

Letters

Influence of process parameters on glass fibre-reinforced polymers manufactured through high pressure resin transfer moulding



Richard Protz^{a,*}, Linus Littner^b, Tim Luplow^c, Jonas Drummer^d, Eckart Kunze^a, Maik Gude^a, Marc Kreutzbruck^b, Sebastian Heimbs^c, Bodo Fiedler^d

^aTUD Dresden University of Technology, Institute of Lightweight Engineering and Polymer Technology (ILK), Holbeinstraße 3, 01307 Dresden, Germany

^bUniversity of Stuttgart, Institut für Kunststofftechnik (IKT), Pfaffenwaldring 32, 70569 Stuttgart, Germany

^cTechnische Universität Braunschweig, Institute of Aircraft Design and Lightweight Structures (IFL), Hermann-Blenk Straße 35, 38108 Braunschweig, Germany

^dHamburg University of Technology, Institute of Polymers and Composites (IPC), Denickestraße 15, 21073 Hamburg, Germany

ARTICLE INFO

Article history:

Received 3 November 2025

Received in revised form 22 January 2026

Accepted 20 February 2026

Available online 6 March 2026

Keywords:

High-pressure resin transfer moulding

Glass fibre-reinforced polymers

Process optimisation

Air-coupled ultrasonic testing

Computed tomography

Compression testing

ABSTRACT

The influence of key process parameters on the production quality of glass fibre-reinforced polymers manufactured by high-pressure resin transfer moulding (HP-RTM) was systematically investigated. Uniform $\pm 30^\circ$ braided preforms were infiltrated under controlled variations of vacuum level, resin discharge rate, and preform fixation. Non-destructive characterisation using air-coupled ultrasonic testing, computed tomography, microscopy but also visual inspection revealed process-induced defects such as in-plane fibre displacements, out-of-plane waviness, voids, and dry spots. Subsequent quasi-static compression testing showed that while Young's modulus remained largely unaffected, compressive strength decreased by up to 26 % under suboptimal processing conditions and was accompanied by a transition from shear-dominated to diffuse, matrix-dominated failure behaviour. Optimal laminate quality was achieved by evacuating the mould cavity to below 1.5 mbar, applying a reduced resin mass flow rate of approximately 10 g/s, and stabilising the preform by dual-sided fixation, resulting in an in-plane fibre orientation of $\pm 30^\circ \pm 1.7^\circ$. The results establish clear process–structure–property relationships and provide quantitative guidance for robust and reproducible HP-RTM processing.

© 2026 The Authors. Published by Elsevier Ltd on behalf of Society of Manufacturing Engineers (SME).

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

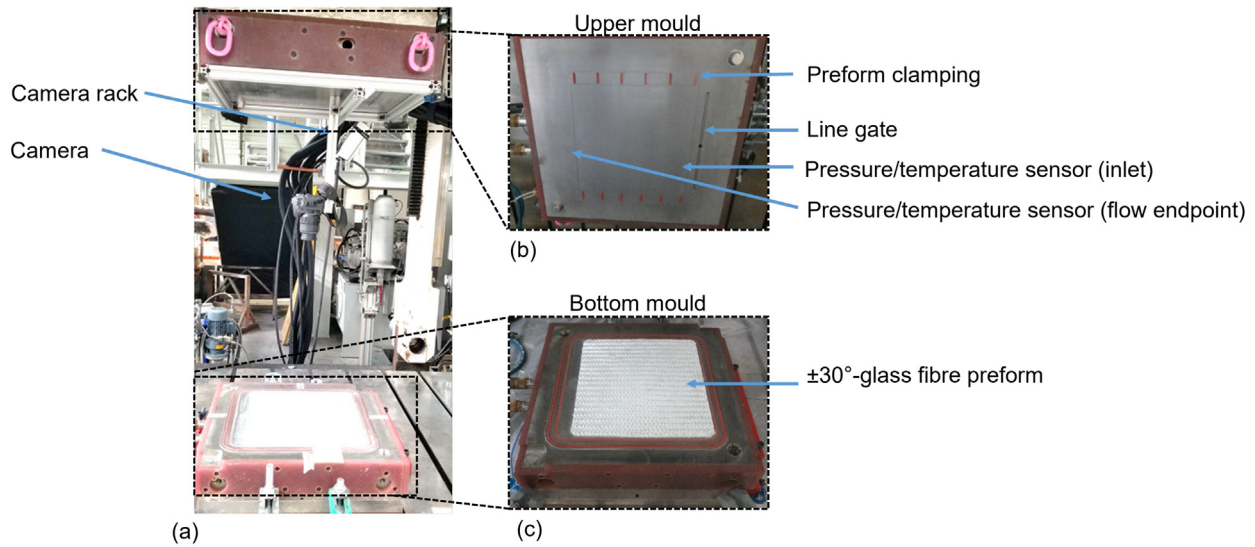
1. Introduction

Fibre-reinforced polymers are widely used in lightweight structures, especially in automotive, aerospace, and wind energy sectors [1–3]. Conventional techniques such as hand lay-up, filament winding, autoclave curing, and resin transfer moulding (RTM) have cycle-time limitations [4,5]. High-pressure RTM (HP-RTM) enables shorter cycles through high-pressure impingement mixing of fast-curing resin systems [6–9] and high automation [10–12,9,13,14]. HP-RTM achieves void contents comparable to autoclave processing while being suitable for mass production [13,11]. However, high flow rates may introduce voids [12,15] and fibre misalignment [16–19]. Misorientation can occur in-plane [20–24] or out-of-plane [25,26], affecting mechanical behaviour. Non-destructive testing is essential to characterise such defects. Air-coupled ultrasonic testing (ACUT) provides volumetric inspection without couplants and detects delaminations, voids, and misalignments

[27–29]. Complementary computed tomography (CT) and microscopy further reveal voids and fibre orientation, while mechanical testing quantifies their impact on performance. Previous RTM studies identified fibre content [30,31], injection flow rate [32–34], intra- and inter-fibre flow front [35,36], pressure [37,34,38,39], and vacuum level [40,39] as key quality factors. Recent HP-RTM studies have addressed data- and physics-driven process modelling, resin selection, flow-induced fibre deformation, and void formation, demonstrating that process parameters such as injection velocity, pressure, and mould design strongly govern impregnation quality and defect evolution [41,42,9,24,15]. In HP-RTM, injection pressure and preform compaction affect in-plane fibre displacement [24,17], while the combined influence of vacuum level, resin discharge rate, and mechanical preform fixation on fibre misalignment, void formation, and mechanical performance has not yet been systematically quantified. This work systematically varies HP-RTM parameters (vacuum, resin flow rate, preform fixation) using $\pm 30^\circ$ braided glass fibre preforms infiltrated with polyurethane resin. By maintaining identical fibre volume and structure, process–structure–property relationships are

* Corresponding author.

E-mail address: richard.protz@tu-dresden.de (R. Protz).



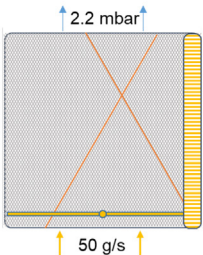
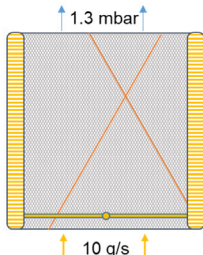
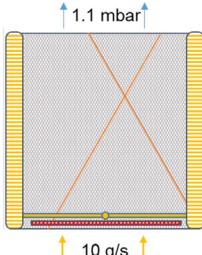
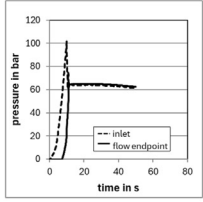
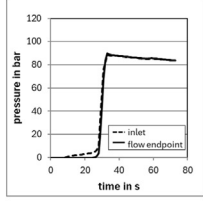
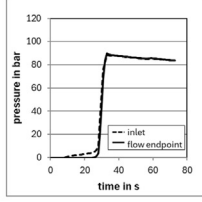
Parameter	Process 1	Process 2	Process 3
Vacuum [mbar]	2.2	1.3	1.3
Resin mass flow rate [g/s]	50	10	10
Lateral preform clamping	On the right side	On both sides	On both sides
Preform clamping on the resin inlet gate side	No	No	Yes
Scheme			
Pressure-time profile during injection			

Fig. 1. HP-RTM plate mould with camera for preform insertion monitoring (a), adjustable fibre clamping in the upper mould (b), inserted $\pm 30^\circ$ -preform in the bottom mould (c) and tabular overview of the parameters of the process studies.

derived to understand misorientation mechanisms and minimise defects.

2. Materials and methods

2.1. Materials and manufacturing process

Test plates were produced by braiding and infiltrated via HP-RTM. The reinforcement was SE 1200 Type 30[®] glass fibre roving (2,400 tex, 16 μ m filament diameter). $\pm 30^\circ$ twill braids were fabricated using a Herzog RF 1/288–100 radial braiding machine and stacked into 10-layer preforms (350 mm \times 350 mm \times 4 mm, Fig. 1). Preform quality and in-plane displacement were evaluated with Fiji ImageJ. Preforms were infiltrated with Loctite Max2 polyurethane and isocyanate hardener (100:132 ratio) at 120 bar

mixhead pressure. Prior to infiltration, the mould was evacuated to a defined vacuum level. The infiltration itself was performed via a linear gate, while the vacuum level was not actively regulated during resin injection. Curing¹ occurred at 80 $^\circ$ C for 30 min and post-curing at 150 $^\circ$ C for 1 h. Pressure, temperature, resin dosing, and flow mass were recorded.

2.2. Process studies

Three process parameters were varied:

1. Vacuum level – influences air removal and infiltration.

¹ Matrix dispensed without accelerator to enable RTM reference tests [22]

2. Matrix discharge rate – determines resin velocity and fibre displacement.
3. Preform fixation – restricts in-plane and out-of-plane movement.

Each configuration represented a distinct infiltration strategy, with five plates per variant (Fig. 1).

2.3. Process analysis and evaluation

During infiltration, cavity pressure, temperature, and flow rate were monitored. Post-processing included defect and fibre architecture analysis. ACUT (inoson, 200 kHz) produced 1 mm-resolution C-scans over 320 mm × 320 mm. Fibre volume fraction was determined according to ISO 1172 [43] on defined locations (Fig. 2). Selected regions were examined by CT (V|tome|x-L 450, GE Phoenix) at 110 kV and 100 μA yielding 11 μm voxel size. Polished cross-sections were analysed microscopically (Zeiss AX10 microscope). Fibre angles were quantified using ImageJ and MATLAB®. Compression tests (DIN ISO 14126 [44]) were performed on a Zwick/Roell Z200 test rig with shear-compression fixtures [45,46]. Tests were run at 1 mm/min with strain gauges on both surfaces. Five samples per variant were tested.

3. Results and discussion

Aiming at a target braiding angle of ±30°, pre-infiltration analysis of photographic documentation on the dry preforms showed an average in-plane fibre orientation of $\pm 29 \pm 1.7^\circ$ across all plates (Fig. 2a). The acute braiding angle provided few crossing points and low structural stability. The 10-layer preforms exhibited a weight of 850 ± 8 g and a coverage rate of 89 %.

3.1. Visual inspection and ACUT measurement

The systematic variation of HP-RTM infiltration parameters resulted in test plates with clearly distinguishable laminate quality, which is consistently reflected in both visual inspection and ACUT measurements (Fig. 2b,c).

In process 1, pronounced amplitude variations indicate severe fibre misalignment, resin-rich regions, and locally insufficient impregnation. The high resin discharge rate combined with single-sided preform fixation caused fibre displacement in the direction of the flow front, leading to fibre-depleted zones near the inlet and fibre accumulation towards the opposite side. This locally impeded resin flow and promoted dry spot formation, an effect further intensified by the low evacuation level.

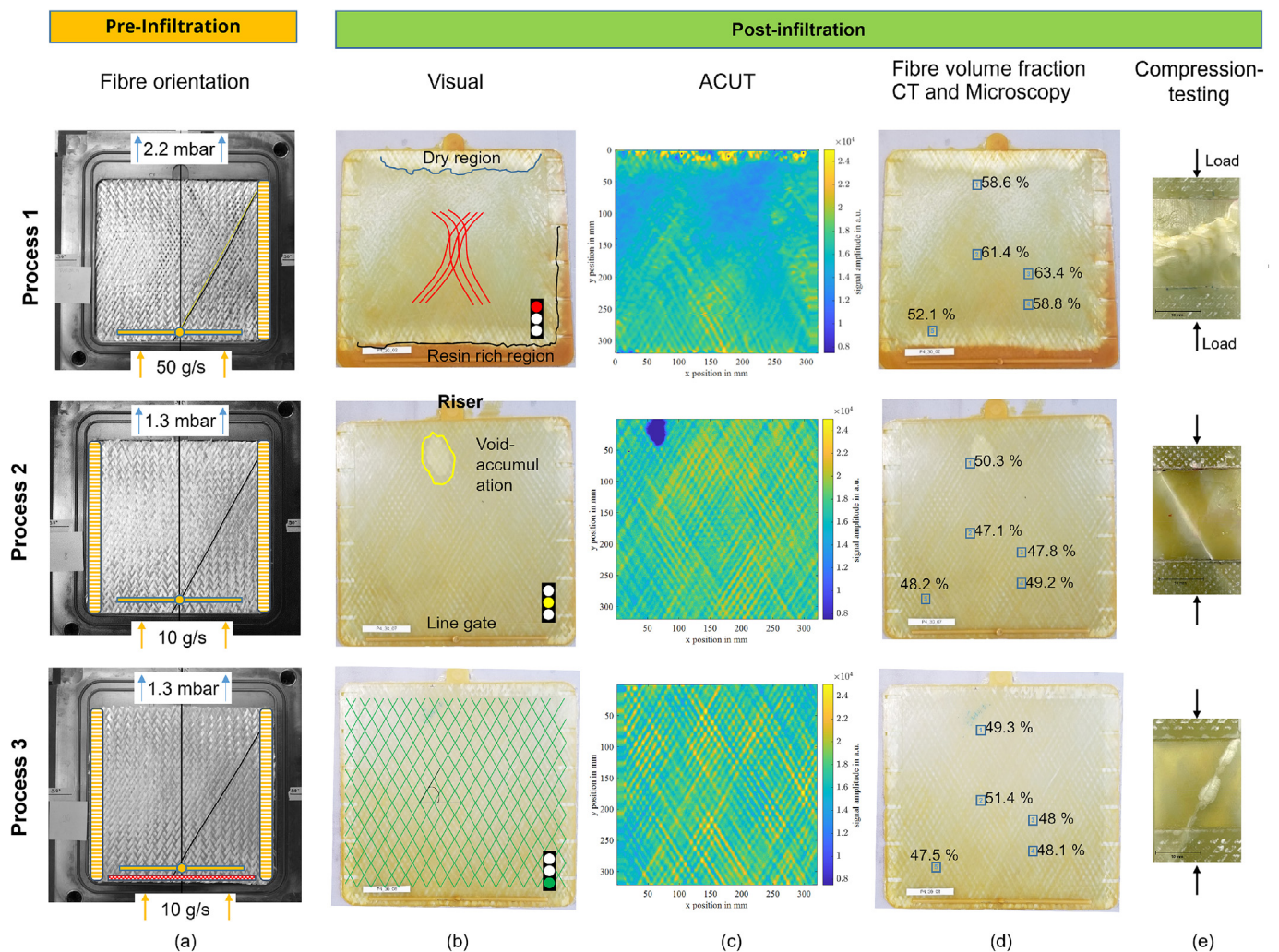


Fig. 2. Analysis of fibre deposition prior to infiltration and presentation of process study parameters (a) and post-infiltration analysis: visual (b), ACUT (c), fibre volume fraction, CT and microscopy (d), exemplary depiction of the different failure modes in the compression test specimens (e).

In process 2, increased vacuum quality, reduced discharge rate, and lateral preform fixation significantly stabilised the infiltration process. This resulted in straighter amplitude patterns and improved laminate homogeneity, although isolated voids remained detectable.

Process 3 exhibited the lowest amplitude variation, confirming homogeneous infiltration, straight $\pm 30^\circ$ fibre orientation, and minimal void content. This quality improvement is attributed to the combination of high vacuum quality, reduced flow-front velocity, and dual-sided as well as gate-side preform fixation.

3.2. Fibre volume fraction

Since all test plates are based on the same preform design, global fibre volume fraction is $49 \pm 1\%$, with the distribution across the test plate varying greatly depending on the process study (Fig. 2d). Process 1 showed the greatest variation. Fibre washout leads to locally accumulated fibres, resulting in high local fibre volume fractions of up to 63.4%. In contrast, processes 2 and 3 produced a more uniform fibre distribution across the entire test panel, with deviations of 1.9% in process 2 and 1% in process 3.

3.3. CT and microscopy analysis

CT and microscopy corroborated these process-dependent quality differences. In process 1, severe in-plane and out-of-plane fibre displacements hindered quantitative CT evaluation (Fig. 3a). By contrast, processes 2 and 3 displayed straighter fibre orientation and reduced waviness (Fig. 3b).

Micrographs confirmed these findings and showed pronounced waviness, mesovoids, and microvoids in process 1 (Fig. 4a), whereas process 2 exhibited uniform compaction with only isolated microvoids (Fig. 4b). Quantitative microscopy analysis revealed broad in-plane orientation distributions in process 1, with many fibres around $\pm 20^\circ$ and $\pm 67^\circ$ (Fig. 4d). Processes 2 and 3 aligned more closely with the $\pm 30^\circ$ target. Out-of-plane orientations were similar across processes due to strong compaction, but process 1 displayed a larger fraction of fibres approaching 90° (Fig. 4e). The table in Fig. 4f summarises the orientation statistics, highlighting large post-infiltration deviations in process 1 (18.7%), compared with smaller shifts in processes 2 (4.6%) and 3 (2%).

Together, visual, ACUT, CT and microscopy confirm that high vacuum is essential for complete infiltration and void reduction, while excessive flow rates promote in-plane fibre displacement. Dual-sided and gate-side preform fixation effectively mitigates these effects, and no further improvement in laminate quality was observed beyond evacuation levels below 1.5 mbar. Process 3 yielded test plates meeting the $\pm 30^\circ \pm 1.7^\circ$ in-plane orientation target.

3.4. Compression testing

Compression tests confirmed the link between process quality and mechanical behaviour. All specimens showed comparable Young's moduli (17–18 GPa), indicating that stiffness, under linear elastic conditions, is rather insensitive to voids or waviness when fibre–matrix bonding is maintained [47]. Strength, however, strongly reflected process quality. Process 1 reached 179 ± 15 MPa, whereas process 2 and process 3 achieved 242 ± 9 MPa and 230 ± 10 MPa, respectively. These differences align with the observed defect levels: misalignments and voids in process 1 reduced strength by 26% compared with process 2, while improved vacuum, reduced flow rate and enhanced fixation in processes 2 and 3 delivered higher strength. The slightly lower value for process 3 may be due to local fibre volume variations. Under compressive loading, specimens from Process 1 exhibit diffuse, matrix-dominated and irregular failure patterns due to pronounced fibre misalignment, whereas the improved fibre orientation and compaction in Processes 2 and 3 lead to well-defined, shear-dominated fracture paths aligned with the principal fibre directions (Fig. 2e).

In summary, high vacuum, controlled resin flow, and robust preform fixation were critical for minimising defects and ensuring higher mechanical behaviour.

4. Recommendations for suitable process parameters for the optimisation of the HP-RTM process

High laminate quality in the HP-RTM process relies on accurate preform positioning and efficient evacuation of the mould cavity. Evacuation below 1.5 mbar was critical for minimising void formation and achieving complete infiltration. Further reduction of the vacuum level to the technical limit of a standard vacuum pump (approx. 0.9 mbar), evaluated selectively, did not provide any additional benefit in laminate quality.

Reducing the resin mass flow rate to approximately 10 g/s lowered flow-front velocity, thereby limiting in-plane fibre displacement and avoiding excessive local pressure gradients during infiltration. Additional lateral and gate-side preform clamping further stabilised fibre orientation, reduced race-tracking and void content [15] and improved laminate uniformity.

The correlation with compression testing confirms that optimised parameters—high vacuum, controlled resin discharge rate, and robust fibre fixation—result in higher compressive strength and more predictable failure behaviour. Effective process optimisation must therefore address both preform handling and infiltration control to ensure consistent structural performance.

The study reveals the following influences of the process parameters on composite quality:

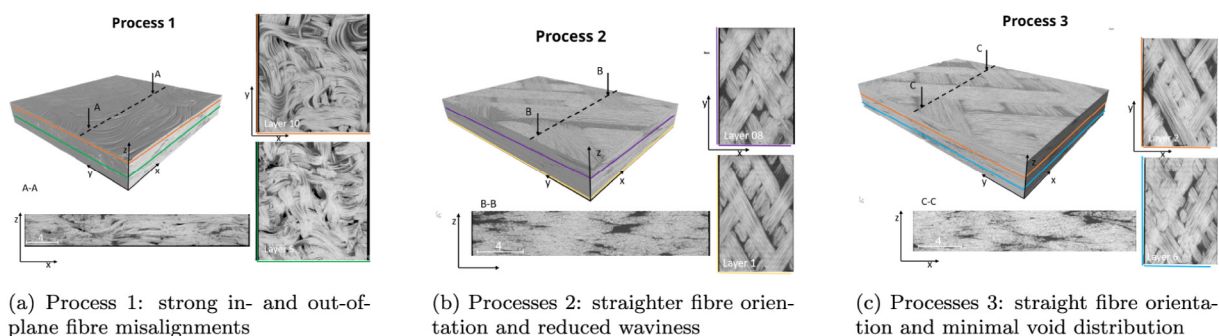


Fig. 3. CT scans showing process-dependent laminate quality.

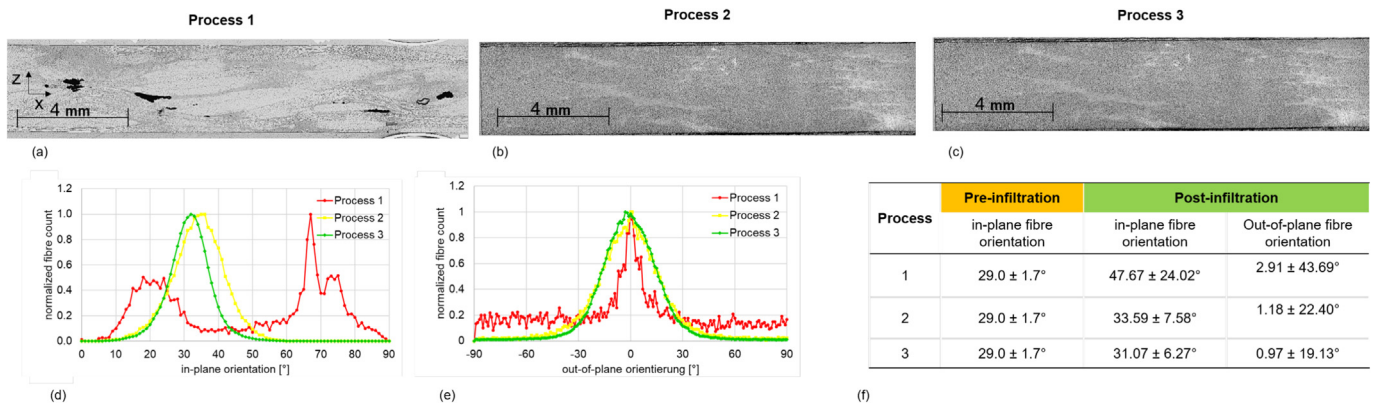


Fig. 4. Microscopy: inferior production quality in process 1 (a), improved quality in process 2 (b) and 3 (c); Distribution of in-plane (d) and out-of-plane (e) fibre orientations for each process; Process-related evolution of the mean in-plane fibre orientation as a result of HP-RTM infiltration and final out-of-plane fibre orientation (f).

- Preform quality (pre-infiltration) ↑↑; In-plane fibre waviness ↓↓
- Vacuum level ↑; Void content ↓
- Resin mass flow rate ↓↓; In-plane fibre waviness ↓↓
- Preform clamping ↑↑; In-plane fibre waviness ↓

5. Conclusion

This study examined the influence of key HP-RTM process parameters on the infiltration of $\pm 30^\circ$ braided preforms with polyurethane resin. Braids were processed under varying fixation strategies, vacuum levels, and resin flow rates, and the resulting plates were characterised by ultrasonic testing, CT, and compression loading. The results show that high vacuum is essential for complete infiltration and minimal void content, with evacuation below 1.5 mbar proving decisive. Elevated flow rates increased flow-front velocity, causing fibre displacement, whereas reducing flow to around 10 g/s improved infiltration uniformity. Dual-sided fixation and gate-side clamping further stabilised fibre orientation and reduced defects. Mechanical testing revealed that Young's modulus is largely unaffected by process variations, while compressive strength and failure mode are highly sensitive to fibre misalignment and infiltration quality. Strength reductions of up to 26 % under suboptimal conditions were directly linked to process-induced fibre misalignment and void formation, underscoring the need for precise control of fibre positioning and infiltration dynamics. Optimised parameters—vacuum below 1.5 mbar, resin flow of 10 g/s, and dual fixation—produced defect-minimised, mechanically stable laminates. Future work will investigate contact phenomena during tool closure and validate these parameters for alternative composite architectures.

CRediT authorship contribution statement

Maik Gude: Writing – review & editing, Project administration, Funding acquisition. **Marc Kreutzbruck:** Writing – review & editing, Project administration, Funding acquisition. **Jonas Drummer:** Writing – original draft, Methodology. **Eckart Kunze:** Writing – original draft, Investigation. **Sebastian Heimbs:** Writing – review & editing, Project administration, Funding acquisition. **Bodo Fiedler:** Writing – review & editing, Project administration, Funding acquisition. **Linus Littner:** Writing – original draft, Visualization, Methodology, Investigation. **Tim Luplow:** Writing – original draft, Investigation. **Richard Protz:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

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.

Acknowledgment

This paper was prepared as part of the PAK 988 package project, including subprojects 428328210, 428323347, 428326921, and 428324840, funded by the German Research Foundation (DFG).

References

- [1] Zhang J, Lin G, Vaidya U, Wang H. Past, present and future prospective of global carbon fibre composite developments and applications. *Compos Part B: Eng* 2023;250:110463. <https://doi.org/10.1016/j.compositesb.2022.110463>.
- [2] Edah GO, Atiba JO, Fayomi OS. Advancements in fibre-reinforced polymers: properties, applications (a mini review). *Next Mater* 2025;8:100743. <https://doi.org/10.1016/j.nxmater.2025.100743>.
- [3] Protz R, Kunze E, Luplow T, Littner L, Drummer J, Heimbs S, Kreutzbruck M, Fiedler B, Gude M. Manufacture, process simulation, modelling and testing of thick-walled thermoset fibre-polymer composite laminates – a review. *Compos Struct* 2025;119678. <https://doi.org/10.1016/j.compstruct.2025.119678>.
- [4] Littner L, Protz R, Kunze E, Bernhardt Y, Kreutzbruck M, Gude M. Flow front monitoring in high-pressure resin transfer molding using phased array ultrasonic testing to optimize mold filling simulations. *Materials (Basel, Switzerland)* 2023;17. <https://doi.org/10.3390/ma17010207>.
- [5] Cao Z, Zhan L, Ma B, Li S, Xie M, Guo J. The key technologies for fiber-reinforced polymer composites manufacturing: a state-of-the-art review. *Thin-Wall Struct* 2025;217:113773. <https://doi.org/10.1016/j.tws.2025.113773>.
- [6] Lorenz N, Müller-Pabel M, Gerritzen J, Müller J, Gröger B, Schneider D, Fischer K, Gude M, Hopmann C. Characterization and modeling cure- and pressure-dependent thermo-mechanical and shrinkage behavior of fast curing epoxy resins. *Polym Test* 2022;108:107498. <https://doi.org/10.1016/j.polymertesting.2022.107498>.
- [7] Rosenberg P, Thoma B, Henning F. Characterization of epoxy and polyurethane resin systems for manufacturing of high-performance composites in high-pressure rtm process; 2015.
- [8] Behnisch F, Rosenberg P, Weidenmann KA, Henning F. Investigation of the matrix influence on the laminate properties of epoxy- and polyurethane-based cfrps manufactured with hp-rtm-process. *AIP Conf Proc*, Author(s) 2017:180003. <https://doi.org/10.1063/1.5016789>.
- [9] Rutt M, Lekakou C, Smith PA, Sordon A, Santoni C, Meeks G, Hamerton I. Methods for process-related resin selection and optimisation in high-pressure resin transfer moulding. *Mater Sci Technol* 2019;35:327–35. <https://doi.org/10.1080/02670836.2018.1557916>.
- [10] Sherratt APR. Computational modelling of resin infiltration and curing in high pressure resin transfer molding, electronic thesis and dissertation repository. 8552; 2022.
- [11] Chaudhari R. Characterization of high-pressure resin transfer molding process variants for manufacturing high-performance composites; 2014. doi:10.24406/PUBLICA-FHG-280078.

- [12] Bodaghi M, Cristóvão C, Gomes R, Correia NC. Experimental characterization of voids in high fibre volume fraction composites processed by high injection pressure rtm. *Compos Part A: Appl Sci Manuf* 2016;82:88–99. <https://doi.org/10.1016/j.compositesa.2015.11.042>.
- [13] Imbert M. High speed reactive resin transfer moulding (rtm) process simulation for mass production of automotive structural parts. *SAE Int J Mater Manuf* 2015;8:503–15. <https://doi.org/10.4271/2015-01-0722>.
- [14] Han SH, Cho EJ, Lee HC, Jeong K, Kim SS. Study on high-speed rtm to reduce the impregnation time of carbon/epoxy composites. *Compos Struct* 2015;119:50–8. <https://doi.org/10.1016/j.compstruct.2014.08.023>.
- [15] Yoon M, Ahn M. Study on molding control factors to reduce void contents in manufacturing cfrp parts by hp-rtm. *Compos Part B: Eng* 2025;296:112231. <https://doi.org/10.1016/j.compositesb.2025.112231>.
- [16] Kundu T. Ultrasonic nondestructive evaluation. CRC Press; 2003. <https://doi.org/10.1201/9780203501962>.
- [17] Bodaghi M, Simacek P, Correia N, Advani SG. Experimental parametric study of flow-induced fiber washout during high-injection-pressure resin transfer molding. *Polym Compos* 2020;41:1053–65. <https://doi.org/10.1002/pc.25437>.
- [18] Krautkrämer J, Krautkrämer H. Ultrasonic testing of materials. Berlin, Heidelberg: Springer Berlin Heidelberg; 1990. <https://doi.org/10.1007/978-3-662-10680-8>.
- [19] Potter K, Khan B, Wisnom M, Bell T, Stevens J. Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures. *Compos Part A: Appl Sci Manuf* 2008;39:1343–54. <https://doi.org/10.1016/j.compositesa.2008.04.016>.
- [20] Hsu DK. Inspecting composites with airborne ultrasound: through thick and thin. In: AIP Conference Proceedings, AIP; 31 July–5 August 2000. p. 991–8. doi:10.1063/1.2184633.
- [21] Alves MP, Cimini Junior CA, Ha SK. Fiber waviness and its effect on the mechanical performance of fiber reinforced polymer composites: an enhanced review. *Compos Part A: Appl Sci Manuf* 2021;149:106526. <https://doi.org/10.1016/j.compositesa.2021.106526>.
- [22] Drummer J, Luplow T, Littner L, Protz R, Heimbs S, Kreutzbruck M, Gude M, Fiedler B. Influence of the position of fibre misalignment in glass fibre-reinforced polymers on mechanical properties, damage behaviour and traceability via non-destructive tests. *Compos Part C: Open Access* 2025;18:100633. <https://doi.org/10.1016/j.jcomc.2025.100633>.
- [23] Bodaghi M, Simacek P, Advani SG, Correia NC. A model for fibre washout during high injection pressure resin transfer moulding. *J Reinf Plast Compos* 2018;37:865–76. <https://doi.org/10.1177/0731684418765968>.
- [24] Zhao S, Rodgers WR, Frieberg B, Newaz G. Study of flow-induced fiber in-plane deformation during high pressure resin transfer molding. *J Compos Mater* 2021;55:2103–14. <https://doi.org/10.1177/0021998320987600>.
- [25] Kommareddy V. Air-coupled ultrasonic measurements in composites. In: AIP Conference Proceedings, AIP; 27 July–1 August 2000. p. 859–66. doi:10.1063/1.1711709.
- [26] Thor M, Mandel U, Nagler M, Maier F, Tauchner J, Sause MGR, Hinterhölzl RM. Numerical and experimental investigation of out-of-plane fiber waviness on the mechanical properties of composite materials. *Int J Mater Form* 2021;14:19–37. <https://doi.org/10.1007/s12289-020-01540-5>.
- [27] Quattrocchi A, Freni F, Montanini R. Air-coupled ultrasonic testing to estimate internal defects in composite panels used for boats and luxury yachts. *Int J Interact Des Manuf (IJIDeM)* 2020;14:35–41. <https://doi.org/10.1007/s12008-019-00611-5>.
- [28] Ma H, Li Y, Shen Y, Xie L, Di Wang. Effect of linear density and yarn structure on the mechanical properties of ramie fiber yarn reinforced composites. *Compos Part A: Appl Sci Manuf* 2016;87:98–108. <https://doi.org/10.1016/j.compositesa.2016.04.012>.
- [29] Luplow T, Drummer J, Protz R, Littner L, Kunze E, Heimbs S, Fiedler B, Gude M, Kreutzbruck M. Influence of multiaxial loading and temperature on the fatigue behaviour of 2d braided thick-walled composite structures. *J Compos Sci* 2025;9:481. <https://doi.org/10.3390/jcs9090481>.
- [30] Hamidi YK, Dharmavaram S, Aktas L, Altan MC. Effect of fiber content on void morphology in resin transfer molded e-glass/epoxy composites. *J Eng Mater Technol* 2009;131. <https://doi.org/10.1115/1.3030944>.
- [31] Olivero KA, Hamidi YK, Aktas L, Altan MC. Effect of preform thickness and volume fraction on injection pressure and mechanical properties of resin transfer molded composites. *J Compos Mater* 2004;38:937–57. <https://doi.org/10.1177/0021998304040562>.
- [32] Almazán-Lázaro J-A, López-Alba E, Díaz-Garrido F-A. The mechanical effect of monitoring and controlling the impregnation in the resin infusion process. *Polym Compos* 2022;43:1916–26. <https://doi.org/10.1002/jpc.26507>.
- [33] Kopparthi PK, Kundavarapu VR, Dasari VR, Pathakokila BR. Determination of flow front velocity and optimal injection pressures for better impregnation of e-glass with polyester in resin transfer mold. *Incas Bull* 2019;11: 87–98. doi:10.13111/2066-8201.2019.11.3.8.
- [34] Olivero KA, Barraza HJ, O'Rear EA, Altan MC. Effect of injection rate and post-fill cure pressure on properties of resin transfer molded disks. *J Compos Mater* 2002;36:2011–28. <https://doi.org/10.1177/0021998302036016244>.
- [35] Caba S. Qualitätsorientierte Prozessauslegung im Resin Transfer Molding. Ph.D. thesis, Universitätsverlag Ilmenau 2021. <https://doi.org/10.22032/dbr.47951>.
- [36] Protz R. Zum Einfluss von Defekten auf das dehnratenabhängige Werkstoffverhalten von Faser-Kunststoff-Verbunden Ph.D. thesis. Technische Universität Dresden, 2021.
- [37] Schillfahrt C, Fauster E, Schledjewski R. Influence of process pressures on filling behavior of tubular fabrics in bladder-assisted resin transfer molding. *Adv Manuf: Polym Compos Sci* 2017;3:148–58. <https://doi.org/10.1080/20550340.2017.1389048>.
- [38] Shen R, Liu T, Liu H, Zou X, Gong Y, Guo H. An enhanced vacuum-assisted resin transfer molding process and its pressure effect on resin infusion behavior and composite material performance. *Polymers* 2024;16. <https://doi.org/10.3390/polym16101386>.
- [39] Kedari VR, Farah BI, Hsiao K-T. Effects of vacuum pressure, inlet pressure, and mold temperature on the void content, volume fraction of polyester/e-glass fiber composites manufactured with vartm process. *J Compos Mater* 2011;45:2727–42. <https://doi.org/10.1177/0021998311415442>.
- [40] Kaynak C, Akgul E, Isitman NA. Effects of rtm mold temperature and vacuum on the mechanical properties of epoxy/glass fiber composite plates. *J Compos Mater* 2008;42:1505–21. <https://doi.org/10.1177/0021998308092204>.
- [41] Cui J, La Spina A, Fish J. Data-physics driven multiscale approach for high-pressure resin transfer molding (hp-rtm). *Comput Methods Appl Mech Eng* 2023;417:116405. <https://doi.org/10.1016/j.cma.2023.116405>.
- [42] Beom Jeong Han, Yong Chai Jeong, Churl Min Kim, Roh Won Kim, Myungchang Kang. Forming characteristics during the high-pressure resin transfer molding process for cfrp. *Advanced Composite Materials* 28 (2019) 365–382. doi:10.1080/09243046.2018.1556236.
- [43] Textile-glass-reinforced plastics – prepregs, moulding compounds and laminates – determination of the textile-glass and mineral-filler content – calculation methods, 1996.
- [44] Fibre-reinforced plastics – composites – determination of compressive properties in the in-plane direction, 2000. German version of EN ISO 14126:1999.
- [45] Häberle JG, Matthews FL. An improved technique for compression testing of unidirectional fibre-reinforced plastics; development and results. *Composites* 1994;25:849–56. [https://doi.org/10.1016/0010-4361\(94\)90290-9](https://doi.org/10.1016/0010-4361(94)90290-9).
- [46] Lee J, Soutis C. A study on the compressive strength of thick carbon fibre-epoxy laminates. *Compos Sci Technol* 2007;67:2015–26. <https://doi.org/10.1016/j.compscitech.2006.12.001>.
- [47] Chen Z, Peng L, Xiao Z. Experimental characterization and numerical simulation of voids in cfrp components processed by hp-rtm. *Materials* (Basel, Switzerland) 2022;15. <https://doi.org/10.3390/ma15155249>.