], for example. For pultrusion, studies accessing UV-curing techniques have been limited to glass fibre profiles.

The first trials of adapting UV curing into pultrusion was presented in the 80s using a UV-transparent die. Later on, UV curing was tested as an out-of-die curing method in which UV radiation was applied at the exit of a forming die. Here, any excess resin was removed, and the impregnated uncured profile was compacted/formed into the desired cross-sectional shape in the forming die. Out-of-die curing has been reported to require two orders of magnitude lower pulling force than conventional pultrusion [76], and it also allows post-die manipulations to apply curved regions on the pultruded profile [77] (known as “bent pultrusion”, to be discussed in Sec. 3.2.4 and Fig. 11). A relatively low peak temperature that is typically reached during UV-cured pultrusion makes it possible to use temperature-sensitive reinforcements such as Nylon6 [78]. Another route is microwave-assisted pultrusion. Here, the material properties together with the electromagnetic characteristics define the microwave interaction [79], meaning that selective heating of the profile with limited loss of energy to the die can be achieved by using a partially microwave-transparent die [80] (Fig. 7). Direct heating of the profile using microwave heating can result in 5 times higher pulling speeds and 1.7 times lower energy consumption as shown in a recent theoretical study by Barkanov et al. [81]. In addition to the energy efficiency, microwave heating can ensure more homogeneous curing throughout the cross section which results in lower residual stresses [82].

In addition to these alternative heating/curing methods, new strategies that exploit material-based technologies to increase efficiency are also investigated in the composites community. For example, an emerging energy-efficient composite manufacturing route is frontal polymerisation. Here, the strategy is to exploit highly reactive resin systems that allow for polymerisation within a very narrow process window. The idea is that with the right curing kinetics, once initiated, a very localised and self-sustained reaction will emerge and propagate throughout the entire material layup without the need for any additional heating [83]. With well-controlled frontal polymerisation, the energy input can be minimised while producing high-performance composite materials [84]. In theory, frontal polymerisation can allow for pultrusion with no or limited external heat source after initiation of polymerisation.

3.1.2. Vacuum, fibre spreading, and fibre treatments to advance product quality

Fibre-matrix bonding, void content, and microstructural uniformity are some of the key aspects that govern the quality and performance of a pultruded profile and composite materials in general. To optimise pultrusion processes, some of the well-known concepts that are widely applied for the general processing of polymer composites now find their way to pultrusion processes. An innovative example of this is vacuum-assisted pultrusion, where an appropriate vacuum pressure can lead to void reduction by extracting entrapped air in the tow during impregnation [85]. Lapointe and Laberge Lebel [86] showed that the vacuum usage reduces the void content and increases the shear strength as a result thereof. Fibre-surface treatment is another commonly used application for fibre-reinforced polymers to enhance impregnation by capillary effects [87] and mechanical performance by improved fibre-matrix bonding [88]. Some of the surface treatment methods that have been applied with positive outcomes for pultrusion are coupling agent treatments [89], liquid nitrogen treatments [90], and corona discharge treatments [91]. Whereas some of these fibre-surface treatment methods should be done before the pultrusion process, corona discharge treatment, for example, can also be performed continuously in the pultrusion line.

Well-dispersed rovings lead to a more homogeneous fibre distribution, and this is another critical aspect to improve the impregnation and mechanical properties of composites. Even in conventional pultrusion, it is common to have a set of static bars (fibre guides, as referred to in Sec. 2.1) on which rovings are organised and spread when passing. However, more advanced techniques can be necessary to enhance fibre spreading. Here, wrap angle, pre-tension of rovings, temperature, and pulling speed are some of the effective parameters related to mechanical fibre spreading [92]. A higher wrap angle or increasing the number of spreader pins result in better fibre distribution and thinner rovings that will lead to an improved impregnation quality. Irfan et al. [92] developed a modified pultrusion process which consists of a fibre spreading unit. This spreading unit provided better lateral spreading and reduced roving thickness, and this resulted in better impregnation and lower void content [93]. Van De Steene et al. [94] applied passive and active spreading methods into a small scale pultrusion die. They designed a spreader-impregnation device for melt impregnation of Polyamide12, and showed that the dispersion quality with both passive and active spreader units is much better than an equivalent unmodified pultrusion process. On the other hand, adding mechanical resistance to the fibre material increases both the probability of broken fibres and the pulling force needed to advance to profile. Therefore, the trade off between these drawbacks and the potential benefits of mechanically-aided dispersion of rovings should be taken into consideration.

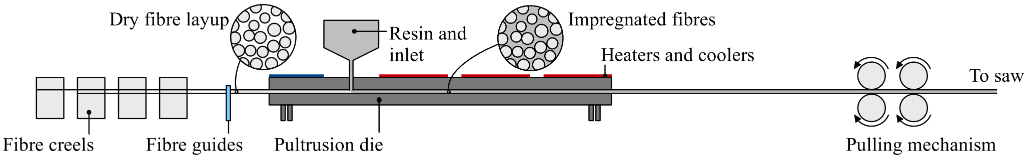

Fig. 3. Schematic of a resin-injection pultrusion line. In the figure, the material flows from left to right.

3.2. *New layup and material forming technologies*

In addition to the production technologies that we reviewed in Sec. 3.1, significant research efforts have been invested in technologies that can enable pultrusion of certain material layups, configurations, and fibre architectures. In this section, we review some of these latest advancements, and how these have helped the pultrusion industry to penetrate new markets and application areas.

3.2.1. *Complex lay-ups, cross-sections, and braidtrusion*

The major fibre orientation of pultruded profiles is traditionally along the profile axis to yield the highest packing of fibres and to provide the tensile strength needed to advance the profile by pulling it. To overcome this resulting transverse strength deficiency, continuous strand mats can be used to provide randomly oriented fibres in combination with surface veils for a better surface finish. Recently, more complex non-woven multi-axial stitched fabrics are used to manufacture complex, load-tailored layups even with fully transversal plies as the stitch yarn itself is designed to take the loads in the pulling direction. Different applications include a U-shaped pultruded profile using triaxial +45°/90°/-45°layup mats [95], or combinations of different biaxial and triaxial mats [96] to manufacture road decks. Cost-efficient, high-volume production of an automotive rear bumper profile [97] has been achieved by the combination of different biaxial, triaxial, and UD non-crimp fabrics. Other potential application fields for cost-efficient manufacturing of complex cross-sections include the production of airfoils for unmanned aerial vehicles [98] as well as wind turbines blades [99]. A different approach called patch-pultrusion combines the pultrusion of conventional reinforcing materials with load-tailored fibre patches that are applied to a textile carrier material using the Tailored-Fibre-Placement technology [100]. This enables the local reinforcement of pultruded profiles for highly loaded areas resulting in an overall lighter and more cost-effective profile.

Braidtrusion is another approach to further improve the multiaxial loading capabilities of pultruded profiles. Braidtrusion (also called “braiding pultrusion” or “pullbraiding”) is a compound word of “braiding” and “pultrusion”, and the process works by combining these two processing techniques. In a braidtrusion process, rovings are intertwined by braiding (similar to the processing of textiles) around a mandrel or core, while the profile is advanced by pulling it. Different kinds of material and processing techniques can be utilised in braidtrusion. For example, Michaeli and Jürss [45] demonstrated the use of thermoplastic (PP) commingled with glass fibres. Similar configurations have also been used to manufacture curved, thermoplastic composite profiles [101], as well as complex cross-sectional shapes such as L-shaped profiles [102]. Braidtrusion has also been conducted with the use of impregnation strategies, for example, resin-bath impregnation [103]. Compared to the use of, e.g., commingled fibres, resin-bath impregnation enables the use of a larger variety of materials, including thermoset resin systems. Recent work has also been completed on more methodical aspects of braidtrusion. For example, Ghaedsharaf et al. [104] investigated the resulting internal geometry and fibre orientation distribution as a result of the material forming that takes place during braidtrusion. Related to braidtrusion, pultrusion-winding is another approach in which a hoop layer is wound around a pultruded core to achieve the helical contact surface that is ideal for composite rebar applications [105,106].

3.2.2. *Multi-stage and multi-material pultrusion*

Multi-stage pultrusion consists of multiple pultrusion stages, where additional material is added in each stage around an initially pultruded profile as depicted in Fig. 8. For thermoset materials, the proposed benefit of a multi-stage system is the better homogeneity of the curing process in each layer as the curing reaction is initiated from both the previously pultruded core and the heated die walls. This concept has been proposed and investigated by Gorthala and Flynn [107] and modelled by Albayati and Gorthala [108], showing a higher degree of cure for a multi-stage die compared to a single-stage process. These multi-die systems can also be used to continuously increase consolidation pressure for the same profile geometry, without adding additional material in the different stages, resulting in a lower void content and higher shear strength [23]. For thermoplastic pultrusion, multiple stages can also be used to improve heat extraction efficiency, as the ratio between available cooling surface and the pultruded volume increases with the number of stages. This has been successfully demonstrated for solid rods using glass-fibre PET commingled yarns as shown in Fig. 9(a) with a two-step pultrusion process [109] as well as for tubes using braided commingled preforms in a three-stage process [110].

Multi-material pultrusion consists of the combination of different reinforcing fibres, polymer matrices as well as embedded metallic structures or sensors. For thermoset materials, pultrusion of hybrid rods with a carbon fibre core and E-glass fibre shell can increase the tensile strength of overhead electrical conductors by 150%, while reducing the thermal expansion and therefore sag by up to 400% [111]. A different application of a multi-material concept is the combined use of carbon and glass-fibre rovings, multi-axial fabrics, and piezo sensors to optimise

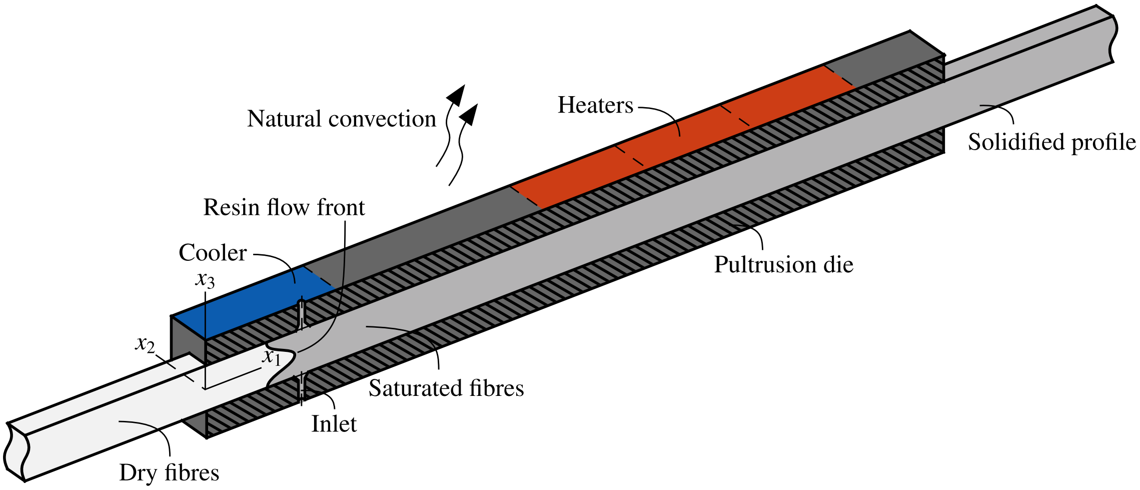

Fig. 4. Cut-view schematic of a pultrusion die that is used for the resin-injection pultrusion concept. Here, the material flows from left to right. The figure indicates placements of heaters, coolers, and resin inlets, and it illustrates how a flow front splits the dry and saturated fibre material. This figure was taken from Sandberg et al. [11].

Table 1
An overview of selected work on pultrusion that reflects the different material compositions and state of the art considering speed and fibre volume fraction for both thermoset and thermoplastic resins, fibre architecture, as well as profile dimensions.

Material technology/fibre architecture	Fibre material	Matrix material	Profile cross section	Fibre volume fraction	Pulling speed mm/min]	Ref.
Unidirectional (UD) Braid	carbon	epoxy	1.75 × 46 mm, 46 × 3.35 mm, T	56–65%	50	[12]
UD	Jute glass	unsat. polyester	Ø12.7 mm	70%	195	[13]
UD (intra-yarn, interlayer hybrid)	Carbon glass	epoxy	Ø12.7 mm	70%	–	[14]
Air text.(UD)	glass	polyurethane	80x80 mm	44%	182	[15]
Cont. strand mat (CSM) Biaxial fabric (BGF) Quadriaxial fabric (QGF) UD	glass	unsat. polyester	750 x 200 mm (hollow)	31–43%	–	[16]
Fabric UD	glass	vinylester	80 × 80 mm, L	59%	200–600	[17]
Tape (TP)	glass carbon	PA12 PEEk	15 × 3mm	50% (PA12) 60% (PEEK)	300–3000	[18]
Parallel (PL) Commingled (CM) Envelopped (EL) powder (PD) Melt (MT)	glass carbon	PP PA6 PES PEEK	10x1.5 mm Ø 8x1, Ø14 × 1mm tube 10 × 50mm U	35–57% (CM) 42–53% (PD) 27–73% (MT)	80-7500 (CM) 80-20400 (MT) 80-2240 (PD)	[19]
Commingled Powder	glass	PP PA12	20 × 2 mm Ø2 mm rods	45%	1000–10000	[20]
Commingled	jute	PLA	23x1.5 tube	43–52%	18	[21]
Melt	glass	PA6	50 × 4 mm 80x4 Omega	45–55%	500–700	[22]
Commingled	flax	PLA	Ø4.76	40%	50–220	[23]
Commingled	glass	PP, PA12, PET PEI, PC	Ø5-Ø40mm	58–65%	0–250	[24] [25]

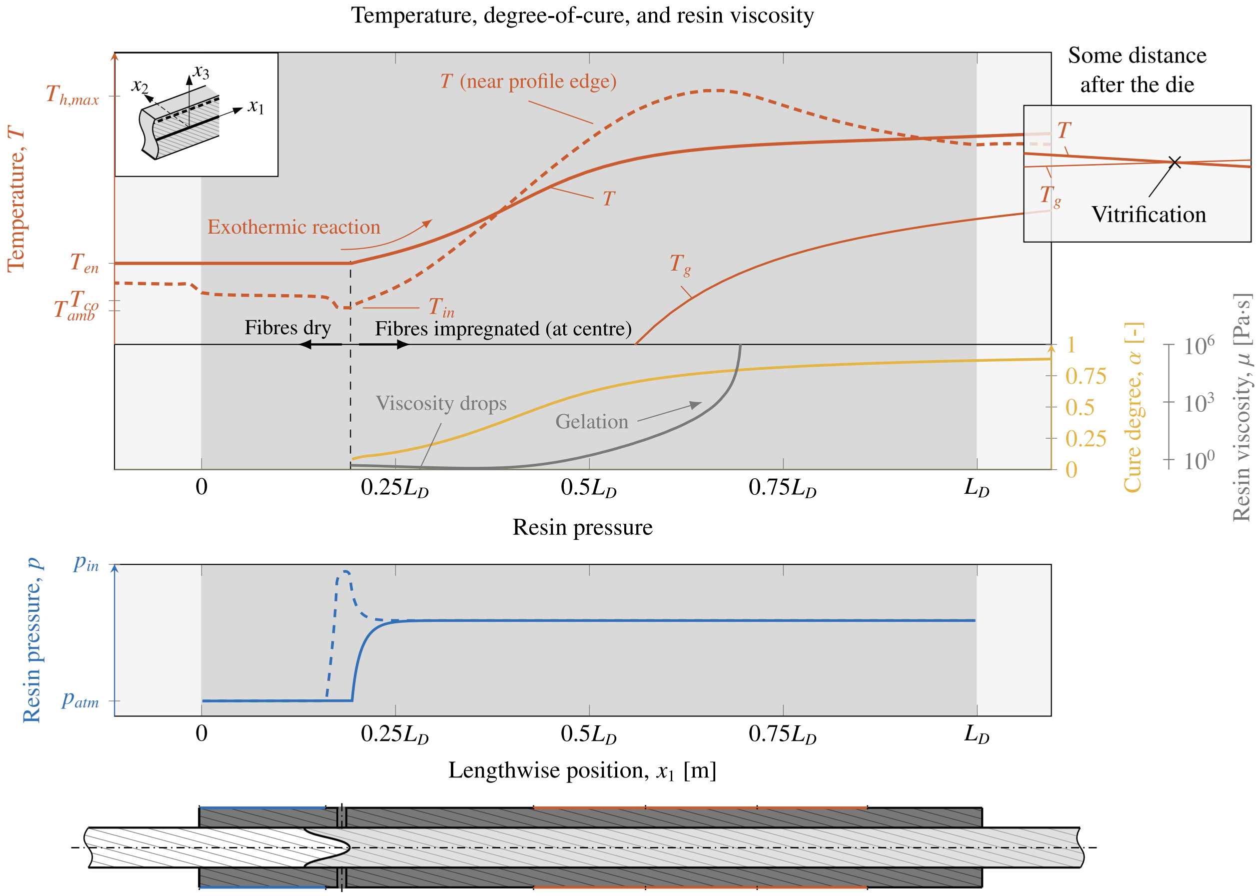

Fig. 5. Typical process diagram for a thermoset resin-injection pultrusion process. In the figure, L_D is the length of the die, and the following subsets apply: "in" = inlet, "atm" = atmospheric, "amb" = ambient, "en" = entrance,"h,max" = max. heater temperature, "co" = cooler. The solid line marks the centre of the profile and the dashed line is near the edge of the profile. This figure was adapted from Sandberg [10].

the mechanical response of a ski-roller while reducing cost and weight [112]. The introduction of a steel sheet into flat and multi-cavity pultruded profiles highlights the benefits of this approach in terms of crash-energy absorption of hybrid metal-composite profiles [113] (an example of such a hybrid profile can be seen in Fig. 9(b)). For thermoplastic pultrusion, a multi-stage process has been used to successfully combine different fibres, matrix polymers, and metal inserts as shown in Fig. 9(b–d) to manufacture hybrid profiles [109]. These profiles allow

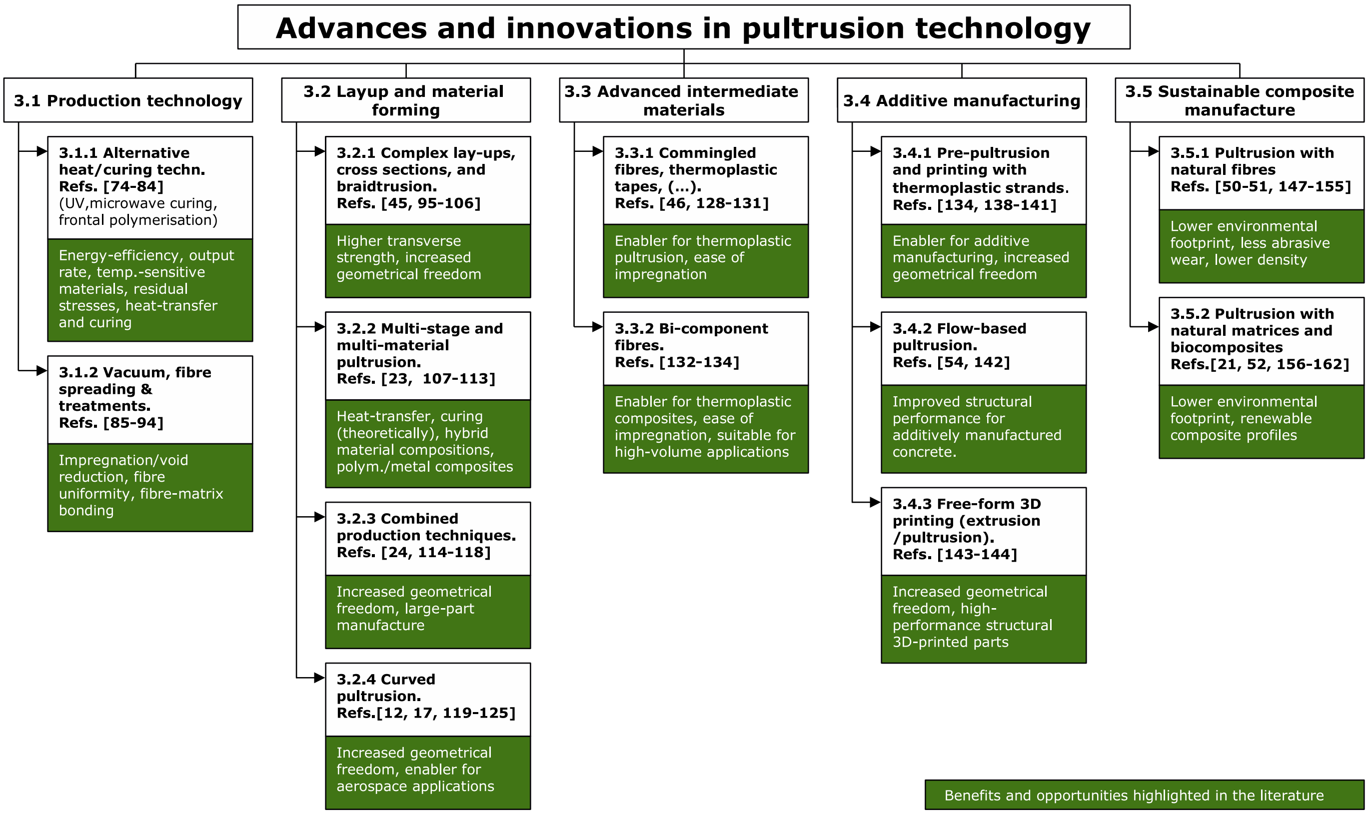

Fig. 6. Outline of the advances and innovations in pultrusion technology that are covered in this paper.

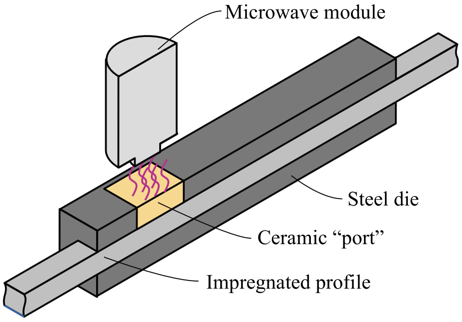

Fig. 7. Illustration of a pultrusion process that utilises microwave technology to enable the curing step of a thermoset resin system. As illustrated, this can be done by integrating a ceramic "port" into the steel die in which microwaves can be transmitted.

engineers to tailor the functionality of the pultruded profile to specific applications, where, e.g., both the electrically insulating properties of glass fibre composites and the electrical conductivity of metals are required. It is important to note that even though multistage thermoset pultrusion has been envisioned in the patent by Gorthala and Flynn [107], and the theoretical work by Albayati and Gorthala [108], empirical evidence proving the actual feasibility of the concept is currently not available for processes that utilise thermoset materials.

3.2.3. *Combined production techniques*

By combining pultrusion with traditional manufacturing techniques, one can achieve both the cost efficiency and material quality of pultrudates while enabling the shape flexibility of traditional forming processes. The combination of pull-braiding and blow-moulding, for example, using a hybrid two-step curing thermoset matrix system, allows pultrusion of a fibre-reinforced tube with a B-stage rubbery resin consistency that is then inflated with a bladder and cured in a closed mould (Fig. 10(a–b)). This allows large scale production of high-quality composite parts (500K/year) while reducing the cycle time to 3–4 min and minimising post-processing and material waste [114]. A different strategy consists of using injection moulding to locally deform a pultruded profile, utilising the reformability and weldability of a thermoplastic matrix. Examples of this include adding out-of-plane components to a pultruded profile such as gears to a pultruded shaft [115] or by partially/completely overmoulding it. By using pultruded polyamide 6 profiles as load-carrying elements that are supported by an

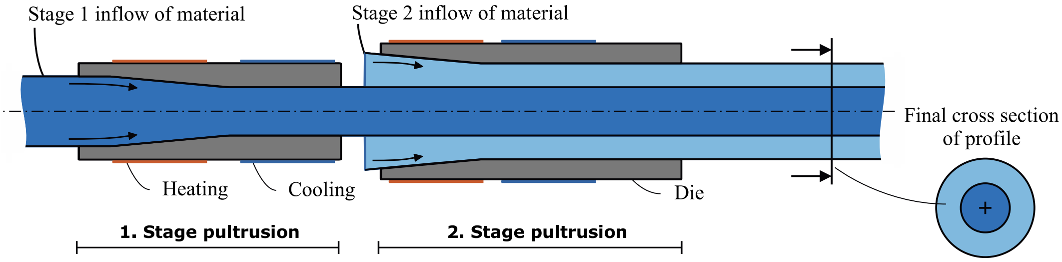

Fig. 8. Multistage pultrusion concept, starting with an initial in the first stage and radial material addition in the second stage.

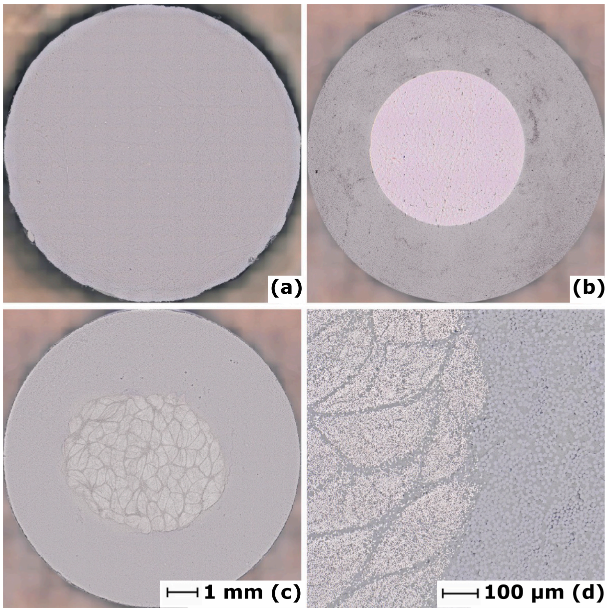

Fig. 9. Micrograph of pultruded rods made from different material combinations in first and second stage: PET/GF (a), aluminium-PET/GF (b), PA12/CF-PET/GF (c, d). This figure was adapted from Volk [109].

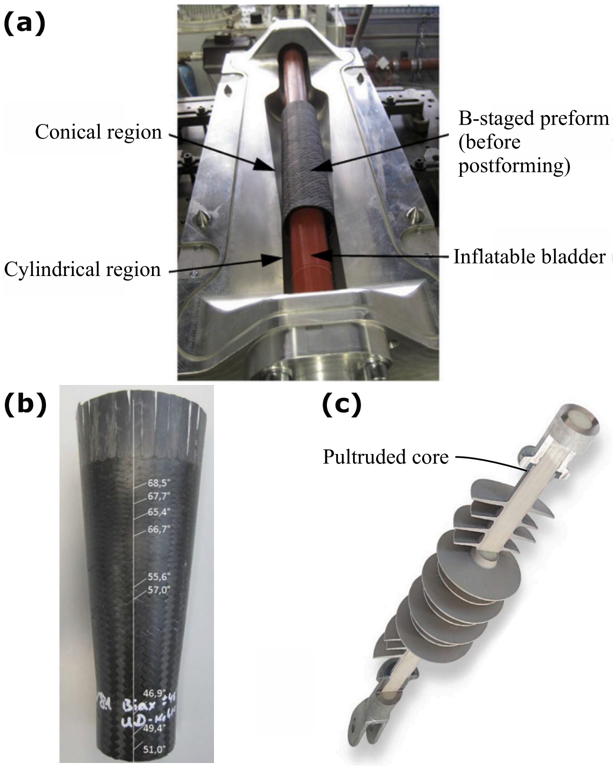

Fig. 10. (a-b) An advanced combined use of two manufacturing processes (pull-braiding and blow-moulding) that enabled new options in terms of shape flexibility (these figures were adapted and reprinted with permission from Bezerra [114]). (c) A high-voltage insulator with cut-out sections. The core of the insulator is a ⌀38 mm rod pultruded from commingled thermoplastic and glass fibres (the figure was taken from Volk [109]).

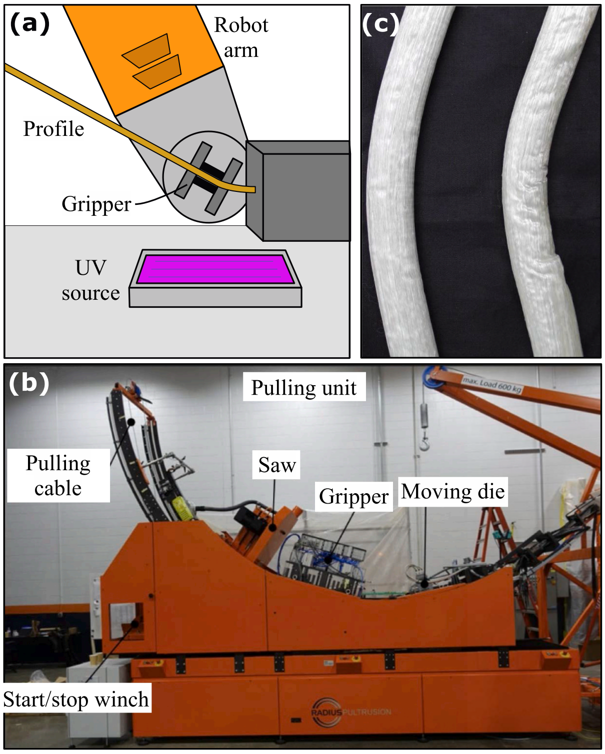

Fig. 11. Three ways to manufacture curved, pultruded profiles: (a) Post-manipulation with a mobile arm and out-of-die UV curing, (b) a mobile die that is moving in a circular motion (this figure was adapted and reprinted with permission of Jansen [120]), and (c) stretch-bending (this figure was adapted and reprinted with permission of Haas and Bose [125]).

injection-moulded structure with included cable routing and other relevant functionality, a cost-effective solution for an automotive roof section has been successfully brought into mass production in the BMW iX-series of electric cars [116]. A comparison of different approaches to combine pultrusion with other post-forming technologies to manufacture thermoplastic composite rebars has been performed by Böhm et al. [117]. Among the studied procedures are contour milling of the surface, form pressing, and helix creation by either reforming the profile or helical winding of an additional tape around the circumference of the rod.

Pultrusion can also be combined with filament winding to increase the diameter of solid pultruded rods to even larger diameters, which can be beneficial for, e.g., high-voltage insulator applications [118] (a cut section of a high-voltage insulator with pultruded a core can be seen in Fig. 10(c)). For cost-efficient pultrusion of smaller series of profiles, the batch-pultrusion approach allows manufacturing profiles of limited length. Conventional continuous pultrusion requires an extensive bobbin creel, yarn guidance system as well as a large material stock, but batch pultrusion circumvents the space requirements and associated equipment and material cost by winding material from a single bobbin into one thick loop that is then fed through the pultrusion die to achieve the required throughput [24].

3.2.4. *Curved pultrusion*

Pultrusion of curved profiles can be achieved through a post-curing process once the material has exited the die [12,77], for example, by use of out-of-die UV curing [119] (Fig. 11(a)). Alternatively, the profile can be produced through a mobile die that is moving in a circular motion while the profile remains stationary [120] (Fig. 11(b)). This technology enables pultrusion to cover an even wider field of possible applications and has been successfully applied to automotive structures such as bumpers [97,121], sports equipment [112], aerospace components [122], marine [123] and infrastructure applications [124]. An alternative post-forming approach called stretch-bending has been developed for thermoplastic pultrudates which allows for wrinkle-free bending of tubes by selectively pre-tensioning the sections close to the centre of the profile [125] (Fig. 11(c)).

3.3. *Advanced intermediate materials for thermoplastic pultrusion*

Thermoplastic pultrusion offers numerous advantages in terms of pultrusion speed [20], recyclability, and shelf life while enabling different processing routes based on the weldability and reshapability of thermoplastics [126]. Over the years, the challenge related to the high melt viscosity of thermoplastics impeding efficient impregnation has been addressed through new, innovative approaches. While reactive thermoplastic resins and low viscosity polymers allow a similar impregnation strategy to thermoset pultrusion, combining the polymer matrix and reinforcing fibres into one intermediate material reduces the impregnation length while offering a wide choice of polymer types [127] (Fig. 12). This section reviews different thermoplastic intermediate material types and their processing strategies.

3.3.1. *Commingled fibres, thermoplastic tapes, prepregs, powders, and towpregs*

The processing of thermoplastic intermediate materials is achieved by preheating the material in a preheating oven close to the final processing temperature. Then, in the heating die, the polymer melts and impregnates the reinforcing fibres as depicted in Fig. 13(b–c) before being cooled until full consolidation in a cooling die. One of the most popular approaches is commingled yarns, where the reinforcing fibres are intermingled with thermoplastic fibres [128] in individual rovings. A lab-scale setup to achieve these processing steps can be seen in Fig. 13. Other strategies include the use of fully impregnated materials such as thermoplastic tapes or prepregs [129,130] as well as powder impregnated yarns or towpregs (Fig. 12(c)). Here, the neat polymer can be applied inline by use of, e.g., electrostatic powder spray [131] before preheating is applied. A significant challenge related to this technique is to apply a sufficient amount of polymer without losing it in the subsequent processing steps. This can be addressed by introducing a polymer sheath around the reinforcing fibres *and* the polymer powder [46]. However, the limited drapeability due to the shear resistance of the sheath has prevented the wide adoption of this approach.

3.3.2. *Bi-component fibres*

To further increase the production output while maintaining a high material quality, bi-component fibres is a novel material technology where each reinforcing fibre is individually clad with thermoplastic polymer (a thermoplastic “sheath”, see Fig. 12(b)). The application of this “coating” occurs directly within filament melt spinning, which makes the manufacturing of such fibres highly efficient, and thus suitable for high-volume applications. The advantage of this new concept lies within the very fast consolidation and low void content of the manufactured material as only extremely short flow lengths (smaller than the diameter of a single fibre) are needed for complete impregnation [132,133]. In terms of pultrusion, initial trials showed that bi-component fibres can readily be processed in setups designed for commingled-fibre pultrusion. In a test case of pultrusion of ∅5 mm thermoplastic rods, bi-component fibres showed a significant effect of lowering the void content [134]. This demonstrates that there is a clear potential for bi-component fibres to become a material concept for high-speed pultrusion of low void content profiles.

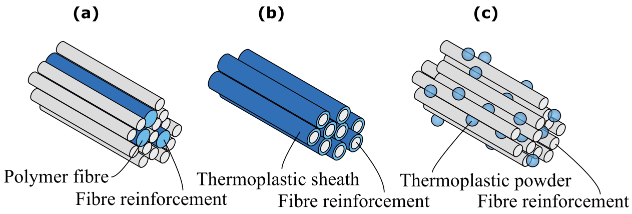

Fig. 12. Overview of some of the strategies that have been used to integrate thermoplastics as an intermediate material in pultrusion processes, (a) commingled fibres, (b) bi-component fibres, and (c) power-impregnated fibres.

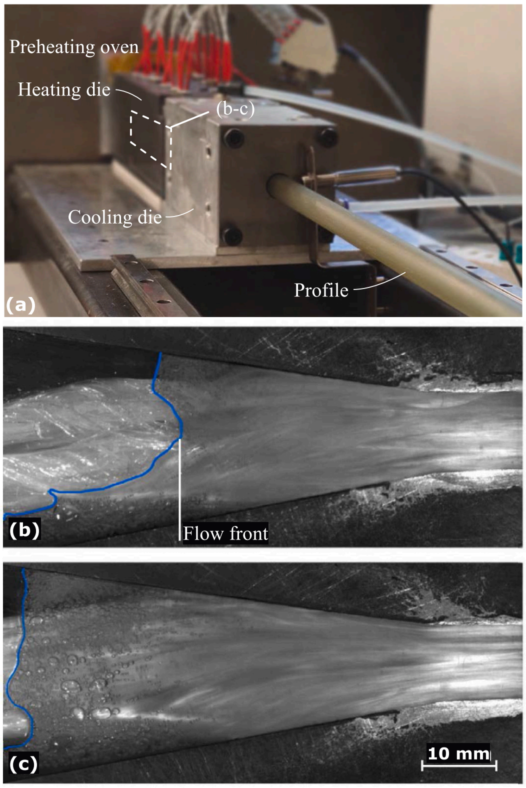

Fig. 13. (a) A lab-scale setup for pultrusion of thermoplastic, commingled fibres. Pictures (b-c) depict the impregnation flow that takes place when the commingled thermoplastic fibres melt. These pictures were adapted from Volk [109] and captured using a transparent die.

3.4. *Pultrusion as an enabler for additive manufacturing*

Three-dimensional (3D) printing or additive manufacturing has gained extraordinary attention in the last 30 years and opened up many opportunities for end-user products [135]. Fibre reinforcement is a promising way to improve 3D printed polymers and other materials by enhancing their mechanical properties [136,137], and here pultrusion has proven as a useful process to enable the implementation in some additive manufacturing technologies.

3.4.1. *Pre-pultrusion and printing with thermoplastic strands*

The manufacture of fibre-reinforced filaments for 3D printing can be realised by means of melt impregnation of the dry fibres [94] or using intermediate materials such as commingled yarns and tapes [138–140]. The latter has advantages such as better fibre matrix adhesion and a potential of higher fibre volume fraction. In principle, fibre-reinforced filaments need to have a uniform fibre distribution, low void content and low fibre volume fraction to achieve a good printing quality. The effects of variation in the roving/yarn can to some extend be compensated for with smaller strand diameters. Another route is multiple die applications [141] or bi-component fibres [134], but with larger nozzle diameters and high reinforcement content, intra- and inter-strand porosities together with insufficient drapeability at corners can arise.

3.4.2. *Flow-based pultrusion*

Flow-based pultrusion is a layer-by-layer, extrusion-based additive manufacturing concept (Fig. 14). While it differs from conventional pultrusion, it does lend from the technology as the name implies. Flow-based pultrusion can be used for 3D printing with continuous fibre reinforcements filaments [54,142], and it is a rather unique additive manufacturing and pultrusion concept since it works without any motorisation to advance the reinforcement fibres. It does, however, require certain rheological properties of the printing material, which can be the reason why the technology has so far only been applied to fresh concrete, a non-Newtonian (viscoplastic) material. For concrete, the rheology develops during extrusion, making the viscosity low enough to permit sufficient fibre impregnation. At the same time, the concrete will be viscous enough in the printing head to pull the fibres and advance the filaments. In Ref. [54], Demont et al. reported successful printing with reinforcement ratios as high as 10%, but even adding very few fibres ($\approx 0.2\%$) was enough to drastically increase the consistency of the printed material and avoid avalanche and slug effects. Nevertheless, it is important to underline that these materials do not have the same fibre composition nor structural properties compared to fibre-reinforced polymer composites.

3.4.3. *Free-form 3D printing (extrusion/pultrusion)*

In contrast to additive manufacturing techniques that allow for layer-by-layer deposition of material, continuous lattice fabrication (CLF) enables the orientation of continuous reinforcing fibres in all spatial directions. This can be achieved through a two-stage process, where a commingled, stretch-broken filament is first impregnated and consolidated in a pultrusion stage and then fed into an extrusion unit that allows for printing on a polymer substrate as well as altering the shape of the pultrudate in other spatial directions [143] (Fig. 15(a–b)). This technique does not depend on support structures or moulds and therefore enables the creation of free-form structures with a load-tailored design to fully exploit the potential of composite materials. A different approach called pultrusion-winding [144] enables the manufacturing of core-less structures by intermittent ultraviolet pultrusion. It consists of a pultrusion head that can freely move in all spatial directions as well as a winding fixture. For straight sections, the profile is fully cured in the pultrusion head while around winding points the curing can be interrupted so that the yarns remains pliable (Fig. 15(c)).

3.5. *Pultrusion as an enabler for sustainable composite manufacture*

Our climate calls for urgent action to reduce the risks of future natural disasters [145]. This concerns the associated risks related to the continued accumulation of CO_2 in our atmosphere, but waste and resource management demand immediate changes as well. As discussed, pultrusion is an enabler in the processing of thermoplastic materials (reviewed in Sec. 3.3), which is a step towards new and better recycling routes compared to the use of thermosetting polymers. This is because thermoplastics can be remelted, making it easier for recyclers to recover the polymer and fibres from the composite part after its end-of-life use [146]. Pultrusion is also a material-efficient processing technique as it has no inherent need for disposable items (vacuum bags, flow mats, etc.), making it a step towards zero-waste processing. Nevertheless, composite processing, use, and recycling do leave an environmental footprint since the processing of synthetic fibres and petroleum-based polymers yield a product that has consumed non-renewable materials and is difficult to recycle. But overall, pultrusion technology can allow the industry to move towards more sustainable composite manufacture, also related to utilising renewable materials, which we will review in this section.

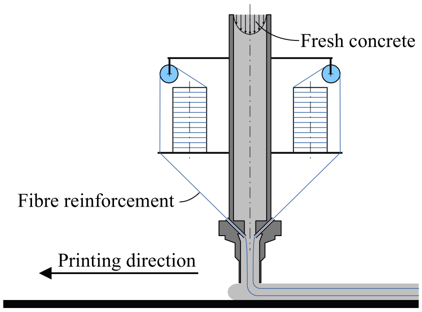

Fig. 14. The concept of flow-based pultrusion for additive manufacture of fibre-reinforced concrete by Demont et al. [54] and Ducoulombier et al. [142].

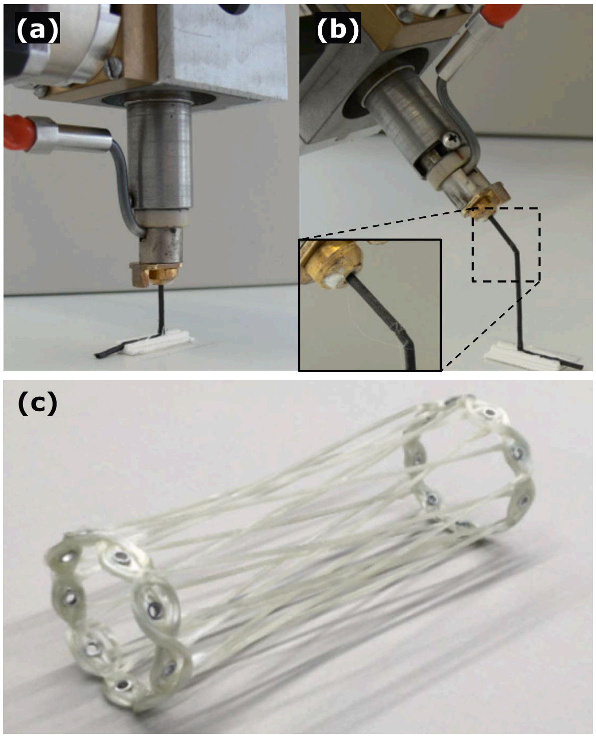

Fig. 15. Additive manufacturing using continuous lattice fabrication (CLF). (a) shows printing of a free-standing structure, and (b) demonstrate the ability to change angle on-the-fly during printing (these figures were adapted and reprinted with permission from Eichenhofer et al. [143]. The printed strand was approximately ∅1.5 mm, given by the diameter of the nozzle). (c) demonstrates an example of the design freedom that can be achieved with pultrusion-freeform winding (this figure was reprinted with permission from Mindermann et al. [144]. The printed strand was approximately ∅3 mm, given by the diameter of the nozzle).

3.5.1. *Pultrusion with with natural fibres*

The utilisation of natural fibres in fibre-reinforced polymer composites has several advantages. Natural fibres are biodegradable, have a low density, cause less abrasive wear on equipment, and are safe to handle (e.g., low risks of skin irritation/irritation of airways). Life-cycle analysis studies have confirmed that composites reinforced with natural fibres are environmentally superior to composites with glass fibre reinforcement [147]. With a current annual growth rate of 10.5%, the global market for biocomposites is expected to grow to $52.72B by 2027 [148], far exceeding the current growth of the fibre-reinforced polymer composite market as a whole (4.5%, [149]).

The most common natural fibres are seed, leaf, and stem fibres [150]. Natural fibres are normally not stable above temperatures exceeding 200 °C, but thermosets, thermoplastics, and natural matrix materials (reviewed in the next subsection) that allow for processing within this temperature range can be used as matrix material [151]. Some thermoplastic polymer matrices, such as PP and PET, are hydrophobic and offer low compatibility with natural fibres, so appropriate surface treatment is needed to obtain a sufficient fibre/matrix interface strength [152]. Natural fibres are staple fibres (of discrete length), but quasi-unidirectional fibres can be processed into a continuous tape by utilising special joining techniques (demonstrated for, e.g., flax and bamboo [153–155]). Flax yarns commingled with PET/PP fibres has been processed using pultrusion [50,51]. The reported studies concluded that pultrusion technology offered good processability for these flax/thermoplastic composites, but sufficient pre-heating is crucial to ensure a sufficient process window when melting the thermoplastics.

3.5.2. *Pultrusion with natural matrices and biocomposites*

One way to introduce renewable materials to a composite, is to introduce them as a filler. While fillers will generally decrease the mechanical properties of the final part, they can be relevant for non-structural components such as secondary or tertiary structures, panels, packaging items, etc. [156–158].

Short natural fibres, wood flour, corn starch, natural rubber, and soy [158], for example, can be used as fillers in thermoset and thermoplastic polymers derived from fossil resources such as polyethylene, polypropylene, polyester, and epoxies [159,160]. However, surface treatment is frequently highlighted as a requirement to obtain sufficient interface strength [152,158]. Compared to a conventional, homogeneous polymer, adding a natural filler increases the viscosity [161,162]. Pultrusion is a proven technology to process viscous matrix systems, and the use of conventional oil-based polymers with natural fillers is something that has been explored for pultrusion. For example, Zhu et al. [53] analysed the effects of using 30 wt% of soy resin as matrix content (i.e., a resin extracted from the soybean) to a pultruded glass fibre composite. Here, it was found that the profile maintained its main mechanical properties, and the profile-advancing pulling force was reduced due to the natural lubrication from the soybean.

In a truly “green composite”, the matrix and fibre reinforcement are both made from renewable materials and the final composite is biodegradable. According to La Mantia and Morreale [158] “biodegradable polymers can be classified according to their origin, i.e., into agro-polymers (e.g. starch), microbial-derived (e.g., PHA) and chemically synthesized from agro-based monomers (e.g., PLA), or conventional monomers (e.g. synthetic polyesters)” [158,163]. For pultrusion with PLA, manufacturability has been demonstrated with flax fibres (Linganiso et al. [52]) and jute spun yarns (Memon and Nakai [21]) as reinforcements. In both cases, the matrix material (i.e., PLA) entered as a commingled fibre, which allowed for sufficient impregnation.

The above-mentioned literature about processing natural fibres and matrices in the pultrusion process is not by any means comprehensive. This may appear surprising taking into account the extensive research efforts on the topic for the composite industry as a whole [164]. Also, taking into account that the first successful report of pultrusion with natural fibres is today more than twenty years old [50], and out of the more than twenty natural fibres types that are suitable for processing into a composite [164], the literature so far only looks into the use of flax and jute fibres. With the current and new potential offered by surface modifications to improve the fibre/matrix interface [152], this is an area where pultrusion offers potential as thermoplastic pultrusion has demonstrated that secondary materials can be added continuously inline the process [46].

4. Conclusions and outlook

In this paper, we have reviewed some of the recent advancements in the pultrusion industry, in particular, innovations in production and material forming technologies, new material technologies for thermoplastic pultrusion, and how pultrusion is an enabler for additive manufacturing as well as renewable composite manufacture. With these innovations, we have argued for a promising outlook and potential for further penetration of new markets of pultruded products but also composite materials more broadly. Based on our assessments and discussions throughout the paper, and with our consortium’s experience from completing multiple academic and industrial projects about pultrusion, we identify the following areas where we see potential for further research and industrial application of pultrusion technologies:

4.1. *New curing, material, and processing strategies*

As reviewed, frontal polymerisation is a curing strategy that is currently finding its way into composite processing. Frontal polymerisation has not yet been utilised in pultrusion processes, but it has the potential of enabling pultrusion with no or limited external heat source. This would reduce costs related to energy released to the ambient surroundings, but also further limit the CAPEX of pultrusion equipment as heater units would become redundant. Since frontal polymerisation techniques utilise rapid-curing resin systems, this curing strategy may also help to increase the production output. To realise frontal polymerisation in pultrusion, new polymerisation kinetics models and resin curing behaviours are needed to be implemented, predicted, and analysed since tight control of the resin cure is required to exploit this strategy. Also, since fast-curing resin systems will introduce steep temperature and cure gradients, the potential impact on process-induced stress and deformation from choosing this cure strategy needs to be fully understood.

Pultruded profiles are traditionally composed of one material composition, but recent studies have investigated the use of different fibres, matrix systems, as well as metals to further improve the cost-efficiency, versatility, and mechanical performance of pultruded profiles. While the initial proof-of-concept results have been promising, a holistic scientific approach is needed for the analyses and syntheses of the different multi-material concepts to understand the challenges and outlook of this technology.

4.2. *Advanced lay-up and combined processing technologies*

Combing pultrusion with other manufacturing techniques offers the potential of achieving the cost-efficiency and quality of pultrusion, together with the design freedom of other conventional processes. As reviewed in the paper, the geometrical freedom of braiding, blow-moulding, injection moulding, hydro-forming, or tailored fibre placement technology can be exploited together with pultrusion processes. Although mostly proof-of-concept cases make up the literature, the first commercial applications are emerging and are expected to have a major impact on the composite industry. In addition to this, curved pultrusion is a processing concept that has expanded the application area of pultruded profiles from straight geometries to curved geometries. After several academic studies, this technology is now successfully being utilised to manufacture critical structural components for high-performance automobiles, e.g., the BMW iX-series of electric cars. Additional development of curved pultrusion towards variable radii pultrusion including helical geometries will remove further barriers and enable additional application areas of pultrusion.

4.3. *Thermoplastic pultrusion*

Thermoplastic pultrusion offers numerous advantages in terms of pultrusion speed, recyclability, and shelf life while enabling new manufacturing routes through weldability and reshapability. Until recently, the industrial applications of pultruded thermoplastic materials were limited to tapes, but now large cross-sectional pultruded profiles that were pressed and overmoulded have found application as structural components in mass-produced automobiles.

Another reason for the increased adoption of thermoplastics is their reaction and solvent-free processing that limits chemical exposure to the environment and the technical personnel compared to thermoset plastics. This, together with new and novel material options such as bicomponent fibres, sets a strong outlook for thermoplastic pultrusion. On the other hand, for the pultrusion of thick thermoplastic profiles, heat extraction after die exit becomes a major challenge. Here, multi-stage pultrusion, which has already been utilised for both homogeneous and multi-material pultrudates, has potential. However, there have been very limited studies about the governing multi-physical phenomena, in particular, the development of residual stresses between the different material stages.

4.4. Pultrusion of renewable materials and sustainable composite manufacture

We discussed in the paper that with pultrusion, the industry can take steps towards more sustainable composite manufacture. Nevertheless, fibre-matrix compatibility is a serious issue for the mechanical properties and performance of natural composites in general, but this challenge can be addressed with the use of different compatibilising agents (for example, surface treatments of the reinforcement fibres). The literature about pultrusion has shown that secondary materials and surface agents can readily be applied inline a pultrusion line due to the continuous nature of the process. This technique has been demonstrated possible for thermoplastic pultrusion and expanding this concept to pultrusion of natural material has the potential of lowering the barriers for further adaption of sustainable composite processing.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] European Pultrusion technology Association (EPTA), website, https://pultruders.org/pultrusion.php, Visited 18-03-2022.
[2] Market Research Verified. Global pultrusion market size by fiber type. 2021. By Resin Type, By Application, By Geographic Scope And Forecast (Report ID: 41778).
[3] The World Bank. Global Economic Prospects. World Bank Group; 2022.
[4] Suzuki T, Takahashi J. Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. In: Proceedings of 9th Japan international SAMPE symposium; 2005. p. 14–9.
[5] Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. Compos Part A-appl Sg 2009;40:1257–65.
[6] Starr T. Pultrusion for engineers. Taylor & Francis; 2000.
[7] Safonov AA, Carlone P, Akhatov I. Mathematical simulation of pultrusion processes: a review. Compos Struct 2018;184:153–77.
[8] Vedernikov A, Safonov A, Tucci F, Carlone P, Akhatov I. Pultruded materials and structures: a review. J Compos Mater 2020;54:4081–117.
[9] Minchenkov K, Vedernikov A, Safonov A, Akhatov I. Thermoplastic pultrusion: a review. Polymers 2021;13:180.
[10] Sandberg M. Numerical modelling of material flow in the resin-injection pultrusion process. 2020. Ph.D. thesis, Technical University of Denmark.
[11] Sandberg M, Yuksel O, Baran I, Hattel JH, Spangenberg J. Numerical and experimental analysis of resin-flow, heat-transfer, and cure in a resin-injection pultrusion process. Compos Part A-Appl S 2021;143:106231.
[12] Struzziero G, Maistros G, Hartley J, Skordos A. Materials modelling and process simulation of the pultrusion of curved parts. Compos Part A-appl Sg 2021;144: 106328.
[13] Zamri MH, Akil HM, Bakar AA, Ishak ZAM, Cheng LW. Effect of water absorption on pultruded jute/glass fiber-reinforced unsaturated polyester hybrid composites. J Compos Mater 2012;46:51–61.
[14] Guo R, Xian G, Li C, Huang X, Xin M. Effect of fiber hybridization types on the mechanical properties of carbon/glass fiber reinforced polymer composite rod. Mech Adv Mater Struct 2021:1–13.
[15] Sandberg M, Hattel JH, Spangenberg J. Simulation of liquid composite moulding using a finite volume scheme and the level-set method. Int J Multiphas Flow 2019;118:183–92.
[16] Kim H-Y, Park K-T, Jeong J, Lee Y-H, Hwang Y-K, Kim D. A pultruded gfrp deck panel for temporary structures. Compos Struct 2009;91:20–30.
[17] Vedernikov A, Safonov A, Tucci F, Carlone P, Akhatov I. Modeling spring-in of l-shaped structural profiles pultruded at different pulling speeds. Polym Bull (Berlin) 2021;13:2748.
[18] Devlin B, Williams M, Quinn J, Gibson A. Pultrusion of unidirectional composites with thermoplastic matrices. Compos Manuf 1991;2:203–7.
[19] Jürss DW. Thermoplastpultrusion-Strangziehen von endlosfaserverstärkten Profilen mit thermoplastischem Matrixwerkstoff: thermoplastics pultrusion-pultrusion of endless fibre reinforced profiles with a thermoplastic matrix system. Verlag der Augustinus-Buchh.; 1995.
[20] Miller AH, Dodds N, Hale J, Gibson A. High speed pultrusion of thermoplastic matrix composites. Compos Part A-appl Sg 1998;29:773–82.
[21] Memon A, Nakai A. Mechanical properties of jute spun yarn/pla tubular braided composite by pultrusion molding. Enrgy Proced 2013;34:818–29.
[22] Babeau A, Comas-Cardona S, Binetruy C, Orange G. Modeling of heat transfer and unsaturated flow in woven fiber reinforcements during direct injection-pultrusion process of thermoplastic composites. Compos Part A-Appl S 2015;77:310–8.
[23] Oswald A, Lapointe F, Laberge Lebel L. Multi-die, vacuum assisted pultrusion of flax/pla thermoplastic biocomposite rods. In: ECCM17-17th European conference on composite materials; 2016. p. 1–8.
[24] Volk M, Wong J, Arreguin S, Ermanni P. Pultrusion of large thermoplastic composite profiles up to ø 40 mm from glass-fibre/pet commingled yarns. Compos B Eng 2021;227:109339.
[25] Volk M, Arreguin S, Ermanni P, Wong J, Bär C, Schmuck F. Pultruded thermoplastic composites for high voltage insulator applications. IEEE Trans Dielectr Electr Insul 2020;27:1280–7.
[26] Li S, Xu L, Ding Z, Lee LJ, Engelen H. Experimental and theoretical analysis of pulling force in pultrusion and resin injection pultrusion (rip)–part ii: modeling and simulation. J Compos Mater 2003;37:195–216.
[27] Åström BT, Pipes RB. A modeling approach to thermoplastic pultrusion. i: formulation of models. Polym Compos 1993;14:173–83.
[28] Jeswani AL, Roux JA. Effect of injection slot location on die-detached tapered injection chamber in resin injection pultrusion. Polym Polym Compos 2011;19: 513–26.
[29] Sandberg M, Hattel JH, Spangenberg J. Numerical modelling and optimisation of fibre wet-out in resin-injection pultrusion processes, ume 18. Athens, Greece: ECCM; 2018.
[30] Han CD, Lee DS, Chin HB. Development of a mathematical model for the pultrusion process. Polym Eng Sci 1986;26:393–404.
[31] Moschiar S, Reboredo M, Kenny J, Vazquez A. Analysis of pultrusion processing of composites of unsaturated polyester resin with glass fibers. Polym Compos 1996;17:478–85.
[32] Han CD, Chin HB. Development of a mathematical model for the pultrusion of unsaturated polyester resin. Polym Eng Sci 1988;28:321–32.
[33] Ma C-CM, Chen C-H. The development of a mathematical model for the pultrusion of blocked polyurethane composites. J Appl Polym Sci 1993;50: 759–64.
[34] Carlsson A, Åström BT. Experimental investigation of pultrusion of glass fibre reinforced polypropylene composites. Compos Part A-Appl S 1998;29:585–93.
[35] Liu X-L. Numerical modeling on pultrusion of composite i beam. Compos Part A-Appl S 2001;32:663–81.
[36] Vedernikov A, Nasonov Y, Korotkov R, Gusev S, Akhatov I, Safonov A. Effects of additives on the cure kinetics of vinyl ester pultrusion resins. J Compos Mater 2021;55:2921–37.
[37] Yuksel O, Sandberg M, Baran I, Ersoy N, Hattel JH, Akkerman R. Material characterization of a pultrusion specific and highly reactive polyurethane resin system: elastic modulus, rheology, and reaction kinetics. Compos B Eng 2021; 207:108543.
[38] Gorthala R, Roux JA, Vaughan JG. Resin flow, cure and heat transfer analysis for pultrusion process. J Compos Mater 1994;28:486–506.
[39] Ding Z, Li S, Yang H, Lee LJ, Engelen H, Puckett PM. Numerical and experimental analysis of resin flow and cure in resin injection pultrusion (RIP). Polym Compos 2000;21:762–78.
[40] Sas HS, Abu-Obaid A, Šimáček P, Gillespie Jr JW, Advani SG. Thermoset pultrusion process: modeling and experimental characterization. In: Proceedings of CAMX conference; 2014. Orlando, FL.
[41] Åström BT, Pipes RB. Modeling of a thermoplastic pultrusion process. SAMPE Quart; 1991.

[42] Lee WI, Springer GS, Smith FN. Pultrusion of thermoplastics—a model. J Compos Mater 1991;25:1632–52.
[43] Åström BT, Pipes RB. A modeling approach to thermoplastic pultrusion. i: formulation of models. Polym Compos 1993;14:173–83.
[44] Åström BT, Pipes RB. A modeling approach to thermoplastic pultrusion. ii: verification of models. Polym Compos 1993;14:184–94.
[45] Michaeli W, Jürss D. Thermoplastic pull-braiding: pultrusion of profiles with braided fibre lay-up and thermoplastic matrix system. Compos Part A-Appl S 1996;27:3–7.
[46] Sala G, Cutolo D. The pultrusion of powder-impregnated thermoplastic composites. Compos Part A-Appl S 1997;28:637–46.
[47] Nejhad MNG. Thermal analysis for thermoplastic composite tow/tape preheating and pultrusion. J Thermoplast Compos 1997;10:504–23.
[48] Dube M, Batch G, Vogel J, Macosko C. Reaction injection pultrusion of thermoplastic and thermoset composites. Polym Compos 1995;16:378–85.
[49] Chen K, Jia M, Sun H, Xue P. Thermoplastic reaction injection pultrusion for continuous glass fiber-reinforced polyamide-6 composites. Materials 2019;12:463.
[50] Van de Velde K, Kiekens P. Thermoplastic pultrusion of natural fibre reinforced composites. Compos Struct 2001;54:355–60.
[51] Angelov I, Wiedmer S, Evstatiev M, Friedrich K, Mennig G. Pultrusion of a flax/polypropylene yarn. Compos Part A-Appl S 2007;38:1431–8.
[52] Linganiso LZ, Bezerra R, Bhat S, John M, Braeuning R, Anandjiwala RD. Pultrusion of flax/poly (lactic acid) commingled yarns and nonwoven fabrics. J Thermoplast Compos 2014;27:1553–72.
[53] Zhu J, Chandrashekhara K, Flanigan V, Kapila S. Manufacturing and mechanical properties of soy-based composites using pultrusion. Compos Part A-Appl S 2004;35:95–101.
[54] Demont L, Ducoulombier N, Mesnil R, Caron J-F. Flow-based pultrusion of continuous fibers for cement-based composite material and additive manufacturing: rheological and technological requirements. Compos Struct 2021;262:113564.
[55] Salling FB, Sandberg M, Spangenberg J, Hattel JH. Numerical and experimental analyses in composites processing: impregnation, heat transfer, resin cure and residual stresses. In: IOP conference series: materials science and engineering, vol. 942. IOP Publishing; 2020, 012003.
[56] Sandberg M, Kabachi A, Volk M, Bo Salling F, Ermanni P, Hattel JH, Spangenberg J. Permeability and compaction behaviour of air-texturised glass fibre rovings: a characterisation study. J Compos Mater 2020;54:4241–52.
[57] Sharma D, McCarty T, Roux J, Vaughan J. Investigation of dynamic pressure behavior in a pultrusion die. J Compos Mater 1998;32:929–50.
[58] Kommu S, Khomami B, Kardos J. Modeling of injected pultrusion processes: a numerical approach. Polym Compos 1998;19:335–46.
[59] Sharma D, McCarty T, Roux J, Vaughan J. Fluid mechanics analysis of a two-dimensional pultrusion die inlet. Polym Eng Sci 1998;38:1611–22.
[60] Ströher GR, Zaparoli EL, de Andrade CR. Parabolic modeling of the pultrusion process with thermal property variation. Int Commun Heat Mass 2013;42:32–7.
[61] Mitlapalli R, Roux JA, Jeswani AL. Chamber length and injection-slot location and multiple slots for tapered resin-injection pultrusion, vol. 14. J Porous Media; 2011.
[62] Ranga B, Roux J, Vaughan J, Jeswani A. Effect of injection chamber length and pull speed of tapered resin injection pultrusion. J Reinforc Plast Compos 2011;30:1373–87.
[63] Jeswani A, Roux J. Impact of fiber volume fraction and resin viscosity with die-detached tapered chamber in resin injection pultrusion. J Manuf Sci E-t Asme 2010;132.
[64] Raper K, Roux J, Vaughan J, Lackey E. Permeability impact on the pressure rise in a pultrusion die. J Thermophys Heat Tran 1999;13:91–9.
[65] Baran I, Tutum CC, Nielsen MW, Hattel JH. Process induced residual stresses and distortions in pultrusion. Compos B Eng 2013;51:148–61.
[66] Baran I, Akkerman R, Hattel JH. Modelling the pultrusion process of an industrial L-shaped composite profile. Compos Struct 2014;118:37–48.
[67] Baran I, Hattel JH, Akkerman R. Investigation of process induced warpage for pultrusion of a rectangular hollow profile. Compos B Eng 2015;68:365–74.
[68] Baran I, Tutum CC, Hattel JH, Akkerman R. Pultrusion of a vertical axis wind turbine blade part-i: 3d thermo-chemical process simulation. Int J Material Form 2015;8:379–89.
[69] Yuksel O, Baran I, Ersoy N, Akkerman R. Analysis of residual transverse stresses in a thick ud glass/polyester pultruded profile using hole drilling with strain gage and digital image correlation. 2018. In: Aip conf proc. AIP Publishing LLC; 1960, 020040.
[70] Yuksel O, Baran I, Ersoy N, Akkerman R. Investigation of transverse residual stresses in a thick pultruded composite using digital image correlation with hole drilling. Compos Struct 2019;223:110954.
[71] Yuksel O, Sandberg M, Hattel JH, Akkerman R, Baran I. Mesoscale process modeling of a thick pultruded composite with variability in fiber volume fraction. Materials 2021;14:3763.
[72] Sandberg M, Yuksel O, Baran I, Spangenberg J, Hattel JH. Steady-state modelling and analysis of process-induced stress and deformation in thermoset pultrusion processes. Compos Part B-eng 2021;216:108812.
[73] Abliz D, Duan Y, Steuernagel L, Xie L, Li D, Ziegmann G. Curing methods for advanced polym composite - a review. Polym Polym Compos 2013;21:341–8.
[74] Endruweit A, Johnson MS, Long AC. Curing of composite components by ultraviolet radiation: a review. Polym Compos 2006;27:119–28.
[75] Abliz D, Duan Y, Steuernagel L, Xie L, Li D, Ziegmann G. Curing methods for advanced polym composites-a review. Polym Polym Compos 2013;21:341–8.
[76] Tena I, Esnaola A, Sarrionandia M, Ulacia I, Torre J, Aurrekoetxea J. Out of die ultraviolet cured pultrusion for automotive crash structures. Compos Part B-eng 2015;79:209–16.
[77] Britnell D, Tucker N, Smith G, Wong S. Bent pultrusion—a method for the manufacture of pultrudate with controlled variation in curvature. J Mater Process Technol 2003;138:311–5.
[78] Alikhani H, Sharifzadeh F, Khoramishad H. The mechanical and physical properties of nylon 6/glass fiber-reinforced hybrid composites manufactured by thermal and ultraviolet-cured pultrusion methods. J Compos Mater 2020;54:2899–912.
[79] Naik TP, Singh I, Sharma AK. Processing of polymer matrix composites using microwave energy: a review. Compos Part A-appl Sg 2022;156:106870.
[80] Kayser T, Link G, Seitz T, Nuß V, Dittrich J, Jelonnek J, Heidbrink F, Ghomeshi R. An applicator for microwave assisted pultrusion of carbon fiber reinforced plastic. In: 2014 IEEE MTT-S international microwave symposium (IMS2014); 2014. p. 1–4.
[81] Barkanov E, Akishin P, Namsone-Sile E. Effectiveness and productivity improvement of conventional pultrusion processes. Polymers 2022;14.
[82] Barkanov E, Akishin P, Emmerich R, Graf M. Numerical simulation of advanced pultrusion processes with microwave heating. In: Proceedings of the VII European Congress on Computational Methods in Applied Sciences and Engineering. 4; 2016. p. 7720–38.
[83] Li Q, Shen H-X, Liu C, Wang C-f, Zhu L, Chen S. Advances in frontal polymerization strategy: from fundamentals to applications. Prog Polym Sci 2022:101514.
[84] Robertson ID, Yourdkhani M, Centellas PJ, Aw JE, Ivanoff DG, Goli E, Lloyd EM, Dean LM, Sottos NR, Geubelle PH, Moore JS, White SR. Rapid energy-efficient manufacturing of polymers and composites via frontal polymerization. Nature 2018;557:223–7.
[85] Mehdikhani M, Gorbatikh L, Verpoest I, Lomov SV. Voids in fiber-reinforced polym composite: a review on their formation, characteristics, and effects on mechanical performance. J Compos Mater 2019;53:1579–669.
[86] Lapointe F, Laberge Lebel L. Fiber damage and impregnation during multi-die vacuum assisted pultrusion of carbon/peek hybrid yarns. Polym Compos 2019;40:E1015–28.
[87] Teixidó H, Staal J, Caglar B, Michaud V. Capillary effects in fiber reinforced polymer composite processing: a review. Front Mater 2022;9.
[88] Tiwari S, Bijwe J. Surface treatment of carbon fibers - a review. Procedia Technology 2014;14:505–12. 2nd International Conference on Innovations in Automation and Mechatronics Engineering, ICIAME 2014.
[89] Cui H, Kessler MR. Pultruded glass fiber/bio-based polymer: interface tailoring with silane coupling agent. Compos Part A-appl Sg 2014;65:83–90.
[90] Budiyantoro C, Rochardjo HS, Nugroho G. Effects of processing variables of extrusion–pultrusion method on the impregnation quality of thermoplastic composite filaments. Polymers 2020;12.
[91] Fathi B, Esfandeh M, Soltani AK, Taghavian H. Effect of corona discharge treatment on dynamic mechanical properties of unsaturated polyester/carbon fiber pultruded composites. Polym-plast Technol 2014;53:162–6.
[92] Irfan MS, Machavaram VR, Mahendran RS, Shotton-Gale N, Wait CF, Paget MA, Hudson M, Fernando GF. Lateral spreading of a fiber bundle via mechanical means. J Compos Mater 2012;46:311–30.
[93] Irfan M, Harris D, Paget M, Ma T, Leek C, Machavaram V, Fernando G. On-site evaluation of a modified pultrusion process: fibre spreading and resin injection-based impregnation. J Compos Mater 2021;55:77–93.
[94] Van De Steene W, Verstockt J, Degrieck J, Ragaert K, Cardon L. An evaluation of three different techniques for melt impregnation of glass fiber bundles with polyamide 12. Polym Eng Sci 2018;58:601–8.
[95] Krebs D. Fundamentals of the pultrusion process for production of FRP components for the requirements of automotive large-scale production. 2018. Ph. D. thesis, Universität Karlsruhe.
[96] Poulton M, Sebastian W. Taxonomy of fibre mat misalignments in pultruded gfrp bridge decks. Compos Part A-appl Sg 2021;142:106239.
[97] Malnatti P. Prime performance: faster processes and higher-performing materials make composites an option on more passenger vehicles. Plast Eng 2021;77:10–5.
[98] Fanucci JP, King MJ, Maass DP, Bystricky P. Extendable joined wing system for a fluid-born body. US Patent US8066922B2; 2003.
[99] Baran I, Tutum CC, Hattel JH, Akkerman R. Pultrusion of a vertical axis wind turbine blade part-i: 3d thermo-chemical process simulation. Int J Material Form 2015;8:379–89.
[100] Heimbucher C. Lokale verstärkung von pultrusionsprofilen durch lastgerechte textilstrukturen zur steigerung der profilfestigkeit in fügebereichen. Faserinstitut Bremen; 2022.
[101] Milwich M. Thermoplastic braid pultrusion. In: Proc. ICCM17–XVII Int. conf. composite materials; 2009. p. 27–31. Edinburgh (UK).
[102] Lebel LL, Nakai A. Design and manufacturing of an l-shaped thermoplastic composite beam by braid-trusion. Compos Part A-appl Sg 2012;43:1717–29. CompTest 2011.
[103] Hamada H, Kameo K, Sakaguchi M, Saito H, Iwamoto M. Energy-absorption properties of braided composite rods. Compos Sci Technol 2000;60:723–9.
[104] Ghaedsharaf M, Brunel J-E, Lebel LL. Multiscale numerical simulation of the forming process of biaxial braids during thermoplastic braid-trusion: predicting 3d and internal geometry and fiber orientation distribution. Compos Part A-appl Sg 2021;150:106637.
[105] Liu Y, Zhang H-T, Zhao H-H, Lu L, Han M-Y, Wang J-C, Guan S. Experimental study on mechanical properties of novel frp bars with hoop winding layer. 2021 Adv Mater Sci Eng 2021.

[106] Jiang C, Chandrashekhara K, Manis P, Belarbi A, Watkins SE. Manufacturing of frp rebars by a combined filament winding and pultrusion process. 1998.
[107] Gorthala R, Flynn DR. Apparatus for and method of producing thick polymeric composites. US Patent 1999;6(7):655.
[108] Albayati M, Gorthala R. Multi-die, multi-stage pultrusion process for hybrid composites: degree of cure and temperature profiles. In: Proceedings of the American society for composites: thirty-first technical conference; 2016.
[109] Volk M. Pultrusion of thermoplastic composite profiles for high voltage insulators, Ph.D. thesis, PhD thesis. ETH Zürich; 2021.
[110] Küppers S, Verfahrenstechnik I, Milwich M. Tpult : energie effizientes pultrusionsverfahren zur herstellung von faserverbundbauteilen mit thermoplastischer matrix in serienanwendungen : abschlussbericht für das verbundprojekt : laufzeit: 01.10.2011-31.03.2015. In: Institut für Textil- und Verfahrenstechnik Denkendorf; 2015. Technische Universität Braunschweig.
[111] Alawar A, Bosze EJ, Nutt SR. A composite core conductor for low sag at high temperatures. IEEE Trans Power Deliv 2005;20:2193–9.
[112] Drebenstedt C, Knobloch M, Löpitz D, Wagner D. Individual functionalization of fiber-reinforced profiles via pultrusion. smart bridge and roller ski. In: 5th international MERGE technologies conference (IMTC), 1 - 2 december 2021. TU Chemnitz; 2021.
[113] Knobloch M, Löpitz D, Wagner D, Drossel W-G. Continuous profile production with hybrid materials by pultrusion. In: Technologies for economic and functional lightweight design. Springer; 2021. p. 201–10.
[114] Bezerra R. Energieeffiziente herstellung komplexer hochleistungsfaserverbundbauteile mittels pultrusion. In: In-Line Flechten, Blasumformung und Endbearbeitung (PulForm). Fraunhofer Verlag; 2016.
[115] Garthaus C, Witschel B, Barfuß D, Rohkamm A, Gude M. Funktionalisierte faser-thermoplast-profilstrukturen. Lightweight Design 2016;9:40–5.
[116] Blank R, Hogger T, Starke J, Wehrkamp-Richter T, Winkler P. MAI Multiskelett : multiaxial beanspruchtes Integralbauteil im Kunststoffspritzguss mit lastpfadgerechten pultrudierten endlosfaserverstärkten Carbonfaserbündeln in Skelettbauweise, Technical Report. Bayerische Motoren Werke; 2017.
[117] Böhm R, Thieme M, Wohlfahrt D, Wolz DS, Richter B, Jäger H. Reinforcement systems for carbon concrete composites based on low-cost carbon fibers. Fibers 2018;6:56.
[118] electrical power S. Progress report presentation. In: Progress report presentation; 2019.
[119] Tena I, Sarrionandia M, Torre J, Aurrekoetxea J. The effect of process parameters on ultraviolet cured out of die bent pultrusion process. Compos Part B-eng 2016; 89:9–17.
[120] Jansen K. Method and device for the production of a plastic profile. US Patent US8066922B2; 2011.
[121] Thieleke P, Bonten C. Influence of the fiber preheating in in-situ pultrusion of continuous fiber-reinforced thermoplastic profiles. In: AIP conference proceedings, vol. 2289. AIP Publishing LLC; 2020, 020054.
[122] Hansen G. Aeropul - curved profiles for aerospace applications manufactured by pultrusion. In: JTI-CS2-2015-CFP02-LPA-02-10 Development of pultrusion manufacturing applications - CLEAN SKY 2. Faserinstitut Bremen e.V.; 2020.
[123] Tonatto ML, Forte MM, Tita V, Amico SC. Progressive damage modeling of spiral and ring compos struct for offloading hoses. Mater Des 2016;108:374–82.
[124] Liu T, Feng P, Wu Y, Liao S, Meng X. Developing an innovative curved-pultruded large-scale gfrp arch beam. Compos Struct 2021;256:113111.
[125] Haas J, Bose B. Formed pultrusion profiles. wrinkle-free forming of pultruded hollow profiles by local stretch bending. 2020 Kunststoffe international 2020;10 (10):40–3.
[126] Biron M. Thermoplastics and thermoplastic composites. William Andrew; 2012. https://doi.org/10.1016/C2011-0-05605-3. eBook ISBN: 9781455730353.
[127] Chang I, Lees J. Recent development in thermoplastic composites: a review of matrix systems and processing methods. J Thermoplast Compos 1988;1:277–96.
[128] Larock J, Hahn H, Evans D. Pultrusion processes for thermoplastic composites. J Thermoplast Compos 1989;2:216–29.
[129] Novo P, Silva JF, Nunes J, Marques A. Pultrusion of fibre reinforced thermoplastic pre-impregnated materials. Compos Part B-eng 2016;89:328–39.
[130] Kerbiriou V, Friedrich K. Pultrusion of thermoplastic composites-process optimization and mathematical modeling. J Thermoplast Compos 1999;12: 96–120.
[131] Parasnis NC, Ramani K, Borgaonkar HM. Ribbonizing of electrostatic powder spray impregnated thermoplastic tows by pultrusion. Compos Part A-Appl S 1996; 27:567–74.
[132] Schneeberger C, Wong JC, Ermanni P. Hybrid bicomponent fibres for thermoplastic composite preforms. Compos Part A-appl Sg 2017;103:69–73.
[133] Schneeberger C, Aegerter N, Birk S, Arreguin S, Wong J, Ermanni P. Direct stamp forming of flexible hybrid fibre preforms for thermoplastic composites. In: SAMPE Europe conference 2020 Amsterdam: The future composite footprints. ume 2. Curran; 2021. p. 889–94.
[134] Aegerter N, Volk M, Maio C, Schneeberger C, Ermanni P. Pultrusion of hybrid bicomponent fibers for 3d printing of continuous fiber reinforced thermoplastics. Adv Industrial Eng Polymer Res 2021;4:224–34.
[135] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F. Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP Annals 2016;65:737–60.
[136] Melenka GW, Cheung BK, Schofield JS, Dawson MR, Carey JP. Evaluation and prediction of the tensile properties of continuous fiber-reinforced 3d printed structures. Compos Struct 2016;153:866–75.
[137] Goh G, Dikshit V, Nagalingam A, Goh G, Agarwala S, Sing S, Wei J, Yeong W. Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics. Mater Des 2018;137:79–89.
[138] Zhuo P, Li S, Ashcroft IA, Jones AI. Continuous fibre composite 3d printing with pultruded carbon/pa6 commingled fibres: processing and mechanical properties. Compos Sci Technol 2022;221:109341.
[139] Ferreira F, Fernandes P, Correia N, Marques AT. Development of a pultrusion die for the production of thermoplastic composite filaments to be used in additive manufacture. J Compos Sci 2021;5.
[140] Vaneker T. Material extrusion of continuous fiber reinforced plastics using commingled yarn. Procedia CIRP 2017;66:317–22. 1st CIRP Conference on Composite Materials Parts Manufacturing (CIRP CCMPM 2017).
[141] Alsinani N, Ghaedsharaf M, Lebel LL. Effect of cooling temperature on deconsolidation and pulling forces in a thermoplastic pultrusion process. Compos B Eng 2021;219:108889.
[142] Ducoulombier N, Demont L, Chateau C, Bornert M, Caron J-F. Additive manufacturing of anisotropic concrete: a flow-based pultrusion of continuous fibers in a cementitious matrix. Procedia Manuf 2020;47:1070–7.
[143] Eichenhofer M, Wong JC, Ermanni P. Continuous lattice fabrication of ultra-lightweight compos struct. Addit Manuf 2017;18:48–57.
[144] Mindermann P, Witt M-U, Gresser GT. Pultrusion-winding: a novel fabrication method for coreless wound fiber-reinforced thermoset composites with distinct cross-section. Compos Part A-appl Sg 2022;154:106763.
[145] Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, De Vries W, De Wit CA, et al. Planetary boundaries: guiding human development on a changing planet. Science 2015;347:1259855.
[146] Cousins DS, Suzuki Y, Murray RE, Samaniuk JR, Stebner AP. Recycling glass fiber thermoplastic composites from wind turbine blades. J Clean Prod 2019;209: 1252–63.
[147] Joshi SV, Drzal L, Mohanty A, Arora S. Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos Part A-appl Sg 2004;35:371–6.
[148] Biocomposites market research report by material type, by fiber type, by application, by region - global forecast to 2027 - cumulative impact of covid-19. Grand View Research 2022:216.
[149] Fiber-reinforced polymer (frp) composites market - growth, trends, covid-19 impact, and forecasts. Grand view research. 2022. 2022 - 2027. p. 190.
[150] Jawaid M, Khalil HA. Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review. Carbohydr Polym 2011;86:1–18.
[151] Pickering KL, Efendy MA, Le TM. A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A-appl Sg 2016;83: 98–112.
[152] Zwawi M. A review on natural fiber bio-composites, surface modifications and applications. Molecules 2021;26:404.
[153] Decorme J, Duval A, Vanfleteren E, Vanfleteren F. Method for producing a continuous web of fibers comprising long natural fibers, and associated apparatus and web. US Patent App 2014;14/356:457.
[154] Khalfallah M, Abbès B, Abbès F, Guo Y, Marcel V, Duval A, Vanfleteren F, Rousseau F. Innovative flax tapes reinforced acrodur biocomposites: a new alternative for automotive applications. Mater Des 2014;64:116–26.
[155] A. W. Van Vuure, E. E. T. DE Los Rios, L. R. O. Serna, Continuous fibrous tape comprising fibres and method for making such tape 2021. US Patent 11,141,935.
[156] Netravali AN, Chabba S. Composites get greener. Mater Today 2003;4:22–9.
[157] Carroll DR, Stone RB, Sirignano AM, Saindon RM, Gose SC, Friedman MA. Structural properties of recycled plastic/sawdust lumber decking planks. Resour Conserv Recycl 2001;31:241–51.
[158] La Mantia F, Morreale M. Green composites: a brief review. Compos Part A-appl Sg 2011;42:579–88.
[159] Park B-D, Balatinecz JJ. Short term flexural creep behavior of wood-fiber/ polypropylene composites. Polym Compos 1998;19:377–82.
[160] Liao B, Huang Y, Cong G. Influence of modified wood fibers on the mechanical properties of wood fiber-reinforced polyethylene. J Appl Polym Sci 1997;66: 1561–8.
[161] Khalil HA, Rozman H, Ahmad M, Ismail H. Acetylated plant-fiber-reinforced polyester composites: a study of mechanical, hygrothermal, and aging characteristics. Polym-plast Technol 2000;39:757–81.
[162] Li T, Wolcott M. Rheology of hdpe–wood composites. i. steady state shear and extensional flow. Compos Part A-appl Sg 2004;35:303–11.
[163] Satyanarayana KG, Arizaga GG, Wypych F. Biodegradable composites based on lignocellulosic fibers—an overview. Prog Polym Sci 2009;34:982–1021.
[164] Li M, Pu Y, Thomas VM, Yoo CG, Ozcan S, Deng Y, Nelson K, Ragauskas AJ. Recent advancements of plant-based natural fiber–reinforced composites and their applications. Compos Part B-eng 2020;200:108254.