Composite Materials Development for Fused Filament Fabrication of RF Systems

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***Abstract*—In this paper we present the development of feedstock materials, specifically tailored permittivity materials used in fused filament fabrication (FFF), for microwave applications. One of the major bottlenecks in utilizing additive manufacturing for useful radiofrequency (RF) applications is the lack of suitable materials. Flexible, high-dielectric constant and low dielectric loss tangent composite materials, consisting of a mixture of polymer and ceramic nanoparticles in controlled volume fractions, are manufactured. Effective medium approximations (EMA) to predict composite properties, such as Bruggeman approximations, are validated with measurements between 18 – 40 GHz and are presented.**

***Keywords*—additive manufacturing, composite materials, dielectric characterization, fused filament fabrication, antennas.**

I. INTRODUCTION

To reduce size, weight, power and cost (SWaP-c), military platforms have been evolving towards a more integrated design approach that efficiently utilizes all available space. In fact, to accommodate limited space constraints many commercial off-the-shelf (COTS) systems will need to be replaced by custom designed and fabricated systems. In the case of RF antennas and electronic systems, this will require exploring innovative design methods, new materials and novel manufacturing approaches to realize cost-effective, customizable and conformal radar and communication systems that do not rely on standard COTS technologies.

An attractive solution to this challenge is offered by the field of additive manufacturing (AM). While the current AM market has been growing rapidly, it is still built primarily around single material based systems, where the applicability of these systems to RF applications is limited. While very good progress has been made on the development of general multi-material AM printers less progress has been made on the development of materials designed specifically for use in RF applications, where the typical dielectric properties at RF or microwave frequencies of base materials are shown in Fig. 1 [1]. In many cases, the lack of suitable materials is the bottleneck that is preventing the applicability of this technology towards real-world applications.

In this paper we present our methods of addressing the material development concerns for AM-RF applications, by demonstrating flexible, high-dielectric constant and low dielectric loss tangent composite filaments feedstock materials that have been characterized between 18 – 40 GHz.

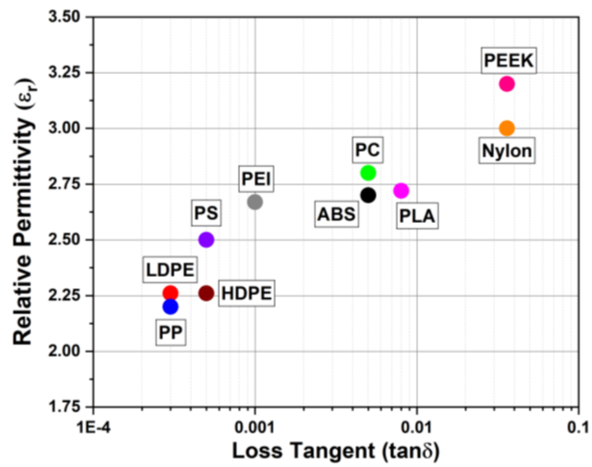

Fig. 1. Reported electrical properties of various commercially available polymer filament materials used in FFF processes. These materials offer a relatively narrow range in dielectric constant.

II. FABRICATION OF FLEXIBLE FILAMENTS AND SAMPLES

Composite materials were prepared using mixing techniques used by other research groups [2, 3]. Pellets of acrylonitrile butadiene styrene (ABS) were dissolved using acetone, afterwards a plasticizer, dibutyl phthalate (DBP), and a surfactant, octyl gallate (OG) were added in small concentrations. These additives are necessary, as the plasticizer acts as a lubricant between molecular chains in the polymer, enabling flexibility even with loading of ceramic powders; however, the addition of too much plasticizer negatively affects the composite by rendering it too elastic. The surfactant is used to prevent aggregation between the ceramic particles.

Ceramic nanoparticles, (diameter < 800 nm) of $BaTiO_3$, $SrTiO_3$, or $Ba_{0.67}Sr_{0.33}TiO_3$ are added in controlled amounts to the mixtures, in volume fractions between 15 – 30%, and allowed to homogenize within the matrix. We specifically selected nanoparticles over microparticles owing to their lower dielectric loss tangents at the expense of a reduced maximum relative permittivity. The suspension was spread onto a chemically inert tray where the acetone was allowed to evaporate. After fully evaporating, the composite slab was cut

Work supported by U.S. Army Research Laboratory, Adelphi.

Submitted On: August 31, 2020
Accepted On: September 5, 2020

https://doi.org/10.47037/2020.ACES.J.351108

into pieces and then ground into approximately 2 mm pellets. The composite pellets were extruded into 1.75mm diameter filaments using a single screw extruder at 190°C. We found that adding more than 40% ceramic powder resulted in a filament that was too brittle for use, even with the addition of plasticizer. To address this, we utilize a hopper-fed approach to printing samples, which we will expand in the future.

These filaments were then printed into 150 mm x 150 mm x 1-2 mm samples for dielectric characterization using an nScrypt 3Dn-300 multi-material platform. Print head and build plate temperatures during deposition were set to 240°C and 110°C, respectively. We also observed that as the loading of ceramic inclusions increases, so too does the viscosity of the material. Care needs to be exercised as these viscous materials are prone to printing defects, such as voids, and we found that use off an overlapping fill pattern minimizes such defects.

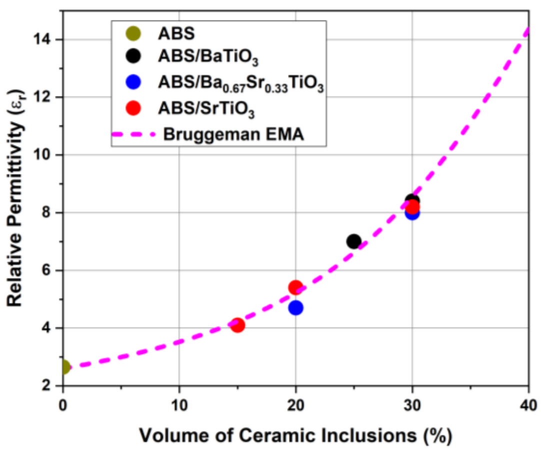

Fig. 2. Mean relative permittivity of the ABS-ceramic composite samples as a function of volume loading compared to EMA predictions (dashed line).

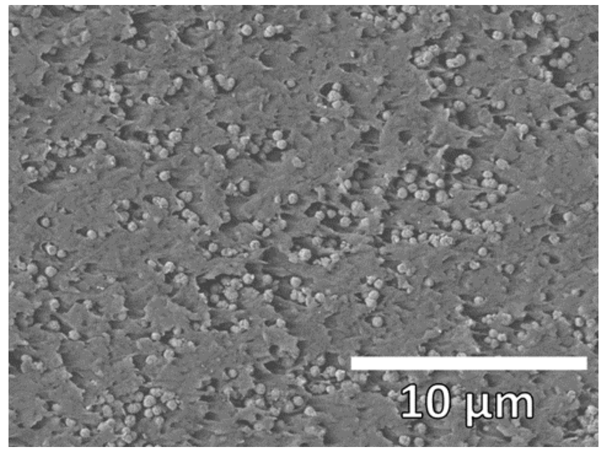

Fig. 3. SEM image of a ceramic nanoparticle-loaded ABS-composite filament showing well-dispersed particles within the polymer matrix.

III. Material Characterization and Results

The composite sample plates were characterized using a free-space focused beam system (VNA model E8364B) between 18 – 40 GHz, with the mean relative permittivity and dielectric loss tangents summarized in Table I.

TABLE I. Dielectric Properties of ABS-Composite Filaments

Ceramic Inclusion	Vol. Loading (%)	Permittivity	Loss Tangent
$BaTiO_3$	25	7.01	0.011
	30	8.39	0.016
$Ba_{0.67}Sr_{0.33}TiO_3$	20	4.72	0.029
	30	8.02	0.069
$SrTiO_3$	15	4.10	<0.01
	20	5.39	< 0.01
	30	8.18	< 0.01

The relative permittivity and dielectric loss tangent increase as the loading of ceramic increases. Surprisingly, all of the ceramic materials measure similar values of permittivity ($\varepsilon_r \approx 5$ at 20% and $\varepsilon_r \approx 8$ at 30% loading) and is shown in Fig. 2 compared to Bruggeman predictions. However, out of all the ceramic nanoparticles, ABS-$SrTiO_3$ shows the most promise as a low-loss tangent candidate.

Scanning electron microscope (SEM) images of a composite filament sample is presented in Fig. 3, which are used to determine the relative dispersion of ceramic nanoparticles within the polymer matrix. We observe that this mixing approach provided well-dispersed materials.

IV. Conclusions

We have produced flexible filament composite materials for AM platforms that contain high dielectric constants and low dielectric loss tangents that are attractive for RF applications. These composites incorporate ceramic nanoparticles into an ABS matrix, aided by a plasticizer and surfactant. Sample plates using these materials were fabricated using an AM platform, and then characterized with a free-space focused beam system between 18 – 40 GHz, where predictions using EMA have been experimentally validated.

Acknowledgment

This work was supported by the U.S. Army Research Laboratory, under the Phase I SBIR Topic “Additive Manufacturing for RF Materials and Antennas”, topic number A18-020.

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