

Focused microwave radiation for the localized curing of polymer resins

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Abstract—The recent development of optical volumetric additive manufacturing (VAM) technology has enabled rapid 3-D printing of optically transparent resins. However, there is growing interest in employing other materials that extend the design space of this technology. Here we leverage focused microwave radiation to expand VAM to a much broader family of resins, including those which are opaque. We use an X-band microwave applicator array coupled to a beam-steering algorithm to focus microwave energy into liquid resins. We performed numerical simulations to demonstrate this microwave energy localization, and will present supporting experimental results.

I. INTRODUCTION

Significant progress has been made in recent years across a broad spectrum of advanced manufacturing techniques [1]. A volumetric additive manufacturing (VAM) technique that relies on rotating a photosensitive resin in a dynamically evolving light field has been recently demonstrated [2]. Unlike most AM processes that print point-by-point voxels serially to build up the 3D volume (e.g., direct ink write), VAM has the capability to print arbitrarily-defined 3D geometries as a unit operation, with no substrate or support structures required. However, this technique is limited to transparent photosensitive liquid resins [3]. Here we propose to leverage microwave radiation focusing to expand the design space of VAM to non-optically transparent polymer resins.

While microwaves have been used for polymer curing, these techniques have primarily been applied to bulk samples [4]. Here we propose a microwave applicator array coupled to a beam-steering algorithm to focus and deposit microwave energy in a wide variety of materials, including those which are optically opaque. The overall concept using a single microwave applicator based localized curing system is demonstrated in Fig. 1. A signal generator produces a time-harmonic electromagnetic signal at X-band. This is then amplified using

an X-Band power amplifier, followed by radiation by an open-ended waveguide in the near field of an epoxy E01080 resin. The focused electromagnetic beam from the waveguide localizes microwave energy inside the resin, leading to spatially-limited curing.

Electromagnetic simulations using a single X-band open-ended waveguide applicator in the near-field of a resin-filled container show localization of electromagnetic fields near the edge of the container. A numerical simulation was performed using a dynamically-evolving microwave field, computed from a time-reversal beam-steering algorithm to demonstrate microwave energy localization according to a desired shape [5]. The selective focusing of high power microwave fields then results in delivery of energy to arbitrary regions in a three-dimensional resin volume.

II. SIMULATION MODEL

Simulations studying microwave radiation from the open-ended waveguide in the near-field (1 in.) of a resin container were performed using the commercial high frequency electromagnetic field simulation software Ansys HFSS. The design of the waveguide is directly from a waveguide model from Fairview Microwave company [6]. The dielectric properties of the epoxy resin are chosen as follows: “ $\epsilon = 5.5$ (dielectric constant) and $\tan \delta = 0.2$ (loss-tangent)”, based on prior literature [7]. The outer diameter, thickness and height of the container are 42, 3.3 and 63 mm respectively. The root mean square (RMS) of the electric fields inside the surface are plotted in Fig. 2. This shows high electric-field density near the boundary of the beaker with the beam spreading radially.

The field profile was used to calculate the focusing spot at various distances away from the boundary of the resin (Fig. 3). The full width at half maximum of the localized field is chosen

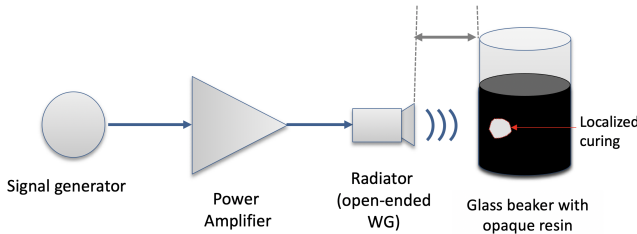


Fig. 1. Proposed microwave curing system using a single waveguide applicator; Electromagnetic signals are generated by a signal generator and power amplifier and radiated using an open-ended waveguide; A glass beaker containing resin is placed in the near-field of the applicator for localized microwave energy delivery.

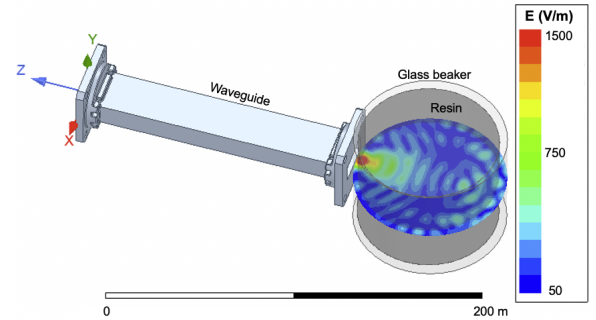


Fig. 2. Electromagnetic simulation model: RMS electric fields distribution in the resin surface due to radiation from the waveguide applicator.

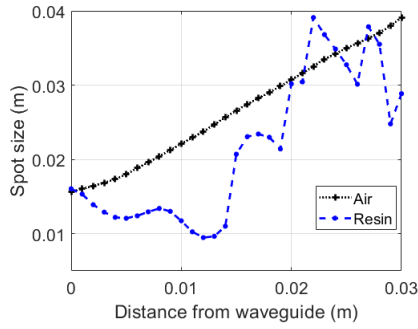


Fig. 3. Focusing spot size obtained from the RMS field distribution from Figure 2 with and without the resin present.

to be the spot size. We see a minimum of 1 cm as the spot size at a distance of 1.2 cm away from the boundary. The spot size increases as we move farther away from the minimum location. A comparison of the spot size without resin shows that the presence of resin leads to a lower spot size due to confinement of electric fields by the dielectric resin [8].

III. MICROWAVE BEAM-STEERING ALGORITHM

A time reversal beam-steering algorithm was developed that can focus microwaves on arbitrary regions of the resin volume. Wave propagation is modeled using a two-dimensional finite-difference time-domain model [9]. The resin sample is placed at the center, with illumination of microwave fields from the antenna array. An antenna array consisting of 30 elements is excited by input pulses that are computed using a time reversal algorithm, described in [5] (Fig. 4). The results show that it is possible to control the microwave energy deposition to match a desired volumetric shape. A laboratory setup to experimentally validate the performance of microwave curing with the open-ended waveguide aperture is shown in Fig. 5.

IV. CONCLUSION

Here we develop a concept based on microwave radiation focusing to expand the VAM paradigm to a wider range of materials. The technique relies on an X-band microwave applicator array coupled to a time-reversal beam-steering algorithm to deliver localized microwave energy to arbitrary regions in a three-dimensional resin volume. Electromagnetic simulations conducted using a single open-ended waveguide applicator determined the focusing spot size of the electric fields. Numerical simulations demonstrated that a time-reversal beam-steering algorithm can focus microwaves for curing in desired regions. This work, together with supporting experimental results which will be presented, lays the foundation for a comprehensive microwave VAM system.

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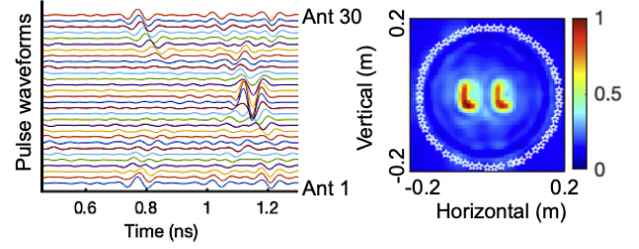


Fig. 4. Finite-difference time-domain simulations of a time-reversal focusing algorithm show microwave energy localization to produce an ‘LL’ shape inside the resin. Excitation pulse waveforms are fed to individual elements of the antenna array (left), beam-steered microwave energy shows localization capability (right).

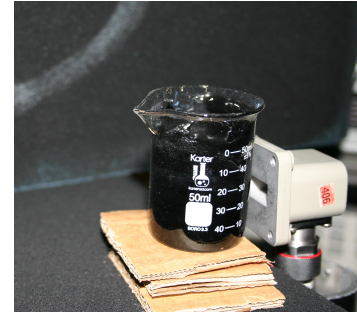


Fig. 5. Experimental setup with an X-band open-ended waveguide placed in the near field of an opaque epoxy resin.

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