# Computational Characterization of Microwave Processing of SiC$_f$/SiC Composites

Jon Binner, Matthew T. Porter
School of Metallurgy and Materials
University of Birmingham
Birmingham, U.K.
j.binner@bham.ac.uk
MTP224@student.bham.ac.uk

Roger Morell
Nathional Physical Laboratory
Teddington, London, U.K.
roger.morell@npl.org

Petra Kumi, Vadim V. Yakovlev
Department of Mathematical Sciences
Worcester Polytechnic Institute
Worcester, MA, USA
pkumi@wpi.edu
vadim@wpi.edu

*Abstract*—**Strong demand from the aerospace industry for composite materials with advanced properties promotes further developments of the related innovative manufacturing technologies. Chemical vapor infiltration (CVI) supported by microwave processing is one of the techniques of composites' production that have shown its legitimate potential for being faster and more energy-efficient than the conventional CVI. In this paper, we discuss the results of computer modeling that aim to break down the complex phenomenon of microwave enhanced CVI into multiple components to help interpret some experimental observations. Patterns of time evolution of temperature fields induced at different frequencies within the operational range of 2.4-2.5 GHz explain variation of the heating rate under constant input power.**

*Keywords—ceramic matrix composites, heating rate, microwave heating, multiphysics simulation, temperature evolution*

## I. INTRODUCTION

The aerospace industry is one of the largest and possibly the most important to the composite materials sector. For many aerospace applications, the exceptional mechanical properties of composites, such as high strength, low weight and high stiffness are of utmost importance [1]. Chemical vapor infiltration (CVI) is an advanced technology known for its proven potential for manufacturing composites with advanced properties [2]. CVI is a process in which a solid substance is deposited into a porous preform by the thermal decomposition of a reactive gaseous mixture. This process may be at least an order of magnitude quicker (<100 h) and more energy-efficient if carried out under the influence of a microwave (MW) or RF field [3]-[6]. However, our most recent advancement of MW-enhanced CVI has provided insight on unexplained experimental observations and a lack of reproducibility.

In this paper, we outline the output of advanced computational study aiming to clarify the puzzling facts, understand causes for the formation of microwave-induced temperature fields, and suggest a means for achieving superior control of the equipment. Simulations were carried out for the process involving heating layered discs of woven SiC fibers.

## II. MODELING TECHNQUES

A computer model reproduces the experimental system, which consists of a large microwave cavity with waveguide excitation (SAIREM's Labotron HTE M30KB CL PRO) and a SiC fabric disc sandwiched between two alumina foam rings encapsulated in a quartz reaction chamber, as shown in Fig. 1. The temperature characteristics of the electromagnetic (EM) and thermal (T) material parameters for quartz and alumina foam in the range from 25 to 1,200°C were calculated from literature data and measured for the SiC fabric; they serve as input data for the model.

A conformal finite-difference time-domain (FDTD) EM model built in the QuickWave$^{TM}$ (QW) [7] environment is capable of generating frequency characteristics for the reflection coefficient at different temperatures, as represented by corresponding values of the EM material parameters. An EM-T coupled model is implemented with the QW Basic Heating Module [7] as an iterative procedure for simulating 3D temperature fields induced at particular frequencies and evolving in time.

Since the frequency characteristic of the magnetron feeding the considered system is unknown, the models do not intend to mimic parameters of the actual MW processing of the ceramic materials. Instead, the objective of the modeling effort was to break down the complex occurrence into multiple components in order to help analyze it, explain some experimental observations and suggests a means of better control over the process.

## III. COMPUTATIONAL RESULTS

The experimental MW system was first analyzed for frequencies at which its operation may be energy-efficient. For the disc of 55 mm diameter and 8 mm height, computations have revealed about 40 strong resonances in the 2.4-2.5 GHz frequency range. Moreover, the positions and depths of some of them significantly vary with temperature. This is illustrated by the characteristics of the reflection coefficient at five different temperatures at a small segment of the frequency interval (Fig. 2). Ten simulations of the heating of the SiC fabric discs at the frequencies at which the reflection coefficient increases, decreases and stays nearly unchanged with increasing temperature were also carried out. Accordingly, the heating at those frequencies appears to happen at very different rates; temperature patterns in Fig. 3 present examples of four typical (from slowest to fastest) processes.

The results show that at frequencies at which the reflection coefficient is low (i.e., when energy coupling is high), the maximum temperature ($T_{max}$) of 1,200°C can be reached in 120-220 s. When the coupling is poor, the SiC disc may not be heated up to $T_{max}$ = 700°C even after 400 s. By both by visual inspection of the pattern and using quantitative metric of uniformity of heating patterns $\eta$ [9], we conclude that the slower processes provide more uniform temperature distributions within the processed composite than the fast ones; that can be contributed to high thermal conductivity of SiC fabric. The values of $\eta$ varies from 0.02 (the slowest
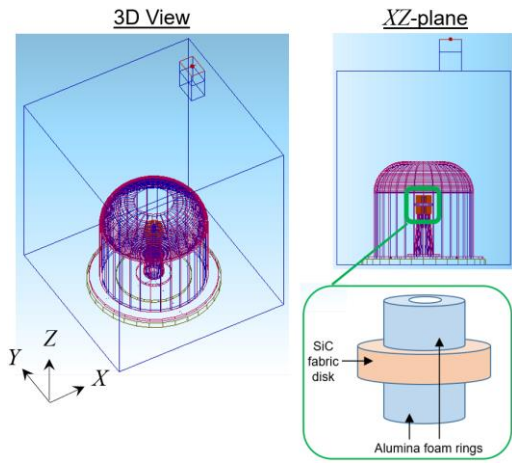
Fig. 1. Three- and two-dimensional views of the model of the SAIREM's Labotron HTE M30KB CL PRO system with the reaction quartz chamber and the processed material (SiC fabric disc).
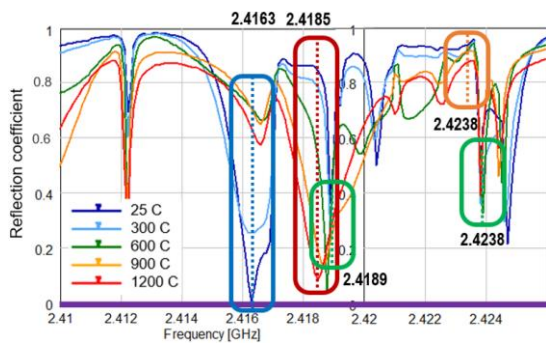


Fig. 2. Fragments of the frequency characteristics of the reflection coefficient computed in the range 2.4-2.5 GHz for five temperatures of the process; SiC fabric disc (diameter 55 mm, height 8 mm) in the Labotron HTE M30KB CL PRO system; dotted lines highlight frequencies at which the reflections increase (2.4163 GHz), decrease (2.4185 GHz), stay low (2.4189 and 2.4238 GHz) and high (2.4238 GHz) with temperature change.



Fig. 3. Temperature evolution of the temperature field in the central horizontal plane through the SiC fabric disc (diameter 55 mm, height 8 mm) (*XY*-plane) and in the central vertical plane through the disc and the alumina foam rings (outer diameter 50 mm, inner diameter 14 mm, height 25 mm) (*XZ*-plane); from slow (at 2.4632 GHz) to fast (at 2.4189 GHz) heating; simulated with the heating time step in the EM-T iterative procedure being 0.5-1.0 s.

The results also indicate that potential benefits to the ME-CVI process would occur with the use of a solid-state MW source (i.e., with a robust control over frequency and magnitude of the excitation).

heating) to 0.1 (the fastest one). More specifically, in the latter, when $T_{max} \sim 1{,}200^{\circ}$C, the minimum temperature ($T_{min}$) may be about 900°C; in the former, when $T_{max} \sim 400^{\circ}$C, then $T_{min} \sim 340^{\circ}$C. Much lower value of thermal conductivity of the alumina foam compared to the one of the SiC fabric makes the surrounding rings effective thermal insulators helping maintain high level of temperature uniformity.

## IV. DISCUSSION AND CONCLUSION

Analysis of temperature patterns suggests that their time evolutions may be combinations of two trends: amplification of the field magnitude in the "hot stops" and spreading of the peaks of the distributions due to thermal conductivity. Simulation of heating by microwaves at different, even very close, frequencies has shown very different heating rates and temperature patterns which has explained the effect of the strong sensitivity of the performance on small changes in geometry. Variation of frequency characteristics with temperature sheds some light on the variation of the heating rate in time with the input power remaining constant.

Computational results reviewed in this paper show and explain all experimentally observed confusing phenomena.
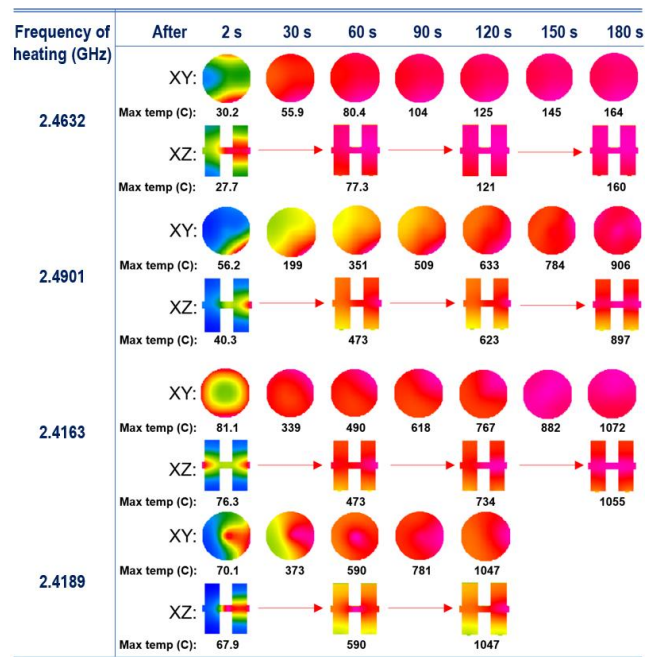
REFERENCES

[1] V. Giurgiutiu, Ed., Structural Health Monitoring of Aerospace Composites, Academic Press, 2015.

[2] O. Florez, R.K. Bordia, D. Nestler, W. Krenkel, and G. Notz, "Ceramic fibers based on SiC and SiCN systems: current research, development, and commercial status," Advanced Engng Materials, vol. 16, no 6, pp. 621-636, 2014.

[3] D. Jaglin, J. Binner, B. Vaidhyanathan, C. Prentice, B. Shatwell, and D. Grant, "Microwave heated chemical vapor infiltration: densification mechanism of SiCf/SiC composites," J. Am. Ceram. Soc., vol. 89, no 9, pp. 2710-2717, 2006.

[4] J. Binner, B. Vaidhyanathan, and D. Jaglin, "Microwave heated chemical vapour infiltration of SiC powder impregnated SiC fibre preforms," Advances in Applied Ceramics, vol. 112, no 4, pp. 235-241, 2013.

[5] V. Venkatachalam, V. Rubio, and J. Binner, "Fabrication and performance of ultrahigh temperature ceramic matrix composites through RF enhanced chemical vapour infiltration," 43rd Intern. Conf. & Expo on Advanced Ceramics and Composites (ICACC 2019), Daytona Beach, Florida, January 2019, p. 207.

[6] J. Binner, V. Venkatchalam, and M.T. Porter, High and ultra-high temperature ceramic matrix composites fabricated by rapid chemical vapour infiltration, 44th Intern. Conf. & Expo on Advanced Ceramics and Composites (ICACC 2020), Daytona Beach, FL, January 2020, pp. 30-31.

[7] QuickWave, 1998-2019, QWED Sp. z o.o., www.qwed.com.pl.

[8] P. Kumi and V.V. Yakovlev, "Computational procedure for quantitative characterization of uniformity of high frequency heating," Proc. 53rd IMPI's Microwave Power Symp., Las Vegas, NV, June 2019, pp. 123-125.