International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Research Paper

Cite this article: Alekajbaf Y, Murali S, Dancila D (2024). Energy efficient microwave curing of carbon fiber reinforced polymer via metamaterial matching and advanced electromagnetic exposure control. *International Journal of Microwave and Wireless Technologies* 1–7. https://doi.org/10.1017/S1759078724000072

Received: 25 August 2023
Revised: 11 December 2023
Accepted: 31 December 2023

Keywords:
carbon fiber; material processing; microwave curing; microwave processing; reinforced polymer

Corresponding author: Dragos Dancila; Email: dragos.dancila@angstrom.uu.se

CAMBRIDGE UNIVERSITY PRESS

Energy efficient microwave curing of carbon fiber reinforced polymer via metamaterial matching and advanced electromagnetic exposure control

Yasin Alekajbaf[1], Suraj Murali[2] and Dragos Dancila[1,2,3]

[1]FREIA, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden; [2]Percy Roc AB, Uppsala, Sweden and [3]Microwave Group, Department of Electrical Engineering, Uppsala University, Uppsala, Sweden

Abstract

This study proposed an effective and sustainable technique for the curing of carbon fiber reinforced polymers (CFRPs) using microwaves. The method involves applying a metallic resonance coating layer to envelop the CFRP composite's surface. Next, the composite is positioned within a multi-mode cavity, which is used as an applicator, and is powered by four 250 W solid-state power amplifiers. To ensure precise control over the heating pattern and achieve uniform heating of the composite, a sophisticated control algorithm is developed. This algorithm can independently regulate the phase, power level, and frequency of each power amplifier. The experimental results confirm the effectiveness of this proposed approach in achieving precise control over the microwave-based curing process for CFRPs.

Introduction

Carbon fiber reinforced polymer (CFRP) composites are of significant importance in industries such as aerospace, wind power, marine, and automotive due to their remarkable mechanical properties, lightweight composition, and corrosion resistance. An earlier version of this paper was presented at the SMWD 2023 Conference [1]. Traditional curing methods for CFRP, including conduction heating and oven curing, suffer from notable disadvantages such as excessive energy consumption, lengthy processing periods, and restricted scalability [2–5]. To overcome these challenges, researchers have proposed microwave-based curing processes as a promising solution with the potential to significantly reduce processing times and energy consumption. Microwave curing exhibits several advantages, including direct volume heating, rapid and selective propagation, and uniform heat distribution [6–8]. Therefore, this method can cure composites with higher quality and more efficiency compared to conventional curing methods [7, 9]. Different applicators, such as waveguides and cavities, distribute the microwaves in various patterns. The dielectric properties of a material, such as the dielectric constant and loss factor, determine its ability to absorb microwaves. However, CFRP, being a highly reflective material, impedes efficient microwave absorption. The high dielectric loss factor of CFRP causes it to behave as a reflector in the electromagnetic field. This property, along with its low penetration depth, renders microwave curing alone inefficient for CFRP [9–13]. The curing process plays a pivotal role in the manufacturing of CFRP composites, as it directly influences the material's final properties. However, the current curing methods, which are mainly carried out in ovens or autoclaves using conductive heating, suffer from imprecise temperature control and can frequently result in part distortion. Furthermore, these methods are often inefficient in terms of both processing time and energy consumption. In recent years, microwave heating has emerged as a promising alternative, offering advantages such as rapid propagation and heating speeds, volumetric heating properties, and the potential to produce high-quality, efficiently processed composite products [5]. Microwave curing offers a promising solution because of its controllability and low energy consumption [14]. However, the widespread adoption of microwave curing for CFRP composites has been limited. The challenge lies in the use of multidirectional CFRP laminates, which are extensively employed in aerospace components. These cannot be directly heated by microwaves due to the shielding effect caused by interlaced electro-conductive carbon fibers. Alternative approaches, such as indirect methods of microwave heating using sensitive mediums or susceptive molds, have been investigated. Nonetheless, these methods have their own limitations in terms of efficiency and flexibility [6, 11, 14]. Various curing methods have been explored to tackle the challenges associated with microwave-based CFRP curing. One approach involves the development of hexagonal, octagonal, and heptagonal cavity designs, aimed at reducing temperature gradients and shortening curing time [15–17]. Additionally, efforts have been made to indirectly heat multidirectional CFRP laminates by employing a lossy medium placed on the composite. However, this method has drawbacks, such as diminishing process efficiency and restricting temperature ramp-up rates [18]. Another viable solution incorporates the use of patch resonators as a matching layer to improve power coupling with the composite. This method has shown success in curing multidirectional CFRPs with specific lay-up configurations, generating a vertical electric field within the CFRP. Consequently, coating the CFRP with this absorber layer has proved to be an effective solution to counter the uneven heating caused by the tendency of carbon fibers to absorb microwaves [9, 12, 13]. Nevertheless, further enhancements are necessary to optimize power coupling efficiency. Therefore, microwave-based curing processes hold significant potential for reducing processing times and energy consumption during the curing of CFRP composites. However, there are still challenges to address, including issues related to uneven heating and limited microwave absorption caused by carbon fibers. Overcoming these obstacles will be crucial to fully harnessing the benefits of microwave curing for CFRP composites. In this paper, we introduce an efficient and sustainable system for the microwave curing of CFRP. In the presented solution, an array of metamaterial patches is employed as a layer of resonators to coat the CFRP and increase its absorption during the curing process. The coated CFRP component is placed in a multi-mode cavity, and the curing process is controlled using an advanced algorithm to achieve a homogeneous thermal distribution.

Microwave-based CFRP curing

Microwave heating is a developing technique for curing CFRP composites, offering several benefits and addressing certain limitations of conventional curing methods. One important parameter for successful microwave heating is the dielectric properties of the CFRP material, including the dielectric constant and loss factor, which determine its ability to absorb microwaves. The benefits of microwave heating for CFRP curing include reduced processing times, energy savings, improved control over temperature distribution, and the ability to switch the curing reaction on and off. The controllability of microwave heating enables uniform volumetric processing, which can lead to improved mechanical properties of cured composites. Additionally, microwave heating offers the potential for scalability and faster production rates. However, there are some limitations to consider, such as equipment issues, high costs of microwave systems, potential lack of penetration in thick laminates, non-uniform curing, void formation, and safety concerns [14]. The main challenges of microwave-based CFRP curing are non-uniform heating and weak microwave absorption issues, stemming from complex interactions between microwave radiation and the conductive nature of the carbon fiber material. As a result, based on previous research, using a multi-mode microwave cavity can provide a more uniform distribution of microwave energy, thereby reducing the occurrence of hot spots and improving overall heating uniformity [19]. Additionally, incorporating microwave susceptors into the CFRP composite, such as metamaterial components and patch resonators that enhance microwave absorption, can increase the efficiency of the curing process. This can be achieved by combining microwave and conduction heating methods [9, 12, 13]. Based on previous research and the approaches discussed, we propose an effective hybrid method to achieve homogeneous heating in CFRP curing. In this method, the CFRP composite is coated with dielectric epoxy, and small resonator parts are strategically placed on it. The coated CFRP is then placed in a multi-mode cavity. Additionally, to achieve a high-performance solution for CFRP curing and optimize homogeneity in this process, a control loop is implemented in the proposed system.

The proposed microwave based CFRP curing system

The proposed system employed to cure CFRP in this paper consists of four main components: the coated CFRP material as the desired sample for microwave curing; a multi-mode cavity as

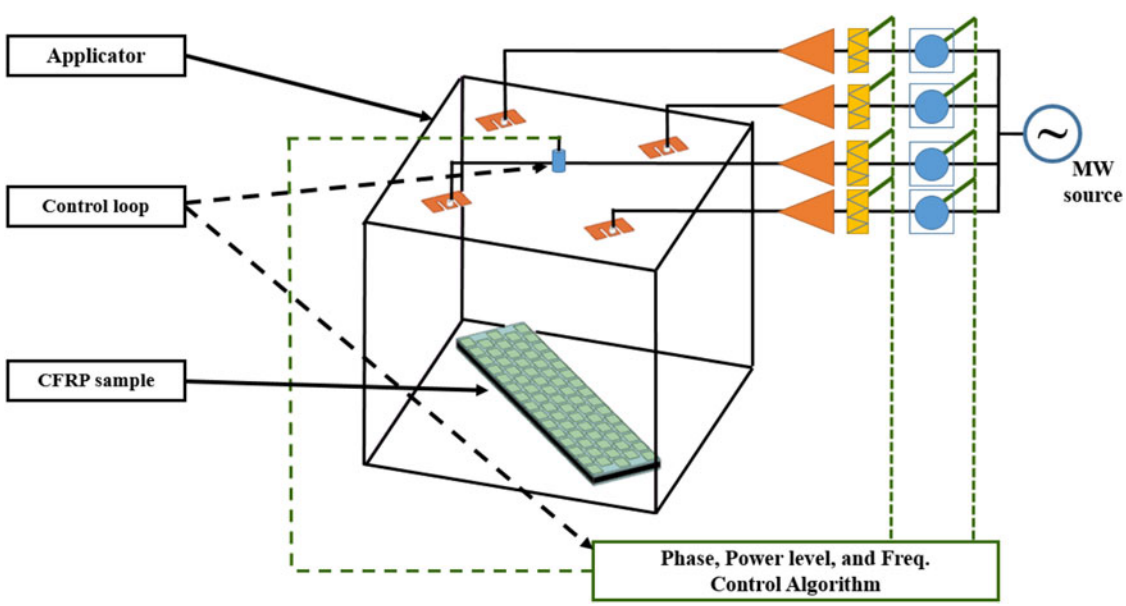

Figure 1. Implemented system for microwave-based CFRP curing, including the coated CFRP composite with the resonance patches, applicator, MW sources, and phase and frequency control.

the applicator; microwave sources to heat the CFRP; and a control and monitoring loop to manage the E-field inside the cavity and achieve optimized heat distribution in the CFRP. Figure 1 illustrates the implemented system for curing CFRP, developed based on the method described in this paper.

CFRP composite

Carbon fiber reinforced polymer is a composite material that combines carbon fibers with a polymer matrix, usually epoxy resin. Characterizing CFRP is crucial for designing a microwave-based curing system, as it poses a fundamental challenge. The CFRP composite is composed of multiple layers of carbon fibers, which can be oriented in different directions and are impregnated with epoxy. These layers are stacked together, and after the curing process, the desired mechanical strength of CFRP is achieved. Therefore, to implement the curing stage using microwaves, it is essential to understand the electromagnetic behavior and properties of CFRP. Unlike homogeneous materials, CFRP exhibits complex electromagnetic properties due to its intricate microstructure. The electrical characteristics of CFRP heavily depend on its orientation and lamination. The fundamental structure of multilayer composites includes unidirectional layers. In this type of CFRP, maximum stiffness and strength are achieved in the direction of the carbon fibers. Another commonly used lamination in CFRP composites is the multi-directional layer which offers strength in all directions [20]. For this study, we utilized HexPly® 8552 (AS4 fiber) woven carbon preform with a 55% fiber volume. The selected CFRP composite consists of four layers of carbon fiber with a total thickness of 2.8 mm. This CFRP composite is shown in Fig. 2. Understanding the permittivity characteristics of CFRP is essential for detailed design and analysis of its electromagnetic behavior using simulation software. This understanding also aids in quality control and ensures consistent and reliable curing of CFRP. However, measuring the permittivity of CFRP is complex due to its composite nature, where carbon fibers are embedded in a polymer matrix. As a result, various methods have been proposed to determine the permeability of complex materials like CFRP [20]. In the CFRP simulations presented in this article, we used the HFSS software and utilized the model provided in the Ansys Granta library, optimizing the values to fit our specific example. Based on this model, another vital parameter to consider in CFRP curing is the conductivity of the material.

Microwave source

As mentioned earlier, the designed system illustrated in Fig. 1 utilizes four separate ports for curing CFRP. Each port is connected to an E-shaped antenna and powered by a 250 W continuous-wave solid-state power amplifier, operating in the frequency range of 2.3–2.7 GHz. This wide frequency range provides the flexibility to adjust the frequency for each port independently, enabling control over the field distribution in the applicator. Additionally, a phase shifter is incorporated at the output of each amplifier, allowing for phase manipulation to engineer the distribution of the electric field inside the applicator. By leveraging these capabilities and employing an optimized control algorithm, it becomes possible to fine-tune the frequency and phase of the electromagnetic wave irradiated inside the material. This allows for an optimized distribution of the electromagnetic field, ensuring homogeneous absorption in the carbon.

Figure 2. Sample of a cured weave sample under test.

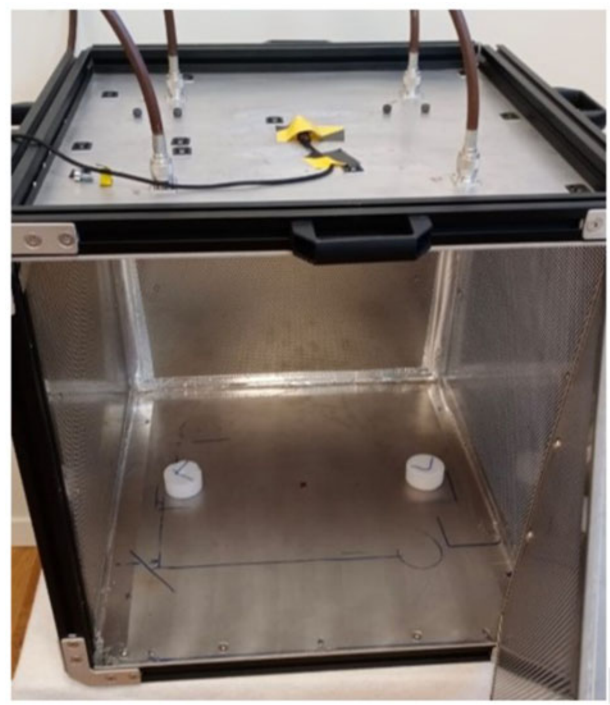

Figure 3. Fabricated multi-mode cavity as applicator.

Exposure chamber

In the heating system presented in Fig. 1, a multi-mode cavity is used as a heating chamber at 2.45 GHz, with dimensions of $500 \times 500 \times 500\ \mathrm{mm}^8$. To propagate electromagnetic waves inside the chamber, four E-shaped antennas are employed. These antennas are powered by four separate solid-state power amplifiers, serving as microwave sources. The input ports are situated in the middle of each quarter of the cavity's upper wall, as shown in Fig. 3.

As previously mentioned, the microwave power within the applicator is distributed through four E-shaped antennas, each driven by amplifiers with the ability to adjust phase, frequency, and power. Figure 4 illustrates the simulated field distribution inside the applicator at a frequency of 2.45 GHz under different phase conditions. As evident from Fig. 4, modifying the phase individually at each input port alters the electric field distribution within the applicator. Consequently, this capacity to control the distribution allows for the regulation of heat distribution, thereby facilitating homogeneous curing.

https://doi.org/10.1017/S1759078724000072 Published online by Cambridge University Press

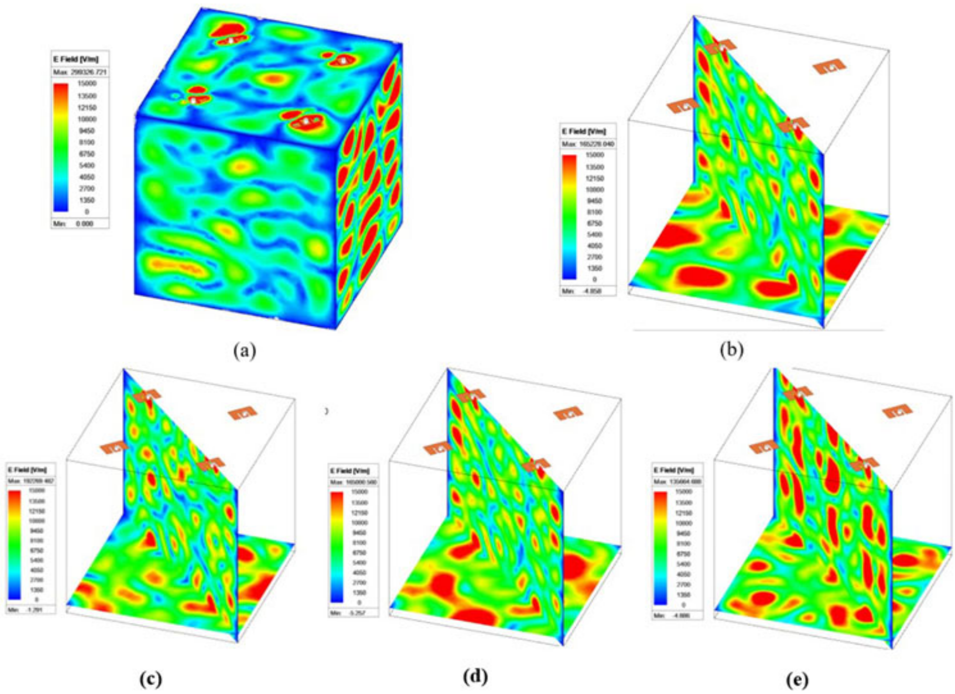

Figure 4. (a) E-field distribution in the designed multi-mode cavity which powered by four MW port with the ability to separately adjust phase and frequency, (b) E-field distribution in [0, 0, 0, 0] phase pattern, (c) [90, 0, 0, 0] , (d) [90, 0, 90, 0], (e) [0, 90, 180, 270].

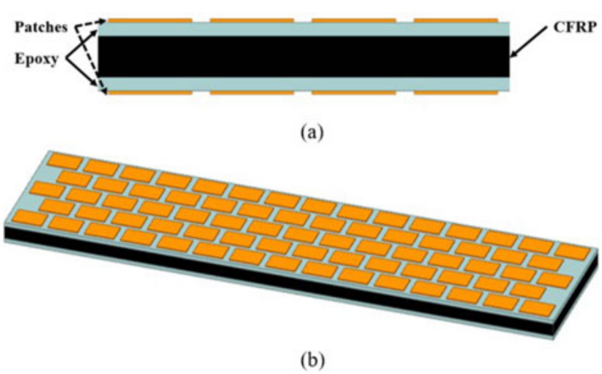

Figure 5. (a) Coated CFRP component by metamaterial patch resonators and (b) metamaterial patch resonators arrangement.

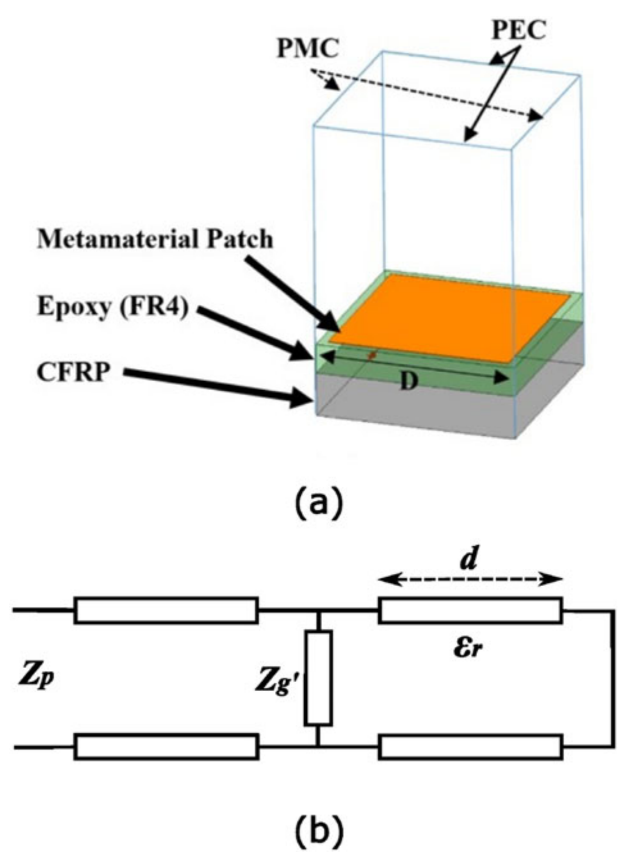

Figure 6. (a) Presented structure for CFRP covered by square patch array resonator and (b) equivalent transmission line model.

Metamaterial matching design

The main challenges of microwave-based CFRP curing are non-uniform heating and weak microwave absorption issues, stemming from complex interactions between the microwave radiation and the conductive nature of the carbon fiber material. Utilizing a multi-mode microwave cavity along with an advanced optimization control loop, as explained in previous sections, can address these challenges by providing a uniform distribution of microwave energy. This approach minimizes the occurrence of hot spots and improves overall heating uniformity. Additionally, incorporating microwave susceptors into the CFRP composite to enhance microwave absorption can further increase the efficiency of the curing process by combining microwave and conduction heating methods. Based on previous research and the approaches

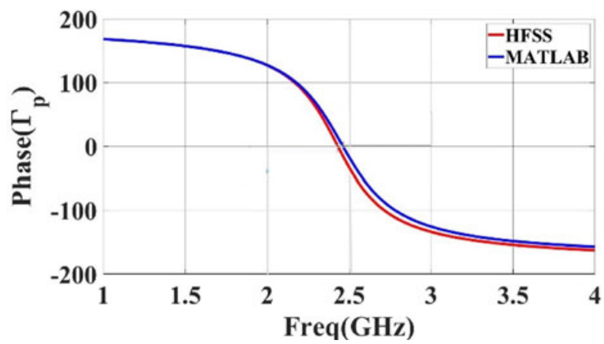

Figure 7. Comparison of the analytical model with HFSS simulations.

discussed, we propose an effective hybrid method for achieving homogeneous heating in CFRP curing. In this method, the CFRP composite is coated with dielectric epoxy, and small resonator parts are placed on it. Subsequently, the coated CFRP is placed in a controllable multi-mode cavity. Figure 5 illustrates the proposed setup for this solution.

According to the periodically structured resonators and the desired frequency, the rectangular resonance patches were designed and simulated using periodic master/slave boundary conditions in HFSS software at 2.45 GHz. As a result, the metallic patches' layer resonates at the frequency of the incident microwaves within a multi-mode controllable cavity, absorbing the electromagnetic field to produce efficient heating in the CFRP. The considered simulation structure and its equivalent transmission line model are shown in Fig. 6.

The analytical equivalent model of square patches is illustrated in Fig. 6b. The equivalent impedance of patches for different incident wave angles is calculated by (1) and (2) [12, 13]:

$$Z^{TE}_{P,\mathrm{inp}} = \frac{j\omega\mu\tan(\beta d)}{\beta}\left(\frac{1}{1-\frac{2k_{\mathrm{eff}}\alpha\tan(\beta d)}{\beta\left(1-\frac{1}{\varepsilon_{r+1}}\sin^2\theta\right)}}\right)V_s f_0, \qquad (1)$$

$$\alpha = \frac{K_{\mathrm{eff}}D}{\pi}\ln\left(\frac{1}{\sin\frac{\pi\omega}{2D}}\right), \qquad (2)$$

where θ is the angle of incidence and k, D, and d, are the wave number, patch width, and dielectric height, respectively. A comparison of the analytical model with HFSS simulations is shown in Fig. 7, with the patches' dimensions: $D = 22.6$ mm, w (patches space) $= 2$ mm, $d = 4$ mm, ε_r (dielectric constant) $= 4.4$ (FR4).

Due to the dependence of the analytical model on the incident wave angle, in a multi-mode cavity, not all patches resonate at the same frequency. Therefore, their absorption rate will be different.

Optimization control unit

Based on the ability to change the frequency and phase, as provided by the power amplifiers, a control loop has been developed to optimize the distribution of the electromagnetic field, consequently achieving homogeneous heat distribution in the carbon fibers. To monitor the carbon fiber baking process, an IR sensor has been utilized for temperature measurement and thermal imaging of the CFRP surface. The control loop manipulates these settings based on the observed feedback. The feedback signal is generated by an infrared (IR) camera placed directly over the target CFRP material. This IR camera records the heating pattern of the CFRP that results from the applied signals. It is important to note the complexity of this feedback loop, which goes far beyond common SISO feedback loops commonly used in mechanical systems, requiring advanced methods of AI. In this way, the overall system is controlled according to the desired heating pattern.

Simulation and experimental results

Thermal characterization

The proposed setup in Fig. 1 is simulated using HFSS and Icepack software to investigate the electromagnetic and thermal behavior, respectively. The simulated heat distribution on the CFRP surface is illustrated in Fig. 8a for several different phase and frequency conditions in the frequency range of 2.4–2.7 GHz. Additionally, the

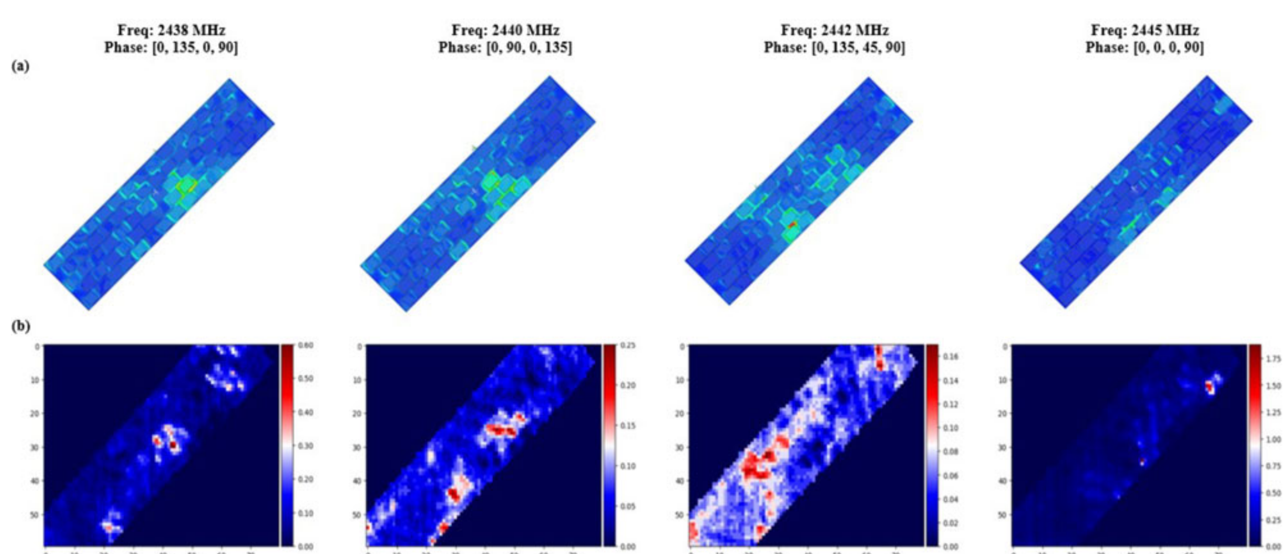

Figure 8. Heat distribution in surface of CFRP: (a) simulation results and (b) experimental results (captured using an optical sensor).

https://doi.org/10.1017/S1759078724000072 Published online by Cambridge University Press

Table 1. Samples of cured CFRPs for studying mechanical properties

Sample	Process	Duration	Temp. (°C)
Sample 1	Microwave	20 min	>>140
Sample 2	Microwave	30 min	180
Sample 3	Microwave	30 min	>>180
Sample 4	Microwave	60 min	>>160
Sample Ref	Oven	2 h at 180°kC	180

Figure 9. Experimental ASTM D790 standard test setup.

experimental results of the presented system under the same phase and frequency conditions are tested in the experimental environment and are shown in Fig. 8b. These results offer a comprehensive view of the effectiveness of the proposed approach. Furthermore, based on the simulation and experimental findings, it can be observed that the development of a control algorithm for phase and frequency at each port could be instrumental in achieving more homogeneous heating in CFRP composites. As seen in the experimental results, the outstanding wave optional distribution in the chamber and its absorption by the patches allows the implementation of the optimal algorithm to achieve a homogeneous process.

Mechanical characterization

In this section, the effects of microwave curing methods with various curing cycles on the mechanical properties of unidirectional CFRPs are evaluated and compared with a CFRP composite cured using a conventional oven as the reference (as Table 1). The stress and strain are two important parameters to investigate mechanical behavior of materials and were calculated according to the ASTM D790 standard (Fig. 9).

Table 2. Calculated mechanical properties of cured CFRP samples

	Max stress (MPa)	Max strain (%)	Young's Modulus (GPa)
Sample 1	1592	1.78	82
Sample 2	1452	1.82	77
Sample 3	1481	1.8	76
Sample 4	1666	1.77	84
Sample Ref	1662	1.93	75

From the obtained stress–strain curves, we extracted the following results: max stress (the point at which the first significant damage occurred and the specimen lost structural integrity), max strain (the strain corresponding to the max stress), and Young's Modulus as the material's stiffness (the slope of the stress–strain curve). The averages of these values for all materials are compared in Table 2. According to Table 2, the highest max stress was observed in both the oven-cured and 60-min microwave-cured composites, with minimal differences compared to others. The oven-cured composite displayed the highest strain at failure but also exhibited the lowest stiffness.

Conclusion

In conclusion, this study has presented a novel, effective, and sustainable approach for the curing of CFRPs using microwaves. By incorporating a metallic resonance coating layer and positioning the coated CFRP within a specifically engineered multi-mode cavity, the method allows for a precise and uniform heating pattern. The development and implementation of a sophisticated control algorithm, which independently regulates the phase, power level, and frequency of each power amplifier, further enhance the method's effectiveness. Experimental results corroborate the efficiency of this innovative technique in achieving meticulous control over the microwave-based curing process for CFRP. The implications of these findings may extend to various industrial applications, offering a promising pathway for enhancing the manufacturing and processing of CFRP with significant potential in both economic and environmental sustainability.

Acknowledgements. The authors would like to thank their colleagues in the FREIA Laboratory, Uppsala University, Uppsala, Sweden, for their assistance and support.

Competing interests. The authors report no conflict of interest.

References

1. **Alekajbaf Y, Murali S and Dancila D** (2023) Efficient and sustainable CFRP manufacturing through microwave-based curing for advanced control exposure optimization. Swedish Microwave Days, 2023, Stockholm, Sweden.
2. **Park SJ** (2015) *Springer Series in Materials Science* **210**, 275–317.
3. **Fitzer E** (1989) Pan-based carbon fibers—present state and trend of the technology from the viewpoint of possibilities and limits to influence and to control the fiber properties by the process parameters. *Carbon* **27**(5), 621–6455.
4. **Kim KW, Kim DK, Kim BS, An KH, Park SJ, Rhee KY and Kim BJ** (2017) Cure behaviors and mechanical properties of carbon fiber-reinforced nylon6/epoxy blended matrix composites. *Composites Part B: Engineering* **112**, 15–21.

5. **Kumar R and S Zafar** (2023) Comparative study of microwave and thermal curing processes in terms of temperature characteristics and mechanical performance of carbon fibre composites. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*.
6. **Mgbemena CO, Li D, Lin MF, Liddel PD, Katnam KB, Thakur VK and Yazdani Nezhad H** (2018) Accelerated microwave curing of fibre-reinforced thermoset polymer composites for structural applications: a review of scientific challenges. *Composites Part A: Applied Science and Manufacturing* **115**, 88–103.
7. **Galos J** (2021) Microwave processing of carbon fibre polymer composites: a review. *Polymers and Polymer Composites* **29**(6), 151–162.
8. **Thostenson ET and Chou T-W** (1999) Microwave processing: fundamentals and applications. *Composites Part A: Applied Science and Manufacturing* **30**(9), 1055–1071.
9. **Zhou J, Li Y, Zhu Z, Xu E, Li S and Sui S** (2022) Microwave heating and curing of metal-like CFRP laminates through ultrathin and flexible resonance structures. *Composites Science and Technology* **218**(August), 109200.
10. **Abliz D, Duan Y, Steuernagel L, Xie L, Li D and Ziegmann G** (2013) Curing methods for advanced polymer composites – a review. *Polymers and Polymer Composites* **21**(6), 341–348.
11. **Zhou J, Li Y, Cheng L and Hao X** (2018) Dielectric properties of continuous fiber reinforced polymer composites: Modeling, validation, and application. *Polymer Composites* **39**, 4646–4655.
12. **Luukkonen O, Simovski C, Granet G, Goussetis G, Lioubtchenko D, Raisanen AV and Tretyakov SA** (2008) Simple and accurate analytical model of planar grids and high-impedance surfaces comprising metal strips or patches. *IEEE Transactions on Antennas and Propagation* **56**(6), 1624–1632.
13. **Luukkonen O, Costa F, Simovski CR, Monorchio A and Tretyakov SA** (2009) A thin electromagnetic absorber for wide incidence angles and both polarizations. *IEEE Transactions on Antennas and Propagation* **57**(10), 3119–3125.
14. **Li N, Li Y, Jelonnek J, Link G and Gao J** (2017) A new process control method for microwave curing of carbon fibre reinforced composites in aerospace applications. *Composites Part B: Engineering* **122**, 61–70.
15. **Nuhiji B, Bower MP, Swait T, Phadnis V, Day RJ and Scaife RJ** (2021) Simulation of carbon fibre composites in an industrial microwave. *Materials Today: Proceedings* **34**(1), 82–92.
16. **Ahn SH, Jeong CH, Lim DM and Lee WS** (2020) Kilowatt-level power-controlled microwave applicator with multiple slotted waveguides for improving heating uniformity. *IEEE Transactions on Microwave Theory and Techniques* **68**(7), 2867–2875.
17. **Chen J, Guo S, Chen K, Zhao G, Zhu X, Hou M and Jiang G** (2023) Microwave curing carbon fiber composites automobile rearview mirror. *Arabian Journal of Chemistry* **16**(8), 104901.
18. **Horikoshi S, Arai Y, Mura H and Serpone N** (2022) Curing of an epoxy adhesive with fixed-frequency microwaves in the presence of a microwave absorber (activated carbon) and with the variable frequency microwave method. *Journal of Applied Polymer Science* **139**(45), e53010.
19. **Chen K, Zhao G, Chen J, Zhu X and Guo S** (2023) Improvements in temperature uniformity in carbon fiber composites during microwave-curing processes via a recently developed microwave equipped with a three-dimensional motion system. *Materials* **6**(2), 705.
20. **Kajfez D** (2011) *Q-Factor Measurements Using MATLAB*, 1st edn. USA: Artech House.

Yasin Alekajbaf received the B.Sc. degree in Electrical Engineering from Jundi Shapur University of Technology, Dezful, Iran, in 2010, and the M.Sc. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran, in 2013. He completed his Ph.D. degree in Electrical Engineering – Circuit and System at the University of Tehran, Iran, in 2020. He is currently affiliated as a postdoctoral researcher in microwave engineering at Uppsala University, Sweden. His current research interests include RF and microwave circuits, solid-state power amplifiers, microwave cavities, high-power microwave applications, microwave heating, and microwave material processing.

Suraj Murali received his B.Tech degree in Computer Science and Engineering from Amrita Vishwa Vidyapeetham, Coimbatore, in 2014 and the M.Sc. degree in Computer Science from Uppsala University, Uppsala in 2018. He has worked with AI-related techniques such as Reinforcement Learning and has professional experience as a software developer with a focus on embedded systems. Currently, he is working to build advanced control systems that drive microwave energy solutions for heating. His current research interests include high-power microwave applications, microwave heating, systems, and control.

Dragos Dancila completed his Ph.D. in Microwave Engineering at the Université catholique de Louvain in 2011, focusing on research related to RF-MEMS and micro-fabrication technologies for millimeter-wave components, which was conducted at IMEC in Belgium. Since March 2019, he has held the position of Associate Professor at Uppsala University, where he currently teaches courses in electronics and microwave engineering. His is heading the microwave group and leads research activities within areas such as millimeter-wave antenna arrays and reflect arrays, RF sensors, and high-power highly efficient RF and microwave amplifiers at the FREIA laboratory. In addition to his academic achievements, Dr Dancila possesses a formal education in Business Management, which he acquired from the Solvay Business School in Brussels. He has also founded the spin-off company Percy Roc AB, with a primary focus on material processing utilizing high-power microwave technology.

https://doi.org/10.1017/S1759078724000072 Published online by Cambridge University Press