Computational Procedure for Quantitative Characterization of Uniformity of High Frequency Heating

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Keywords: Dissipated power, FDTD, heating patterns, temperature, uniformity metrics.

INTRODUCTION

For many years, heating uniformity has been a prevalent topic in research on the effects of electromagnetic (EM) thermal processing. With the appearance of special means for visualization of heating patterns such as IR cameras capturing distribution of heat on the surface, or modeling tools capable of simulating 3D fields inside the objects, the task of pattern characterization has become relevant. However, it is usually handled via visual inspection leading to a qualitative conclusion. Review of computations aiming to character-rize the phenomenon in quantitative terms (see, e.g., [1]-[5]) do not suggest an existence of a commonly accepted metric for heat patterns induced by high frequency EM treatment.

In this paper, we propose an approach that allows one to numerically characterize the level of uniformity of high frequency heating by evaluating the distributions of dissipated power and temperature. We report on the development of a computational tool, which (*i*) visualizes 2D or 3D matrices representing the patterns, (*ii*) analyzes their structures using a special standard-deviation-based metrics, and (*iii*) identifies the heat distribution characterized by the best uniformity.

METHODOLOGY

The developed computational procedure quantifies uniformity of high frequency EM heating by processing the patterns (matrices) produced by numerical simulation of the scenario in question; to this end, we employ the Finite Difference Time Domain (FDTD) solver *QuickWave* [6]. EM computation outputs distributions of dissipated power P_d, whereas the coupled EM-thermal simulation results in fields of temperature T.

The metric of uniformity of dissipated power is introduced, following [1]-[5], as

$$\lambda_P = \frac{\sigma}{\mu}, \tag{1}$$

where σ is standard deviation of P_d data points from the average value and μ is the mean of P_d. Computational experiments with 2D matrices show that lower λ_P values correspond to better uniformity, and multiple smaller "peaks" in the pattern/matrix seem to have a bigger effect in increasing λ_P than a single high peak.

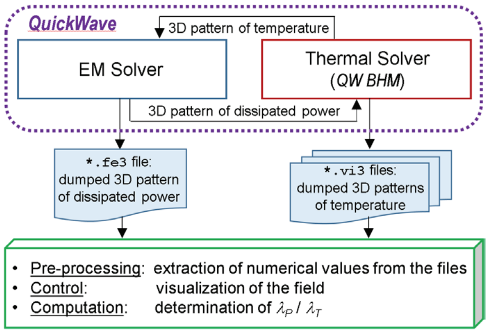

Figure 1. Operations of the computational procedure and its association with *QuickWave*.

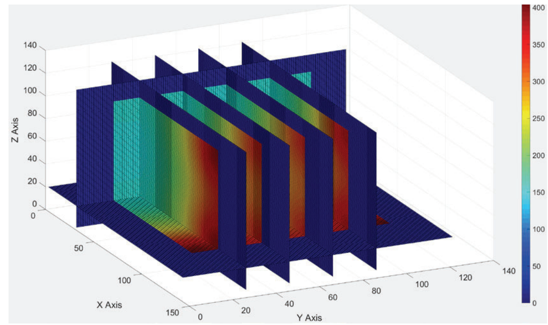

Figure 2. Visualization of a temperature pattern in a rectangular sample of a ceramic material at a particular time of the heating process.

In an iterative simulation of the EM-thermal coupled phenomenon, the EM process happening on a nanosecond scale is assumed to occur instantly, whereas heat diffusion is considered as taking place on the scale of real time (seconds). Temperature field is computed after each iteration, and a series of temperature patterns represents evolution of temperature distribution in the course of thermal processing. Hence n temperature patterns should be used to characterize the process. Accordingly, we define the metric of temperature uniformity in the microwave heating process as:

$$\lambda_T = \frac{\sum_{i=1}^{n} \frac{\sigma_i}{\mu_i}}{n}, \qquad (2)$$

where σ_i and μ_i represent, respectively, standard deviations and the means of temperature data points after every ith heating time step; all heating time steps are assumed to be equal.

The procedure is implemented in *MATLAB*; it extracts the required data from `*.fe3` and `*.vi3` files (containing P_d and T fields, respectively) dumped from *QuickWave*, visualizes (to better control the process) the patterns in 2D or 3D, and calculates $\lambda_{P,T}$. The flow-chart in Figure 1 provides some details on functionality of the developed computational tool. Downloaded numerical data can be visualized using various means of the *MATLAB* graphics system. One example of possible 3D visualization of a temperature pattern is shown in Figure 2.

RESULTS AND DISCUSSION

The procedure was tested with several computational projects involving EM and coupled (EM-thermal) simulations. In this summary, we report its use in virtual experimentation with microwave heating of a SiC fabric as a part of microwave-assisted chemical vapor infiltration. A coupled model of the process carried out in SAIREM Labotron HTE M30KB CL PRO system uses temperature-dependent EM and thermal material parameters of a stacked SiC plies and simulates evolution of the temperature field induced at resonant and non-resonant frequencies.

Figure 3 shows how two typical heating processes in the system evolve. When the processed SiC disk is heated at a resonant frequency, thermal runaway quickly develops: after reaching 636 ºC for the first 19 s, maximum temperature increases by 420ºC for the

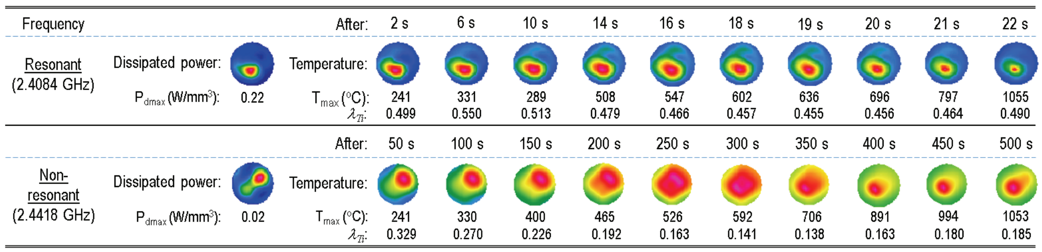

Figure 3. Non-normalized temperature patterns on the top of a 55×8 mm disk of stacked SiC fabric plies heated in SAIREM Labotron (power 1.1 kW); patterns at resonant and non-resonant frequencies are computed with 1 and 5 s heating time steps, respectively. Individual metrics (λ_{Ti}) and maximum temperature (T_{max}) are shown along with corresponding patterns of dissipated power.

last 3 s. The process is quick; high values of λ_T (0.51) and λ_{Ti} (in Figure 3) reflect significant non-uniformity of the heating process. In contrast, when heating at a non-resonant frequency, due to low energy coupling, the heating process is much slower (1053ºC is now reached for 500 s instead of 22 s), and the metric of uniformity is lower (λ_T = 0.21) going to lowest values in the second half of the process due to the effect of thermal conductivity.

CONCLUSION

Two metrics for quantitative characterization of uniformity of heating of materials by high frequency EM waves have been introduced. The developed computational procedure dealing with simulated data on dissipated power and temperature distributions quantitatively characterizes the levels of uniformity of those patterns. In the computational study of high temperature microwave processing of SiC fabric plies, the procedure was been used to track and analyze evolution of temperature field and proved to be a helpful CAD tool. It can be also easily adapted to work with data from IR cameras.

ACKNOWLEDGMENT

The work was supported by the AFRL (via Leidos, Inc.) (Grant No P010200226) and the 2018 WPI Summer Undergraduate Research Fellowship (SURF).

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