Comparison of Microwave and Thermal Oven Curing of Carbon Fibre–Epoxy Tape Segments

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1. Abstract

Carbon fibre reinforced polymer (CFRP) composites are widely used in structural applications due to their high specific stiffness and strength-to-weight ratio. However, high-throughput processing of CFRP prepreg tapes and similar products remains a challenge due to slow convective and conductive heat transfer during conventional curing, resulting in extended processing times and thermal gradients. Microwave processing offers volumetric heating using electromagnetic energy in conjunction with carbon fibre (CF) reinforcements, which has been reported to reduce cycle times and energy consumption in composite manufacturing. Its effectiveness is governed by electromagnetic field-material interactions and resin curing kinetics. This study investigates the feasibility of microwave-assisted curing of CF-epoxy tape. A comparative experimental framework was implemented against conventionally oven-cured specimens. The characterization includes quasi-in-situ infrared thermography for transient temperature field analysis, differential scanning calorimetry for assessing the degree of cure, scanning electron microscopy for inspecting microstructural features and fibre–matrix interaction, and ASTM D790 three-point bending tests for flexural response. The results indicate that microwave irradiation is associated with volumetric heating and accelerated cure progression in CF-epoxy tape systems. Mechanical testing reveals a processing-dependent flexural response, consistent with observed differences in microstructural development between curing routes. From this investigation, conclusions are drawn regarding the efficacy of microwave heating for the rapid fabrication of CF-epoxy tape products.

2. Introduction

Carbon fibre reinforced polymer (CFRP) composites are widely utilized across aerospace, automotive, and other industrial sectors due to their high specific stiffness, superior strength-to-weight ratios, and excellent fatigue resistance [1]. To meet high-volume production requirements, industrial manufacturing has shifted from manual wet lay-ups to standardized, pre-engineered intermediate products like continuous towpregs and unidirectional prepreg tapes. In these formats, fibres are precisely pre-impregnated with a polymer matrix (predominantly thermosets) under controlled manufacturing conditions, ensuring maximum load-bearing efficiency along the

primary axial direction [2]. Fabricating these semi-processed materials and similar tape products used as structural reinforcements is associated with significant thermal processing constraints when conventional heating methods are used that rely on slow convective and conductive heat transfer and therefore require extended processing times to avoid non-homogeneous temperature distribution and heat damage, resulting in limited throughput, high energy consumption, and a risk of process-induced residual stresses and mechanical deformation in the final composite components.

Direct volumetric heating offers an innovative alternative by generating thermal energy uniformly and instantaneously within the material's bulk using high-frequency electromagnetic microwaves [1], [3], [4]. Carbon fibre (CF) materials serve as efficient internal microwave susceptors, converting electromagnetic energy into heat via localized resistive Joule heating alongside resin-phase dipolar and interfacial (Maxwell-Wagner) polarization [5], [6]. This mechanism enables several advantages for composite manufacturing, including significantly accelerated reaction kinetics (cure cycle reductions by 40-60%) [7], [8], [9], improved energy efficiency (up to a 97% reduction) [3], uniform volumetric heating that mitigates residual stresses, and enhanced fibre-matrix interfacial bonding that augments mechanical performance [3], [5], [6]. Despite these benefits, microwave processing remains constrained by electromagnetic shielding effects, limited penetration depth, and arcing risks at exposed CF tips [3], [10]. Although indirect susceptive molds [7] and metamaterial matching layers [11] have been used to process complex multi-layered structures, existing studies focus on batch-processed composites cured under vacuum bagging and autoclave pressure. A key research gap remains in understanding baseline wave-material coupling and curing kinetics during fabrication of standalone intermediate formats, i.e., individual unidirectional prepreg tapes and similar products.

This study investigates the feasibility of microwave-assisted curing of CF-epoxy tape segments using an unmodified domestic microwave oven under unconsolidated conditions. Microwave-processed samples are compared with conventionally oven-cured counterparts. A multiscale characterization framework was employed, including infrared thermography for transient temperature analysis, differential scanning calorimetry (DSC) for assessing the degree of cure, scanning electron microscopy (SEM) for microstructural assessment, and three-point bending tests to evaluate flexural response. From this investigation, conclusions are drawn regarding the efficacy of microwave heating for rapid tape fabrication.

3. Experimental Procedures

3.1. Materials

The material system comprised a polyacrylonitrile-based continuous CF reinforcement phase and a bisphenol A-based epoxy system. The reinforcement was a commercial 24K CF tow (type H2550, HS Hyosung Charlotte, NC, USA) with a nominal tensile strength of 4.9 GPa, a tensile modulus of 250 GPa, and a 2% strain limit. The matrix comprised a two-part thermosetting epoxy system of EPON 826 and the amine-based curing agent EPI-CURE 9551 (Westlake Epoxies, Houston, TX, USA). When fully cross-linked, the neat epoxy exhibits a nominal glass transition

temperature of 110°C, a tensile strength of 69.9 MPa, a Young's modulus of 2.8 GPa, and a maximum elongation at break of 10.6%.

3.2. *Sample Preparation*

The epoxy matrix was blended at a 100:36 weight ratio immediately before fabrication. Continuous CF bundles were cut into segments with an approximate length of 250 mm, impregnated with 1.0 mL of the resin mixture, and then trimmed to 64 mm in length.

3.3. Curing Procedures

Composite specimens were processed using two thermal pathways to evaluate the impact of the heating mechanism on the matrix cross-linking and final material properties. Oven-cured specimens were processed in a laboratory oven (6903 Isotemp, Fisher, Waltham, MA, USA) using an 80-minute (min) isothermal stage at 80°C, followed by a 160-min stage at 121°C. Microwave curing was performed in a 2.45 GHz multimode domestic microwave applicator (NNST67KS, Panasonic, Osaka, Japan) equipped with inverter technology for continuous power delivery and improved thermal control [12]. The system featured 11 discrete power levels, ranging from P0 to P10, with a maximum output of 1.2 kW. Surface temperature evolution and spatial thermal gradients were captured in real time using an infrared camera (X8500sc, Teledyne FLIR, Wilsonville, OR, USA).

Microwave processing was compared between static (non-rotational) and dynamic (rotational) configurations, corresponding to fixed and varying exposure to the electromagnetic field within the applicator. The horizontal position of samples relative to the cavity floor was maintained using a standardized multi-tiered assembly. The dynamic configuration (Figure 1) consisted of four inverted ceramic cups that supported a glass plate positioned on the revolving turntable. For the static configuration ([13], [14]), an identical assembly was placed on the stationary cavity floor. Under both conditions, the specimens were placed in glass Petri dishes on a PTFE tape and positioned prior to the start of a test within previously mapped low-field regions to minimize arcing [12], [13], [14]. Four more microwave processing configurations were evaluated: (i) atmospheric (ambient air) or water-submerged conditions, and (ii) cavity loading with or without a 20 mL water beaker. Trials systematically varied microwave power (P0–P10), exposure duration (3 seconds (s) to 3 mins), mounting configuration (static or dynamic), environmental condition (atmospheric or water-submerged), and cavity loading (with or without water beaker) to identify a stable processing window defined by thermal repeatability, the absence of arcing, and the avoidance of thermal runaway. Glass plates and sample containers were replaced between trials to maintain consistent dielectric and thermal conditions.

4. Material Characterization

4.1. Differential Scanning Calorimetry

The degree of cure (DOC) was determined via differential scanning calorimetry (DSC) (model DSC Model 1, Mettler Toledo, Columbus, OH, USA). Specimens (5-7 mg) from microwave-cured, oven-cured, and uncured reference samples were sealed in hermetic aluminum pans and tested under a 50 mL/min dry nitrogen purge. The temperature profile comprised a 3-min

isothermal hold at 25°C, followed by a linear ramp at 10°C/min to 350°C. The DOC, α, was calculated using Equation 1:

$$\alpha = \left(1 - \frac{\Delta H_{\text{residual}}}{\Delta H_{\text{total}}}\right) \times 100\% \quad (1)$$

where $\Delta H_{\text{residual}}$ is the residual exothermic enthalpy of the cured specimen (J/g), and ΔH_{total} is the total curing enthalpy of the uncured composites (J/g). To evaluate volumetric curing uniformity, microwave-processed specimens were sectioned into five longitudinal sections for individual analysis, following the approach of Kumar and Zafar [5].

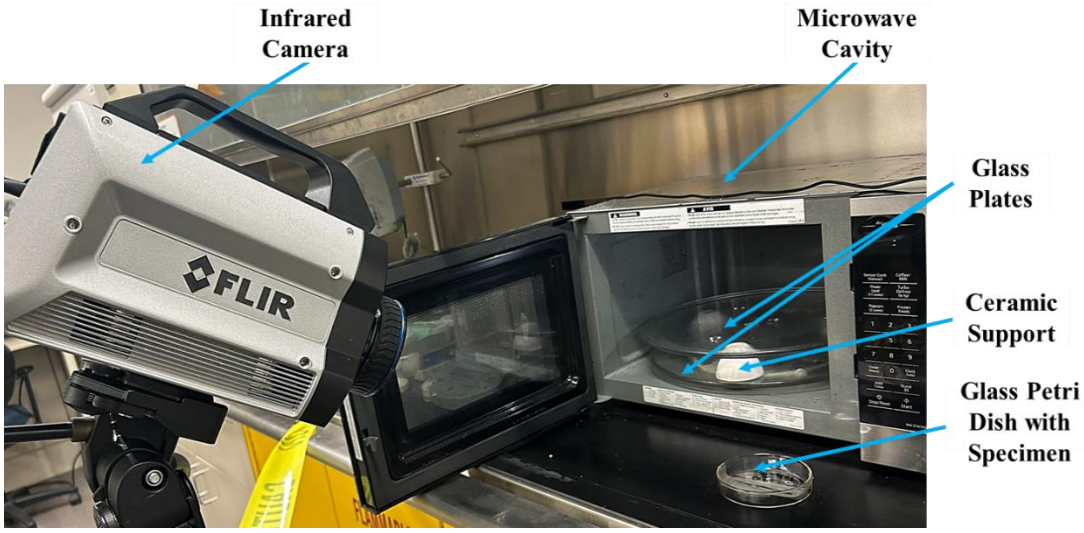

Figure 1. Dynamic (revolving turntable plate) microwave curing setup with infrared thermal imaging.

4.2. Flexural Testing

Flexural properties were evaluated via a three-point bending configuration in accordance with ASTM D790-17 [15], using a universal mechanical tester (model Mach-1 MA056-v500c Biomomentum, Laval, QC, Canada) equipped with a 250 N load cell. Deflection and crosshead speed were calculated based on coupon geometry with a 16:1 span-to-thickness ratio. Flexural strength (σ_f MPa) and flexural modulus (E_f, GPa) were calculated using Equations 2 and 3:

$$\sigma_f = \frac{3PL}{2bd^2} \quad (2)$$

$$E_f = \frac{L^3 m}{4bd^3} \quad (3)$$

where P is the maximum load (N), L is the support span length (mm), b is the specimen width (mm), d is the specimen depth (mm), and m is the slope of the tangent to the initial linear portion of the load-deflection curve. Six replicates were tested per condition for statistical reliability.

4.3. Scanning Electron Microscopy

Microstructural morphology and fibre-matrix interfacial bonding were evaluated via scanning electron microscopy (SEM) (Zeiss Sigma FESEM, Oberkochen, Germany). Specimens (10 mm

by 10 mm) were sectioned from the post-flexural fracture zones to inspect damage mechanisms. Samples were mounted on aluminum stubs with conductive carbon adhesive and sputter-coated with a 16-nm gold layer to minimize surface charging. Imaging was performed at an accelerating voltage of 5 kV using an in-lens detector at magnifications ranging from 500× to 5000×.

5. Results and Discussion

5.1. Microwave Processing Behavior and Specimen Morphology

The behavior during microwave heating exhibited strong sensitivity to the processing conditions. High-power exposure (P8-P10) led to immediate arcing and rapid temperature excursions within seconds, whereas intermediate power levels (P6) yielded fewer sparks, particularly when a 20 mL water-filled beaker was used as a cavity load, suggesting improved field stability [16]. Infrared thermography revealed pronounced configuration-dependent heating behavior. Under static atmospheric condition at P6 (40 s exposure), the specimen reached approximately 87°C. Conversely, under static water-submerged conditions at P6, heating was suppressed, reaching ~36°C after 150 s and ~105°C after 3 min microwave exposure. This highlights the high-loss dielectric nature of water, which increases electromagnetic attenuation and reduces penetration depth [12], dissipating the incident energy into the surrounding medium (water) rather than converting it into volumetric heating within the composite. Under dynamic atmospheric processing at P6 (40 s exposure), the specimen exhibited rapid and repeatable heating, reaching 265 ± 22°C, indicating highly efficient microwave-material interaction and volumetric heating of the CF [8], as observed in Figures 2 (A) and (B). Consequently, the dynamic atmospheric configuration at P6 for 40 s was selected for specimen fabrication and evaluation.

Post-curing examination revealed distinct morphological differences between processing routes, see Figure 2 (C). Oven-cured specimens exhibited a flat, uniform surface, characteristic of gradual thermal curing and controlled degassing. In contrast, microwave-cured specimens displayed a domed, uneven surface profile, which appears consistent with rapid cure kinetics that cause restricted resin flow, gas formation and/or gas expansion, and increased porosity/void content [8].

5.2. Degree of Cure from Differential Scanning Calorimetry

DSC evaluated microwave curing efficacy by quantifying the residual reactivity of the epoxy matrix. This is critical because the final cross-linking density of the matrix directly governs the structural integrity and interfacial bonding of the CF-reinforced composite [4]. The comparative thermograms in Figure 3 (A) show a broad exothermic peak for the uncured resin, representing the total available polymerization enthalpy. In contrast, both microwave- and oven-cured specimens exhibited negligible residual exothermic heat flow, indicating near-complete polymerization. Thus, microwave curing achieved a DOC comparable to the 100% cure achieved by conventional oven curing within a drastically compressed 40 s cure cycle. This represents a 99.8% reduction in processing time compared to the 240 min required for the oven-cured samples.

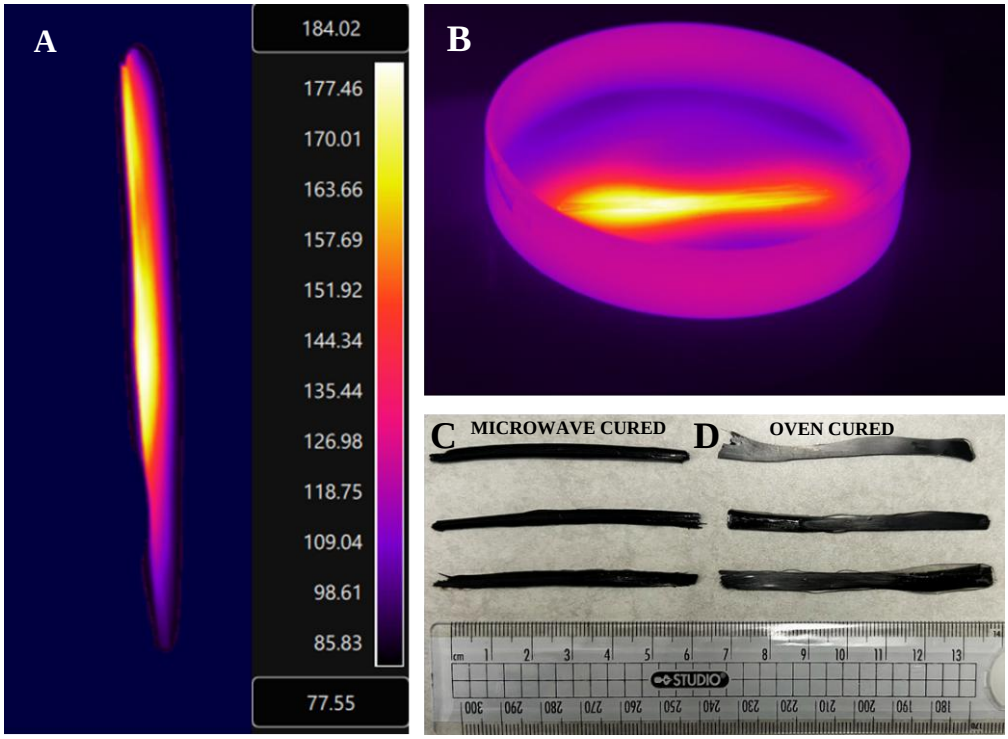

Figure 2. Thermal and macroscopic characterization of CFRP specimens: infrared thermograms of microwave curing profile after (a) 1 min and (b) 3 min of exposure; post-cure macroscopic surface morphology of (c) microwave-and (d) oven-cured samples.

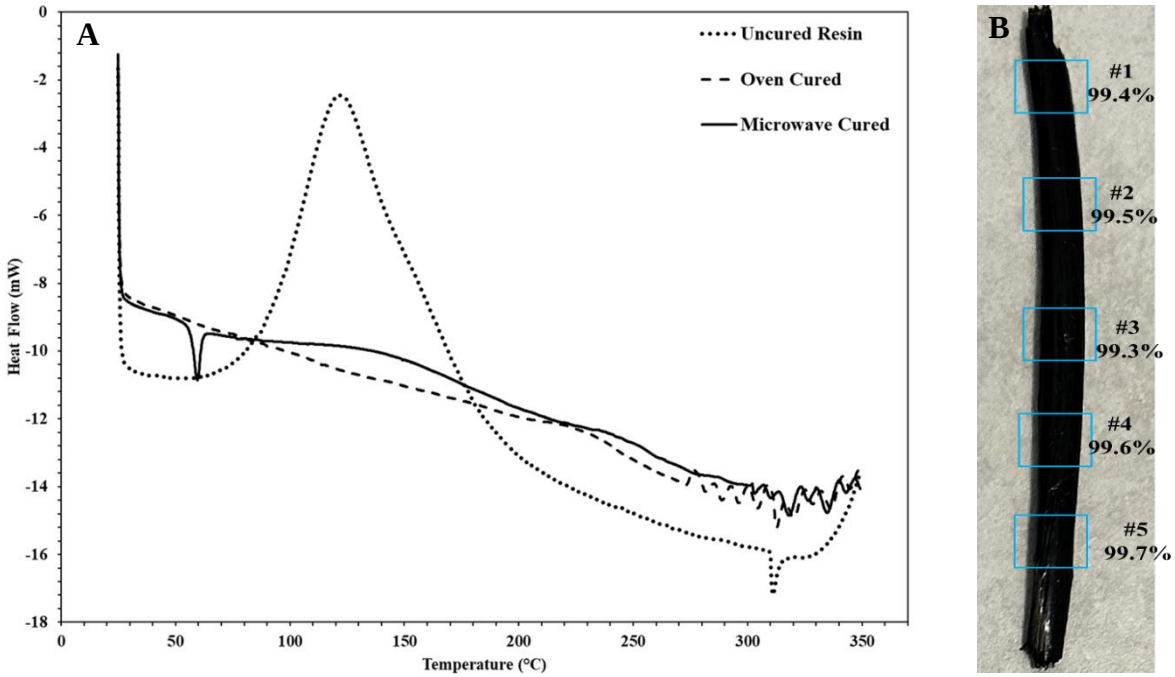

Figure 3. DSC characterization of CFRP specimens: (a) thermograms of uncured, microwave-cured, and oven-cured samples; (b) longitudinal sampling locations and corresponding DOC values for the microwave-cured specimen.

The observed processing efficacy is attributed to several mechanisms: volumetric heating for synchronous energy absorption throughout the material thickness [5]; matrix dipole polarization

that enhances molecular mobility under the alternating electromagnetic field [4]; and localized heating from the CF acting as internal susceptors to accelerate cross-linking at the fibre-matrix interface [6], [8]. Figure 3 (B) shows the longitudinal sampling locations and corresponding DOC values across five sections of a microwave-cured specimen. Quantitatively, these specimens achieved a mean DOC of 99.5% ± 0.13%. This high uniformity suggests that the microwave-assisted processing configuration effectively minimized spatial curing variability, likely due to the combined influence of dynamic specimen rotation [4], continuous inverter-based power delivery [12], and volumetric microwave heating within the thin CFRP tape geometry [4].

5.3. Flexural Performance and Failure Behavior

Three-point bending tests conducted using the mechanical tester (Figure 4 (A)) evaluated the flexural response of microwave- and oven-cured specimens. Microwave-cured samples exhibited an average flexural strength of 299.64 ± 62.59 MPa and a flexural modulus of 22.59 ± 4.91 GPa, whereas oven-cured specimens showed higher values of 507.29 ± 82.32 MPa and 28.29 ± 5.14 GPa, respectively. In terms of failure behavior, microwave-cured specimens exhibited localized compressive indentation beneath the loading nose without global fracture (Figures 4 (B) and (C)), whereas oven-cured specimens failed by brittle fracture with complete separation (Figure 4 (D)). This behavior indicates that load transfer in microwave samples was dominated by localized contact stresses rather than a uniform global bending stress state, restricting the contribution of the full beam cross-section to bending resistance.

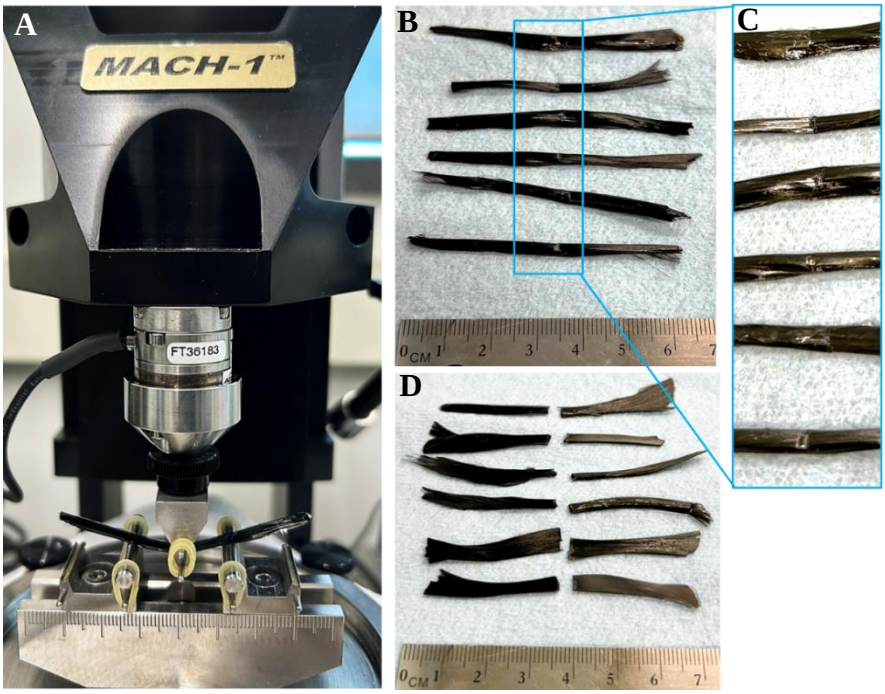

Figure 4. Flexural behavior of CFRP specimens: (A) three-point bending test setup; (B) microwave-cured specimens after testing; (C) localized compressive indentation in microwave-cured specimens; and (D) brittle fracture in oven-cured specimens.

Since DSC results indicated a comparable degree of cure (Section 5.2), the reduced flexural performance of the microwave-cured specimens is more likely attributable to microstructural and morphological differences arising during processing. The domed morphology observed in Section

5.1 suggests that the rapid 40-s microwave cycle may have restricted resin flow and volatile removal prior to gelation, inducing localized structural discontinuities [9], [10], and through-thickness heterogeneities in fibre packing and matrix distribution [5], [9] under the present unconsolidated conditions. These processing-induced defects can reduce load-bearing continuity [5] and contribute to the observed stress localization and compressive indentation-dominated failure. Conversely, the 240 min oven-curing cycle likely enabled gradual removal of volatiles and structural equilibration, yielding a more uniform load-bearing structure [16] capable of sustaining global bending stresses prior to fracture. Overall, these results suggest that while microwave curing rapidly achieves a high DOC, the mechanical response remains sensitive to processing-induced structural variations that may develop during rapid, unconstrained curing.

5.4. Microstructural Analysis of Fractured Specimens

SEM was used to examine post-flexural fracture surface morphology and fibre-matrix interfacial characteristics of microwave- and oven-cured CFRP specimens, see Figure 5.

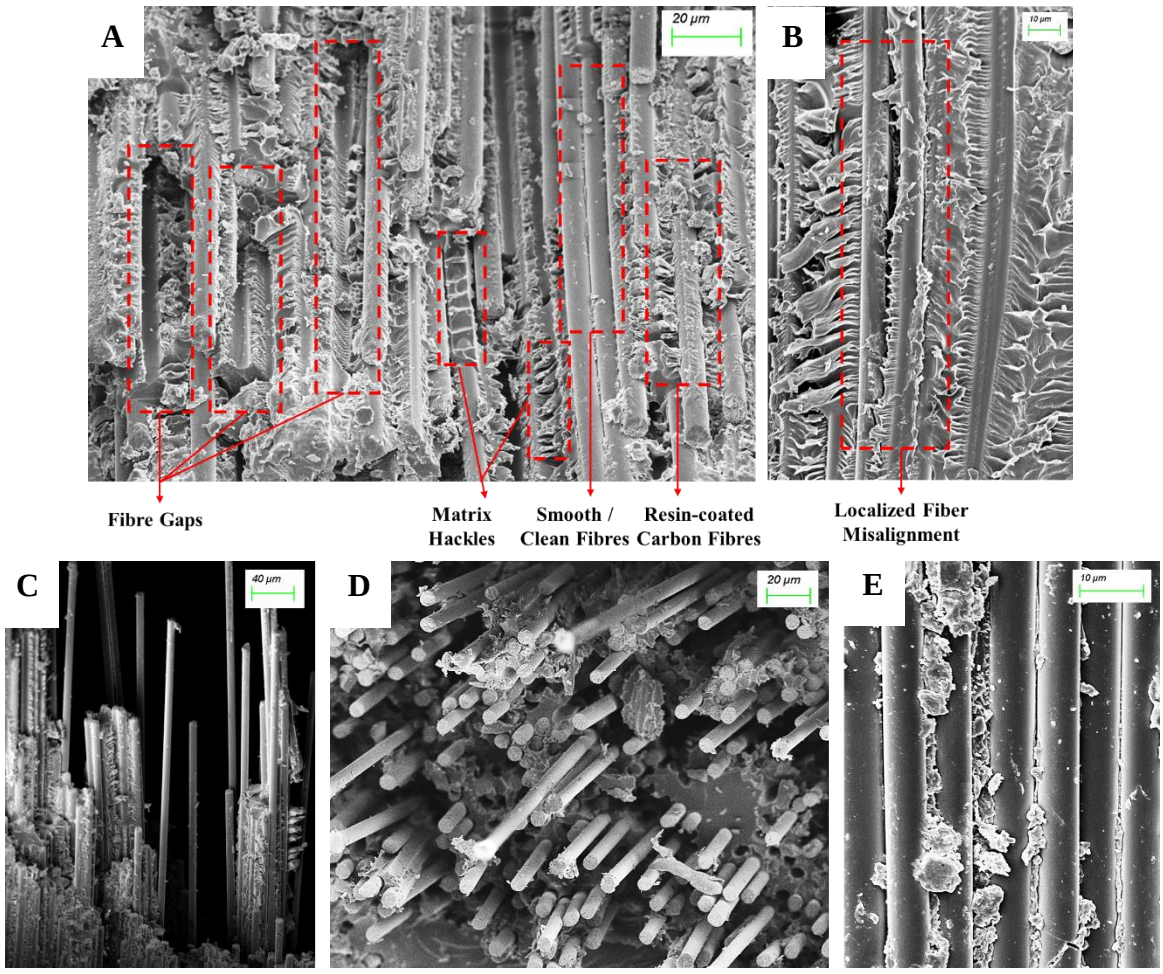

Figure 5. SEM fractographs: (A, B) microwave-cured specimens showing mixed cohesive/interfacial failure and localized discontinuities; (C–E) oven-cured specimens showing a more uniform fracture morphology and clean fibre surfaces.

Microwave-cured specimens exhibited heterogeneous fracture surfaces (Figures 5 (A) and (B)) characterized by the coexistence of resin-coated fibres (cohesive failure [6]), exposed smooth

fibres (interfacial debonding [10]), matrix hackle regions, fibre gaps, and local fibre misalignment. These discontinuities indicate restricted resin flow and incomplete fibre wetting prior to gelation during the rapid 40 s microwave cycle under unconstrained conditions [10], resulting in non-uniform load transfer and localized stress concentrations, consistent with indentation-dominated flexural failure, as seen in Section 5.3. In contrast, oven-cured specimens exhibited predominantly smooth fibre surfaces with limited resin adherence (Figures 5(C)-(E)), consistent with adhesive-dominated interfacial failure [6], [10], and may explain the associated brittle fracture observed in flexural testing [10]. The fracture morphology exhibited a more uniform and continuous fibre architecture with no observable fibre gaps, likely due to improved resin flow, gradual degassing, removal of volatiles, and structural equilibration prior to complete crosslinking during the prolonged 240-min curing cycle, yielding a uniform load distribution (Section 5.3). Ultimately, since DSC results confirmed comparable degrees of cure (Section 5.2), the observed mechanical differences (Section 5.3) can be attributed to processing-induced microstructural heterogeneity rather than chemical conversion differences.

6. Conclusion

This study demonstrates the feasibility of microwave-assisted curing of CF-epoxy tape segments under unconsolidated conditions. The microwave curing process achieved a degree of cure comparable to conventional oven curing (99.5% ± 0.13%) while reducing the curing cycle to 40 seconds, compared with 240 minutes for the oven-cured control, representing a 99.8% reduction in processing time. Infrared thermography further indicated a volumetric heating response under microwave exposure, consistent with internal electromagnetic energy absorption within the CF-epoxy system. However, despite comparable chemical conversion, the two processing routes exhibited distinct mechanical responses under flexural loading. Oven-cured specimens demonstrated higher flexural strength and modulus with brittle fracture, whereas microwave-cured specimens showed reduced flexural performance and localized indentation-dominated failure. These differences indicate that mechanical response is governed not solely by the degree of cure but also by processing-induced structural development under the applied curing conditions. Microstructural characterization supports this interpretation, suggesting that rapid microwave curing under unconsolidated conditions yields a heterogeneous fibre-matrix morphology compared with the more uniform structure observed during extended conventional thermal curing. Overall, the results indicate that while microwave curing offers substantial reductions in processing time, improved control of microstructural evolution is required to achieve mechanical equivalence with conventional thermal processing routes.

7. References

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