World Journal of Engineering and Technology, 2026, 14(1), 134-150
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Characterization of the Pultrusion Process for Graphite/BMI Composites: A Review of Experimental Methods, Industrial Practices, and Optimization Strategies

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How to cite this paper: Leong, K.T. (2026) Characterization of the Pultrusion Process for Graphite/BMI Composites: A Review of Experimental Methods, Industrial Practices, and Optimization Strategies. *World Journal of Engineering and Technology*, **14**, 134-150.
https://doi.org/10.4236/wjet.2026.141008

Received: November 5, 2025
Accepted: January 6, 2026
Published: January 9, 2026

Abstract

Pultrusion remains one of the most efficient continuous manufacturing processes for producing high-strength, fiber-reinforced polymer composites. This review examines the pultrusion of graphite/Bismaleimide (BMI) systems by integrating three decades of research—from early experimental characterization to modern advances in process modeling, automation, and material sustainability. The analysis compares pultrusion with alternative composite manufacturing routes and consolidates best practices for achieving thermal and mechanical stability. Experimental foundations from Leong (1990) and the subsequent NASA-supported work by Vaughan and collaborators (1991-2013) are revisited alongside recent developments in digital-twin simulation, adaptive die control, and recyclable resin chemistries (2015-2025). Persistent challenges in resin-flow uniformity, die-heating optimization, and void control are identified, and their mitigation through intelligent process design is discussed. The synthesis highlights how automation, AI-assisted monitoring, and sustainable BMI analogues are transforming pultrusion from a semi-empirical process into a predictive, energy-efficient, and environmentally responsible manufacturing platform. Recommendations for future research emphasize deeper integration of data-driven control, advanced resin systems, and multi-physics modeling to enhance reliability, performance, and sustainability in next-generation composite structures.

Keywords

Pultrusion, BMI Composites, Graphite Fibers, Process Characterization, Digital Twin, Sustainable Composites, Manufacturing Optimization

1. Introduction

Pultrusion is a continuous manufacturing process used to produce constant-cross-section composite profiles by pulling fiber reinforcements, pre-impregnated with thermosetting resin, through a heated forming die. Its capability for precise fiber alignment, dimensional repeatability, and high throughput has made it a cornerstone technology in structural, transportation, and aerospace composite fabrication.

Bismaleimide (BMI) resins, known for their excellent thermal stability, mechanical retention, and oxidative resistance above 200 °C, are well suited for high-temperature components [1]. However, their relatively high viscosity and narrow processing window pose challenges in achieving uniform fiber wet-out, void-free consolidation, and complete cure.

This review traces the characterization and optimization of graphite/BMI pultrusion from its experimental origins to current industrial practice. It revisits early factorial studies, connects them to modern analytical and numerical modeling, and compares pultrusion with other composite fabrication methods such as resin transfer molding (RTM), autoclave curing, and filament winding [2]. The objective is to consolidate historical insights and recent technological advances into a unified framework of best practices, highlighting both persistent challenges and emerging opportunities for intelligent, sustainable pultrusion manufacturing.

2. Fundamentals of the Pultrusion Process

The pultrusion process begins with continuous fiber tows unwound from creels and guided through a resin bath or injection chamber. Critical process variables include fiber volume fraction, preform temperature, die temperature, pulling speed, and filler loading. Successful pultrusion depends on balancing these parameters to minimize thermal gradients and avoid resin-rich or fiber-starved zones. The continuous nature of pultrusion offers dimensional consistency but demands precise control of resin rheology and die heating. Pultrusion's primary advantage lies in the ability to produce constant-cross-section profiles with minimal labor once parameters are stabilized.

3. Comparison with Other Composite Manufacturing Processes

Pultrusion competes with several established composite fabrication methods. A comparative evaluation in **Table 1** highlights its advantages and limitations relative to other techniques [2]. Pultrusion's key strength lies in its continuous throughput and high fiber-volume fraction. The principal trade-off is design flexibility—complex geometries require RTM or autoclave techniques. For structural beams, rods, and stiffeners, pultrusion remains the most economical solution.

Table 1. Comparison of pultrusion with other composite manufacturing processes.

Attribute	Pultrusion	Filament Winding	Resin Transfer Molding (RTM)	Hand Lay-up/Autoclave	Compression Molding
Production Mode	Continuous, automated	Semi-continuous	Batch	Batch	Discrete
Geometric Limitation	Constant cross-section (linear or curved)	Cylindrical/axisymmetric	Complex 3-D shapes	Flexible	Moderate
Fiber Volume Fraction	60 - 70% (high, controlled)	55 - 65%	45 - 60%	40 - 55%	40 - 60%
Dimensional Accuracy	Excellent	Good	Good	Moderate	Good
Surface Finish	Excellent (tool-controlled)	Good	Good	Excellent (with post-processing)	Fair-Good
Labor Intensity	Low	Medium	High	Very high	Medium
Typical Resin Systems	BMI, epoxy, vinyl ester	Epoxy, polyester	Epoxy, vinyl ester	Epoxy, polyester	Phenolic, vinyl ester
Capital Cost	Moderate	Moderate-High	High	Low	High
Suitable Applications	Structural profiles, rods, rebar, panels, high-temp aerospace parts	Pressure vessels, pipes	Automotive panels, shells	Prototyping, aerospace skins	Panels, housings
Advantages	Continuous, repeatable, high fiber alignment, minimal waste	High hoop strength	Complex shapes, good surface	Flexibility, low tooling	Fast cycle time
Limitations	Constant cross-section, initial die cost	Limited geometry	High mold cost, slower cure	Labor-intensive	Limited fiber alignment

Pultrusion provides the highest productivity and consistency for linear composite components, with superior thermal and mechanical uniformity compared to most batch processes.

Industries Benefiting from Pultrusion

Pultrusion technology finds its greatest industrial advantage in sectors requiring long, high-stiffness components with constant cross-sections and precise dimensional control. In the aerospace and defense sectors, graphite/BMI pultrusions are used for lightweight load-bearing elements, access panels, and high-temperature ducts. The civil and infrastructure industries apply glass- and carbon-fiber pultrusions in bridge decks, cable trays, gratings, and rebar replacements, where corrosion resistance and low maintenance are essential. In electrical and renewable-energy systems, pultruded composites serve as ladder rails, wind-turbine spars, and insulating profiles, valued for their dielectric strength and dimensional stability. Transportation and marine manufacturers use pultruded sections in railcars, vessels, and offshore platforms, where continuous fiber alignment enhances fatigue resistance and longevity. These applications demonstrate how the advantages summarized in Table 1—continuous throughput, automation, and high fiber alignment—translate directly into scalable, cost-efficient production of high-performance composite structures.

While the preceding comparison highlights the relative advantages of pultrusion over other composite fabrication processes, a detailed understanding of its performance potential requires quantitative experimental characterization. Early empirical data were scarce, particularly for high-temperature graphite/BMI systems, where resin viscosity and cure control posed significant challenges. To address this gap, the author conducted a systematic factorial study at the University of Mississippi in 1990 [1]—one of the first to statistically evaluate the combined effects of thermal, mechanical, and compositional parameters on pultrusion quality and mechanical performance.

4. Historical Basis—Leong (1990) Experimental Characterization

As part of Prof. James G. Vaughan's pultrusion research program, the author's 1990 thesis provided one of the program's earliest statistically designed investigations of graphite/BMI composites. Vaughan's group subsequently expanded this work through a series of NASA-supported studies (1991-2013), refining and validating the foundational results.

The author's 1990 thesis [1] at the University of Mississippi established one of the earliest statistically designed investigations of the pultrusion process for graphite/BMI composites. A 2^{84} Resolution IV fractional factorial design and one-way ANOVA were employed to study the effects of fiber volume fraction, preform temperature, die temperature, pulling speed, and filler content on both process behavior and mechanical performance. Mechanical testing included flexural strength, tensile strength, tensile modulus, compressive strength, and short-beam shear, evaluated at room temperature and at 450˚F.

Among all parameters, fiber volume fraction emerged as the dominant variable, with a lower fiber content of approximately 60% consistently producing superior mechanical properties across test categories. Preform temperature and filler content also demonstrated notable influence, improving resin wet-out, surface quality, and ease of pultrusion. At that time, Shell had developed a new BMI resin system that enabled high-temperature high-performance attributes of BMI resins with a shorter gelation time. Although post-curing remained necessary to achieve full polymerization, this advancement removed the primary processing barrier that had previously made BMI resins non-pultrudable. It was this breakthrough that formed the basis of the author's 1990 study—to experimentally characterize the pultrusion process for high-temperature BMI/graphite composites.

These experiments demonstrated that precise thermal management during preheating and die entry is essential for void-free consolidation and consistent cure. The findings gave the first quantitative basis for continual process optimization and later served as the experimental benchmark for the NASA-supported pultrusion studies led by Prof. James G. Vaughan (1990-2013). The correlations established between thermal variables and mechanical response continue to inform current process-modelling and best-practice guidelines presented in this review (Table 2).

Table 2. Chronological summary of key process variables and research milestones in graphite/BMI pultrusion (1990-2025).

Period	Principal Researchers/Institution	Focus Area	Key Process Variables Investigated	Representative Findings/Outcomes	Reference Range
1990	K. T. Leong, Univ. of Mississippi	Experimental factorial design and process characterization	Fiber volume, preform temperature, die temperature, pulling speed, filler content	Identified fiber volume, preform temp., and filler as dominant variables; established 60 % fiber optimum; emphasized thermal control and post-cure needs.	[1]
1991-1996	J. G. Vaughan *et al.*, NASA/Univ. of Mississippi	Heat-transfer and cure-kinetics modeling	Die-zone profiles, cure gradients, fiber-resin interaction	Developed first finite-difference/finite-element pultrusion models predicting temperature and cure evolution.	[3]-[9]
1996-2006	Vaughan, Valliappan, and collaborators	Process coupling and sensor validation	Resin-flow behaviour, pressure evolution, cure degree	Established coupled flow-pressure-cure models and validated thermal/cure predictions using embedded thermocouple and dielectric sensors.	[10]-[12]
2000-2013	Vaughan group	Process scaling and parameter optimization	Pull-speed effects, injection-chamber geometry, fabrication variability	Extended model to industrial scale; confirmed parameter sensitivity trends and surface-finish correlations.	[11]-[13]
2013-2020	Period of limited published research specific to graphite/BMI pultrusion. Industrial and academic work focused on automation, real-time monitoring, and general pultrusion process scaling rather than BMI-specific systems. Established thermal-cure and flow-pressure models from 1991-2011 continued to guide industrial practice.	[13]			

Continued

2020-2025	IKV (Germany), ORNL (USA), industrial R&D groups	Digital-twin and AI-based process optimization	Sensor fusion, predictive maintenance, sustainability metrics	Advanced real-time monitoring, digital-twin concepts and data-driven control have been proposed and, in some cases, demonstrated for continuous composite processing, with increasing application to pultrusion lines.	[14]-[21]

This timeline highlights the progressive expansion from empirical parameter identification to predictive, AI-assisted industrial implementation.

Although few new publications appeared between 2015 and 2020, this period marked an important transition in which the earlier NASA and University of Mississippi research [13] [14] continued to inform industrial pultrusion practice, particularly in automated control and data-driven process monitoring that set the stage for post-2020 digital and AI-assisted developments.

5. Key Findings and Discussion

The factorial analysis demonstrated strong interactions between thermal and mechanical variables. Higher preform temperature improved resin wetting but excessive heating caused premature gelation. Filler additions improved heat conduction, while pull speed affected surface finish and void formation. These observations remain consistent with modern CFD-based pultrusion models, confirming that resin viscosity and temperature distribution dominate product quality.

5.1. Foundational Works by Vaughan and Collaborators

Foundational studies by Vaughan and collaborators at the University of Mississippi [1] [3]-[7] [10]-[13] established the framework for pultrusion process characterization. Vaughan & Hackett (NASA CR-184275) documented die heating and pull-force behavior. Lackey & Vaughan linked pull load to resin cure, while Chachad, Roux & Vaughan developed 3D models later validated by Valliappan & Vaughan. These contributions underpin predictive modeling and process-control strategies still used today.

5.2. Review of Vaughan's Publication Contributions (1990-2013)

The pultrusion research program led by Prof. James G. Vaughan at the University of Mississippi started as early as 1988 with the thesis by Leong in 1990 [1], following which, this research program formed a coherent sequence of experimental, analytical, and industrially relevant studies spanning over two decades. The following key publications summarize that progression and their collective impact on composite process science.

- [3] Vaughan & Hackett (1991, NASA CR-184275): Reported experimental and analytical pultrusion process characterization for high-performance composites and developed predictive modelling capability to calculate temperature and degree-of-cure profiles for parametric study of key processing variables (e.g., die temperature settings, pull speed, and fibre volume fraction). It included a validated 1-D and 2-D finite element formulation capable of predicting temperature profile and degree of cure.
- [4] Gorthala, Roux, Vaughan and Hassouneh (1992) examined how DSC cure-kinetic parameters influence heat-transfer predictions in pultrusion, demonstrating prediction of parameters and their interaction between material, pull speed, fiber volume and die temperatures. This work compares model prediction against experimental result.
- [5] Lackey & Vaughan (1994): Showed that pull-load behavior is strongly influenced by degree of cure, demonstrating that thermal conditions directly affect pultrusion mechanical stability together with other factor's interactions. The study also highlighted the need for further work on cure-dependent pull-force behaviour and fibre/matrix interactions under varying processing conditions.
- Early 2D heat-transfer and cure modelling was established by Gorthala *et al.* [6], providing validated predictions of temperature and degree of cure in graphite/epoxy and fiberglass/epoxy pultrusion. This work was later extended into full 3D simulation capability enabling prediction of thermal and cure distributions in irregular, non-uniform cross-sections.
- [7] Chachad, Roux & Vaughan (1996) developed a 3D thermo-chemical pultrusion model for graphite/epoxy composites, predicting transient temperature and degree of cure distributions using Patankar's finite-difference method. Their results demonstrated how exothermic reaction kinetics and cross-sectional geometry influence cure behavior, providing a practical tool for optimizing pultrusion heating and processing conditions.
- [10] Valliappan, Roux, Vaughan & Arafat (1996): provided a coupled numerical model for die and post-die temperature and cure, showing that cure can continue after die exit and supporting the need to manage post-die thermal history and line speed, and fiber-volume optimization in high-performance composites.
- [11] [12] Post 1996 process characterization and scaling extensions: Following the core 3-D thermal-cure model developments in the mid-1990s, subsequent work shifted toward process characterization, fabrication variability and pressure driven flow effects relevant to industrial scale up. Lackey *et al.* (2008) quantified statistical variability in pultruded composite fabrication, linking processing conditions to surface finish and geometric consistency in fibre reinforced profiles. In parallel, Gadam *et al.* (2000) developed a pressure-rise model for tapered pultrusion dies, demonstrating the strong influence of pull speed, resin viscosity and die-inlet geometry on resin consolidation and void

suppression. Together, these studies bridged the transition from laboratory scale thermal cure modelling to manufacturing-relevant optimization and quality control.

- [13] Ranga *et al.* (2011) Resin-injection pultrusion (RIP) process optimization.: Building on earlier thermal cure and flow pressure models, Ranga *et al.* (2011) investigated the influence of tapered injection-chamber length and pull speed on resin wet-out and injection pressure stability in RIP. The study demonstrated that chamber geometry and line speed jointly control impregnation quality and pressure requirements, providing a direct link between earlier numerical modelling and industrial-scale process optimization.

Collectively, these investigations by Vaughan and his collaborators transformed pultrusion from an empirical manufacturing method into a science-based process with predictive modelling capability and sustainable process engineering. Their integration of cure kinetics, resin flow, and temperature control laid the theoretical groundwork for today's digital simulations and adaptive control systems. The next phase of progress—emerging after 2015—extended these foundational principles into industrial automation, sustainability, and artificial-intelligence-driven process optimization, as summarized in the following section.

5.3. Industrial and Academic Progress Since 2015

Following the conclusion of Prof. James G. Vaughan's active involvement in the pultrusion research program, the field entered a period of rapid expansion and modernization. The foundational principles established through the 1990-2013 University of Mississippi studies—encompassing heat-transfer analysis, resin-flow coupling, and in-die cure kinetics—remain foundational to contemporary modeling and process optimization. Since 2015, research and industry have broadened the scope to incorporate automation, sustainability, and complex geometries. The most significant developments can be grouped as follows:

A. Curved and variable-geometry pultrusion [15]

Recent reviews such as such as Talabi *et al.* (2024), demonstrate the feasibility of producing curved and variable-section pultruded profiles through adaptive die alignment and controlled pulling trajectories. Finite-element models now compensate for bending stresses and non-uniform cooling, extending the process beyond constant-cross-section parts. These innovations respond directly to Vaughan's early observation that real components often deviate from idealized geometry.

B. Sustainable resin systems [17] [18]

Between 2018 and 2025, researchers introduced recyclable thermoset systems and vitrimer-based pultrusion (Kumar *et al.*, 2025, Journal of Composites Science 9(10):559). These resins enable reversible cross-linking and closed-loop recycling without significant mechanical degradation, aligning with global moves toward low-VOC, sustainable manufacturing. This direction represents the chemical evolution of the BMI-based systems first explored at the University of Mississippi.

C. Hierarchical and hybrid composites [16]

Work at the University of Bristol (Pickard *et al.*, 2024) applied pultrusion to fabricate hierarchical rods containing nano- and micro-reinforcements. Improved wet-out and void fractions below 1 % were achieved through vacuum-assisted resin injection and tailored preform compaction. These outcomes extend Vaughan's objectives of void elimination and thermal uniformity using twenty-first-century materials and instrumentation.

D. Real-time monitoring and digital twins [18]-[20]

Industrial R&D, including work at IKV (Germany) on residence-time visualization in pultrusion profiles [18], and broader automation studies [19], points toward integration of sensor data with data-driven control and digital-twin concepts. This work essentially realizes the "coupled flow-pressure-cure modelling" advocated in Vaughan's NASA reports. Digital-twin architectures now couple finite-element solvers with live sensor feedback to predict curing and residual stress in real time.

E. Automation and process scaling [19]-[21]

Modern production lines increasingly use robotic pullers, multi-zone temperature mapping, and adaptive control algorithms that have demonstrated measurable reductions in energy use and improved dimensional stability in continuous composite processes [19]-[21]. These systems transform pultrusion from a semi-empirical process into a high-precision, data-driven manufacturing platform.

Collectively, these developments confirm that Vaughan's foundational framework remains valid while the technological focus has evolved. The current era integrates his principles with artificial-intelligence control, sustainable materials, and industrial automation. This continuity supports the relevance of the recommended parameters presented in Section 8 and the research roadmap outlined in Section 9 are directly relevant to contemporary pultrusion challenges and opportunities.

The convergence of these post-2015 academic and technological developments has now matured into industrial-scale implementation, where automation, digital control, and sustainable processing are redefining pultrusion as a precision manufacturing discipline.

Although pultrusion has evolved from laboratory experimentation into a precision manufacturing discipline, several long-standing technical challenges remain central to its optimization. Resin-flow uniformity continues to influence complete fiber wet-out and void prevention, especially at high fiber-volume fractions where pressure gradients and preform compaction interact. Die-heating control demands carefully balanced temperature zoning to ensure uniform cure without inducing residual stresses or thermal overshoot. Void formation and control persist as dominant contributors to mechanical variability, affected by filler content, resin rheology, and pulling speed. These interrelated factors define the enduring technical frontier of BMI pultrusion and provide the direct motivation for the automation, sensing, and adaptive-control strategies examined in Section 6.

6. Industrial Practices and Modern Developments

Recent pultrusion advances include resin-injection systems, multi-zone die heating, and automated pulling and cutting mechanisms that improve productivity and dimensional consistency [16] [15] [20] [21].

Digital-twin implementations now enable predictive control of heater-zone temperatures and pulling speed using real-time sensor feedback [14] [15] [20].

Finite-element and CFD tools reproduce coupled heat transfer, cure kinetics, and residual-stress formation with high fidelity [6]-[10] [12] [13].

Machine-learning algorithms are increasingly applied to forecast cure completion and optimize die-temperature profiles dynamically [19] [20].

Modern industrial processes have also adopted cleaner resin formulations and closed injection systems to reduce VOC emissions [18] [20].

BMI pultrusion, once confined to research, is now being commercialized for aerospace secondary structures and high-temperature conduits [21].

Integration with robotic handling and in-line NDT inspection ensures traceable, defect-free profiles meeting aerospace and energy-sector standards [20] [21].

7. Economic and Industrial Relevance

The economic attractiveness of pultrusion lies in its ability to combine continuous throughput, dimensional consistency, and low labor intensity, making it one of the most cost-effective processes for producing advanced composite structures [20] [21]. Compared with autoclave curing or filament winding, pultrusion typically reduces labor and energy costs by 30 - 50%, while achieving superior fiber alignment and repeatability.

In recent years, the introduction of adaptive heating, closed injection systems, and automated pullers has further reduced operating costs and material waste [15] [21]. Energy-optimized dies and intelligent temperature control now allow production lines to run continuously for weeks with minimal operator intervention, improving yield and reducing downtime [15] [19]. When implemented within the optimized process window summarized in Section 8, these best-practice parameters directly translate into measurable industrial gains—typically reducing scrap rates by 10 - 15%, lowering energy consumption through improved thermal efficiency, and enhancing component reliability through consistent cure quality. The economic return of these improvements is particularly evident in sectors where reliability and material utilization dominate total cost of ownership—such as aerospace, energy, infrastructure, and transportation.

The global pultrusion market, estimated at over USD 3.8 billion in 2024, continues to grow steadily at approximately 5% annually, driven by demand for lightweight, corrosion-resistant, and electrically insulating materials [21]. BMI- and carbon-fiber-based pultrusions occupy the high-performance segment, serving thermal-stable and high-temperature applications that cannot be met by conventional polyester or vinyl ester systems. Emerging vitrimer and hybrid thermoset systems promise further economic advantages by enabling recyclability and compliance with evolving environmental regulations [18].

From an industrial standpoint, the increasing adoption of digital-twin monitoring and AI-based process control has introduced a new paradigm of predictive manufacturing economics—reducing waste through real-time corrective feedback and optimizing cure energy consumption [19]-[21]. These advancements extend the legacy of early experimental studies by translating their process insights into tangible cost and performance gains.

As the next section outlines, the best-practice parameters derived from decades of experimental and industrial data now form a validated operational window that balances technical performance and economic viability, establishing pultrusion as a cornerstone technology for sustainable composite manufacturing.

8. Best Practices and Recommendations

The characterization of the pultrusion process for graphite/BMI composites—spanning more than three decades, beginning with the author's 1990 thesis under Prof. Vaughan and continuing through the NASA-supported program and present industrial practice—has converged on a consistent and validated set of process parameters. These conditions reflect the cumulative evolution of experimental research, analytical modelling, and full-scale industrial application.

Building upon the factorial design established in Leong (1990) thesis and its subsequent validation by Vaughan and collaborators (1991-2013), the present synthesis incorporates more recent developments in automation, adaptive die heating, digital-twin monitoring, and sustainable resin technology (2015-2025). Each recommendation therefore represents an experimentally confirmed and economically viable balance between process efficiency, mechanical performance, and product reliability.

Table 3 consolidates these best-practice parameters for graphite/BMI pultrusion, while **Table 4** cross-references them with their supporting literature from both historical and modern studies. Together, they define a robust operational window for maintaining consistent cure quality, minimizing voids, and ensuring thermal uniformity across a wide range of industrial applications.

Table 3. Recommended best practices for BMI/graphite pultrusion (Validated 1990-2025).

Category	Recommended Practice	Rationale/Purpose	Supporting References
Preform Heating	Maintain 100 - 130˚C preform entry temperature; use infrared or induction pre-heating for uniform temperature distribution.	Promotes resin wet-out without premature gelation; modern IR/induction systems improve heating efficiency and consistency.	[1] [7] [16] [21]
Die Temperature Profile	Multi-zone heating 160 - 220˚C (entrance → exit); employ dynamic zone control or adaptive heating algorithms.	Ensures progressive cure and uniform conversion; adaptive control reduces thermal spikes and energy use by 15 - 25%.	[1] [10] [12] [14] [15]

Continued

Fiber Volume Fraction	60 - 70%	Optimizes stiffness and tensile strength while maintaining sufficient resin flow for wet-out.	[1] [11]
Filler Addition	Add 5 - 10 wt % thermally conductive fillers.	Improves heat transfer through the composite, enhancing cure uniformity and dimensional stability.	[1] [17]
Pull Speed	0.15 - 0.25 m min^{-1}, with adaptive feedback control.	Balances productivity and cure completeness; adaptive feedback minimizes voids and surface defects.	[1] [11] [18] [21]
Quality Monitoring and Control	Integrate embedded thermocouples, dielectric or fiber-optic sensors linked to digital-twin monitoring.	Provides real-time assurance of cure and temperature; enables predictive correction of process drift.	[14] [16] [19] [21]

Notes: Parameter ranges derive from author's 1990 thesis under Vaughan and the subsequent NASA/University of Mississippi studies (1991-2013), validated by modern digital-twin and industrial-scale results (2015-2025).

Each recommendation in **Table 3** is directly supported by prior experimental or analytical findings.

Foundational evidence originates from the author's 1990 thesis [1], with refinements stem from Vaughan's group and later numerical and industrial studies [3]-[7] [10]-[13] [16]-[19].

To provide full traceability, **Table 4** expands these relationships, mapping every process recommendation to its corresponding sources.

Table 4. Cross-reference summary of recommended practices and supporting literature.

Process Category	Principal Supporting References	Validation Highlights/Notes
Preform Heating	[1] [7] [16] [21]	Preform temperature identified as a dominant variable in Leong (1990) [1]; 3D modelling by Chachad *et al.* (1996) [7] showed sensitivity of cure to inlet temperature; industrial relevance supported by hierarchical composite studies (Pickard *et al.* 2024) [16] and trend data from EPTA (2024) [21].
Die Temperature Profile	[1] [10] [12] [14]	Accurate die-wall temperature control essential for uniform cure, as demonstrated by 2D and 3D thermal-cure models (Gorthala *et al.* 1994 [10]; Gadam *et al.* 2000 [12]). Real time adjustments and automated data acquisition in Gardiner, G. (2020) [14].
Fiber Volume Fraction	[1] [11]	Optimum 60 - 70% volume fraction maintains structural stiffness and is consistent with Leong (1990) [1] and fabrication-variability observations by Lackey *et al.* (2008) [11].
Filler Addition	[1] [17]	Thermal-conductivity and heat-stability effects of additives first discussed in Leong (1990) [1]; vitrimer-based pultrusion studies (Kumar *et al.* 2025) [17] outline modern opportunities for tailored thermal response; specific filler wt% recommendations derive from Leong (1990) [1].
Pull Speed	[1] [11] [14] [18] [21]	Strong correlation between pull speed, cure state, and surface finish documented by Leong (1990) [1] and Lackey *et al.* (2008) [11]; Gardiner, G. (2020) [14] reinforces the need for speed-linked thermal control; residence-time visualization (IKV 2025) [18] and industry trends (EPTA 2024) [21] highlight the operational significance of pull-speed optimization.

Continued

Quality Monitoring and Control	[14] [16] [19] [21]	Embedded sensors validated temperature and cure monitoring in Valliappan & Vaughan (1996) [8]; modern automation and sustainability analyses. Rahman, M. R. (Ed.). (2020) [19] and Gardiner, G. (2020) [14] support real-time optimization; industry reports (EPTA 2024) [21] reinforce adoption trends. ML-based approaches discussed by Malashin *et al.* (2025) [20].

The synthesis of best-practice parameters in **Table 3** and **Table 4** represents the culmination of more than three decades of pultrusion research, establishing the present benchmark for graphite/BMI process optimization. These validated process ranges form a reliable operational baseline that unites experimental design, industrial implementation, and economic efficiency. The remaining challenge—and opportunity—lies in extending these principles through advanced multiphysics modelling, intelligent sensing, and sustainable material systems, as outlined in the subsequent section on Future Research Directions.

9. Future Research Directions

Building upon more than three decades of pultrusion characterization, recent industrial progress shows that several of the research goals articulated by Vaughan's program have now been partially achieved. However, further integration of material innovation, digital control, and sustainability is required to fully realize the predictive, adaptive pultrusion platform envisioned in the early NASA reports [3] [4].

In Vaughan & Hackett (1991, NASA CR-184275), the authors observed that "the pultrusion process presently lacks a comprehensive scientific model capable of predicting temperature, pressure, and cure gradients," recommending "further coupling of resin flow, pressure, and cure kinetics." Vaughan (1991) likewise noted that "extension of the model to three-dimensional geometries and inclusion of transient resin-flow effects will be required to apply these results to production tooling." These public-domain NASA statements remain technically relevant but must now be reframed in light of the industry's transition toward data-driven manufacturing.

Current research gaps and opportunities include:

1) Dynamic, Full-Scale 3-D Modelling. Extend validated laboratory-scale models to high-speed, multi-die production lines, including transient pull-speed variation and moving-die thermal profiles.

Unresolved question: How can 3-D coupled flow-cure-stress models be experimentally validated at industrial scale without disrupting continuous operation?

2) Real-Time AI-Assisted Control. Combine embedded thermocouples, dielectric sensors, and machine-vision data within unified digital-twin frameworks capable of self-correcting process drift. Supported by automated data acquisition, and simulation-based digital twins [14], recent reviews on real time adjustments to speed [19], Rahman, M. R. (Ed.). (2020) [19], and ML-based optimization strategies [20].

Unresolved question: What level of data granularity and sensor latency can AI algorithms tolerate before predictive accuracy in cure and void detection begins to degrade?

3) Energy-Efficient Adaptive Heating. Apply predictive algorithms for die-zone power optimization, minimizing energy use while maintaining cure uniformity. Supported by highlights predictive framework for real time adjustments for energy efficiency [14]; industry-trend reports [21] note increasing emphasis on energy efficiency.

Unresolved question: How can real-time feedback be coupled to thermokinetic models to prevent thermal overshoot while achieving full cross-link conversion?

4) Advanced Resin Chemistries and Sustainability. Develop low-VOC, vitrimer-based, and bio-derived analogues to BMI systems to improve recyclability and regulatory compliance. Supported by modern vitrimer pultrusion pathways [17] and AI-enabled materials-design insights [20].

Unresolved question: How can vitrimer formulations balance the recyclability of dynamic covalent networks with the high thermal stability (Tg > 250˚C) demanded by BMI-type aerospace systems?

5) Predictive Maintenance and Lifecycle Modelling. Use data-driven correlations between pull-force history, die wear, thermal cycles, and composite property evolution to forecast maintenance intervals and reliability. Automation and sustainability literature supports this direction [19], while industry-trend analyses highlight the growing adoption of digital quality monitoring [21].

Unresolved question: Can machine-learning models trained on production-line data reliably quantify die degradation and predict property drift over long continuous runs?

6) Cyber-Physical Integration and Data Integrity. As pultrusion becomes cloud-linked and digitally networked, data-management standards and security frameworks will be required to preserve reproducibility and intellectual-property protection across distributed manufacturing environments. Industry reports [21] and automation studies [19] emphasize the need for secure digital infrastructure.

Unresolved question: What digital-security framework can preserve proprietary process data while enabling multi-site predictive analytics across global manufacturing facilities?

Collectively, these directions merge the historical objectives of the University of Mississippi's pultrusion research with the technological imperatives of Industry 4.0. Achieving them will convert the process from an empirically optimized operation into a fully predictive, intelligent, and sustainable manufacturing platform—completing the trajectory first initiated with the author's 1990 thesis under Prof. James G. Vaughan and carried forward through the 1990-2013 Vaughan pultrusion program.

The evolution of graphite/BMI pultrusion research—from the early factorial experiments of 1990 through Vaughan's comprehensive process-modelling program and into today's data-driven automation—illustrates a continuous refinement of scientific understanding and industrial practice. The forward-looking strategies outlined above ensure that this foundation will remain relevant as pultrusion enters the era of intelligent, energy-efficient, and sustainable composite manufacturing.

10. Conclusions

This review has traced the evolution of graphite/BMI pultrusion research from its experimental origins in 1990 through the NASA-supported studies at the University of Mississippi and into the modern, digitally integrated era of composite manufacturing. The Vaughan pultrusion research program (1990-2013), initiated with the author's 1990 thesis [1], identified the governing variables of preform heating, die-zone temperature, filler content, and pulling speed; these findings were subsequently validated and refined in later NASA-supported studies. Together, these studies established the scientific foundation for understanding the thermal, rheological, and mechanical behavior of BMI-based pultrusion systems.

Contemporary work confirms the enduring validity of those principles while expanding the process envelope through adaptive die heating, infrared pre-treatment, real-time sensing, and recyclable/vitrimer resin systems. The comparative evaluation of experimental, analytical, and industrial evidence presented here demonstrates that pultrusion remains the most efficient route for producing continuous high-performance composites when optimized for heat transfer and resin flow. The best-practice parameters summarized in **Table 3** and **Table 4** provide a validated operational window for achieving consistent quality, reduced waste, and improved energy efficiency across both laboratory and industrial scales.

Looking forward, the integration of artificial-intelligence-assisted control, digital-twin monitoring, and sustainable resin chemistries will define the next stage of pultrusion development. These advancements will transform a once semi-empirical process into a predictive, adaptive, and self-regulating manufacturing platform. The continuum from the 1990 thesis to today's Industry 4.0 technologies therefore represents not a conclusion but an ongoing trajectory of innovation—one that honors the University of Mississippi's pioneering work while extending its relevance to the composite manufacturing challenges of the twenty-first century.

Acknowledgements

The author gratefully acknowledges Prof. James G. Vaughan of the University of Mississippi for his supervision and guidance during the 1990 thesis work that initiated the 1990-2013 Vaughan pultrusion research program. That program established the experimental and analytical foundations for graphite/BMI composite processing and continues to inform contemporary industrial and academic developments.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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