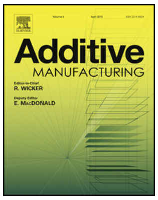
Additive Manufacturing 18 (2017) 221–227

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma



Full Length Article

Vacuum-filling of liquid metals for 3D printed RF antennas

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ARTICLE INFO

Article history:
Received 4 April 2017
Received in revised form 23 August 2017
Accepted 8 October 2017
Available online 10 October 2017

Keywords:
3D printing
Liquid metals
Antennas
Vacuum filling
Microchannels

ABSTRACT

This paper describes a facile method to fabricate complex three-dimensional (3D) antennas by vacuum filling gallium-based liquid metals into 3D printed cavities at room temperature. To create the cavities, a commercial printer co-prints a sacrificial wax-like material with an acrylic resin. Dissolving the printed wax in oil creates cavities as small as 500 μm within the acrylic monolith. Placing the entire structure under vacuum evacuates most of the air from these cavities through a reservoir of liquid metal that covers a single inlet. Returning the assembly to atmospheric pressure pushes the metal from the reservoir into the cavities due to the pressure differential. This method enables filling of the closed internal cavities to create planar and curved conductive 3D geometries without leaving pockets of trapped air that lead to defects. An advantage of this technique is the ability to rapidly prototype 3D embedded antennas and other microwave components with metallic conductivity at room temperature using a simple process. Because the conductors are liquid, they also enable the possibility of manipulating the properties of such devices by flowing metal in or out of selected cavities. The measured electrical properties of fabricated devices match well to electromagnetic simulations, indicating that the approach described here forms antenna geometries with high fidelity. Finally, the capabilities and limitations of this process are discussed along with possible improvements for future work.

1. Introduction

Additive manufacturing (AM) processes are highly compelling for radio frequency (RF) and microwave electronic components, whose performance is largely dictated by their geometry and whose feature sizes are within the capabilities of modern 3D printers. For these devices, 3D printing offers additional degrees of freedom for RF design through configurations not possible with planar fabrication methods. For example, an electrically small conformal antenna formed by printing silver ink onto hemispherical surfaces supports a bandwidth that exceeds any linear or planar antenna with equivalent maximum dimension [1]. Moreover, in comparison to conventional manufacturing techniques, AM can reduce the number of processing steps and the resources required to build a prototype [2] and thus simplify the construction of custom geometries. For RF components such as waveguides, horn antennas and reflectors, these additively manufactured counterparts show the promise of being low cost [3,4], light-weight alternatives [5,6] while enabling corrugated [7], curved [8], or other complex conductive structures [9–11].

While complex dielectric geometries can be fabricated using a wide variety of AM processes [12], RF devices also require low-loss conductors. However, most AM techniques print non-conductive polymeric materials, and hence, must be followed by a separate metallization process. Surface metallization techniques such as electron beam evaporation [8] and sputtering [8,13] produce highly conductive layers but cannot readily coat internal surfaces. Other methods, such as electroless plating [5,7], can be used to metallize internal surfaces, but it is difficult to deposit metal layers more than a few microns thick, thereby limiting its use for components operating at the lower portion of the microwave band. Diffusion limitations also make it difficult to coat 'dead-end' capillaries evenly using electroless plating [14]. Alternatively, dispensing of conductive inks [1,15] or pastes can form finer metallic patterns on curved and planar printed surfaces. Although efforts have been directed towards developing highly conductive silver nanoparticle inks [15], they require a precise rheology for dispensing, followed by annealing at temperatures of at least 90 °C, that

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https://doi.org/10.1016/j.addma.2017.10.012
2214-8604/

can lead to deformation or even melting of the 3D printed parts constructed using commercial high-resolution inkjet 3D printers [16]. Recently, silver suspension pastes have been used to metalize hollow cavities in order to fabricate simple electronic components such as resistors and LC resonant circuits [17]. Here, viscous pastes with silver-nanoparticle suspensions were injected into 3D printed microfluidic channels, that later solidify as the solvent evaporates during the ink curing process. The reduced volume on solidification or curing results in a lower packing density of the paste filled inside the cavities (and in extreme cases, cracking) that decreases the electrical conductivity [18]. Finally, these methods are incapable of creating reconfigurable electronic devices since the suspension dries after deposition, acting as a rigid conductor in the final device.

Gallium-based alloys such as EGaIn (an eutectic alloy of gallium and indium in 3:1 wt. ratio) pose an attractive substitute to conductive pastes because they are liquid at room temperature [19] with high conductivity of $\sim 3.4 \times 10^6$ *S/m* [20], low viscosity [21], and non-toxicity [22]. The fluidic nature of these alloys has recently been exploited to fabricate multi-axial Helmholtz coils [23] as well as reconfigurable [24,25] or flexible antennas such as a microstrip patch antenna [26], dipole antenna [27] and a planar inverted F-antenna (PIFA) [28] using an injection-based filling technique of relatively simple microfluidic channels constructed via 3D printing or soft lithography. Unlike simple RLC elements [17], antenna structures often consist of closed cavities without outlet paths for the metal. Some of them require wide planar surfaces and such geometries cannot be filled using direct injection without leaving internal voids [26]. Therefore, an alternative approach is needed to metallize RF components with closed cavities.

Here, we demonstrate a vacuum filling approach to embed liquid metals [19] in cavities constructed within a 3D printed acrylic monolith. The internal conductive structures consist of both straight and curved channels with high aspect ratios in addition to thin planes that constitute 3D printed RF transmission lines and antennas. We demonstrate the ability of our method to create a broad range of conductive shapes by printing a planar patch antenna with an embedded vertical coaxial transition and an axial mode helix antenna composed of curved and straight microchannels as well as a planar conducting ground. Furthermore, we examine the fabricated cylindrical channels to understand the accuracy of the internal dimensions produced using this technique. Combining this fabrication process with mechanical or electrochemical actuation [25,29] could lead to embedded microfluidic RF devices that are multi-functional and reconfigurable.

2. Materials and methods

Processes involving casting of molten metal have been traditionally used to obtain nano-scale metallic structures with high aspect ratios at elevated temperatures [30]. High pressure die-casting processes [31,32] typically use vacuum to avoid porosity in the casted part due to air entrapment. In case of metallizing 3D printed parts using liquid metal, a vacuum-driven filling process can similarly facilitate elimination of air voids without the need for repeated perturbation [33] in a hands-free manner. In addition, a room temperature filling process enables metallization of 3D printed soft polymeric and elastomeric substrates that have low heat distortion temperature. A high temperature filling process would be restricted to printed thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), or polycarbonates printed using fused deposition modeling (FDM) [18,34] which is not suited for high resolution printing and requires complex support material removal procedures.

The proposed fabrication process is illustrated in Fig. 1. The CAD model of the antenna structure, designed with an EM simulator (HFSS, Ansys Inc.), is printed with a ProJet® 3500 HDMax [16] inkjet printing machine that uses VisiJet M3 Crystal® material – a photocurable dielectric resin used to encompass the liquid metal. M3 Crystal was selected due to its natural appearance, low warping during support material dissolution process, high mechanical strength and resistance to solvent exposure. The regions to be metalized are printed using a dissolvable wax-like support material (VisiJet S300®) to reinforce overhangs and free-standing geometries. The inkjet nozzles eject polymer droplets in the form of voxels that change its phase from a liquid to a gel, which is later flattened using a planarizer to form a thin film. The deposited layer is then UV-cured using a lamp with a wavelength of 365 nm. The wax material, when printed, solidifies instantaneously on the aluminum printpad as it is held at room temperature. These structures are printed at a layer thickness of 29 μm in the Ultra High Resolution (UHD) mode of the printer.

Once the part is printed, we hold the printpad in a freezer for two minutes to allow the mismatch in thermal expansion coefficient between the aluminum and the printed part to delaminate it from the printpad. The part is then transferred to a heated ultrasonic cleaning bath containing EZRinse-C® cleaning solution supplied by 3D Systems to dissolve away the printed wax supports at around 55 °C for two hours. The sample is then washed thoroughly with warm water to remove the remaining dissolved wax settled on the inner walls. Drain holes added at the edge of the antenna structure during the design stage simplify the removal of the support material and water. Finally, to evaporate any of the trapped water or surfactant, we transfer the part into a Thermo Scientific 280A vacuum oven held at 55 °C for 12 h.

Once the part is clean and dried as shown in Fig. 1a, a photocurable glue (Norland Optical Adhesive, NOA 63) seals the drain holes that assisted with the removal of the support materials. A snap-off reservoir (3D printed separately) is then mounted on the cleaned part and sealed as shown in Fig. 1b to aid the vacuum filling process. The reservoir is filled with a volume of EGaIn that is at least 30% more than expected to completely fill the antenna (avoiding entrance of air into the hollow cavities during vacuum-filling) and then kept inside a vacuum chamber at a pressure of −30 in. Hg relative to surrounding atmospheric pressure for 30 min. Returning the chamber to atmospheric pressure allows the liquid metal to rapidly fill the antenna cavities as illustrated in Fig. 1c (Appendix – Video A demonstrates this process for a scaled cross-sectional model of a patch antenna). The atmospheric pressure drives the metal into the cavities as shown in Fig. 1d. Finally, the reservoir is removed and replaced with a subminiature type A (SMA) connector that is affixed using NOA 63 to seal the device, as seen in Fig. 1e.

3. Antenna designs and measurements

3.1. Microstrip patch antenna

We first selected a common type of microstrip patch antenna to test the viability of the method. Patch antennas have wide and thin planar surfaces found in many types of antennas, yet these are difficult to fill uniformly by injecting metal due to the trapped air. To accurately design the device, we measured the complex permittivity of the VisiJet M3 Crystal® material using a resonant cavity method. Two cylindrical copper cavities were fabricated with the radius 1.1 cm and 3.825 cm and height equal to their radius. The changes in the resonance frequency and quality factor between an air-filled cavity and a cavity filled with M3 Crystal were observed to measure the dielectric constant ε_r' and loss tangent, respectively. Measurements of three different material samples led to an average relative dielectric constant of 2.96 (2.959 ± 0.003) and an average loss tangent of 0.047 (0.047 ± 0.0035) at 6 GHz. These values were