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Effect of Particle Geometry on Electric Field Distribution, Partial Discharge, and Dielectric Strength of Iron-Polymer Composites

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***Abstract*— With the goal of designing metal-polymer composites with tunable electrical properties and optimal electrical integrity, this work studies the effects of filler particle size and shape on the electric field and breakdown characteristics of iron-polymer composites. Polydimethylsiloxane-iron (PDMS-Fe) composites were fabricated, and partial discharge inception electric field (PDIE) and breakdown electric field (E_{bd}) were measured. Two-dimensional models of each sample were qualitatively analyzed using finite element analysis (FEA). According to the results of this investigation, PDMS-Fe composites fabricated with large, irregularly shaped iron (Fe) particles had a lower PDIE and E_{bd} than composites fabricated with smaller, spherical Fe particles. It was also concluded that ellipses are not an accurate representation of irregularly shaped Fe particles for the purpose of FEA electric field modeling.**

Keywords—metal-polymer composites, partial discharge, dielectric strength, electric field distribution

I. Introduction

Stretchable electronics, specifically those intended for use in wearable technology, must be able to withstand deformation as well as electrical stress without premature mechanical or electrical failure or reduced performance. Therefore, conductors and dielectrics used in traditional electronics, such as metals, ceramics, and other rigid materials, are not ideal for stretchable electronics [1]. This issue is frequently resolved using soft, deformable conductors and dielectrics such as liquid metal polymer composites (LMPCs), which are often fabricated from polydimethylsiloxane (PDMS), a soft, stretchable polymer, and eutectic gallium-indium-tin alloy (GaInSn or galinstan), which is liquid at room temperature and has high conductivity and low reactivity and toxicity [2]–[4]. The conductivity and relative permittivity of LMPCs can be increased by increasing the volume concentration of GaInSn [5]. However, this also reduces the electrical integrity of the composites by lowering partial discharge inception electric field (PDIE) and dielectric strength. The reduction in dielectric quality is caused by the displacement of PDMS by GaInSn, which reduces the effective thickness of the PDMS, causing higher intensity electric fields in the PDMS. High concentrations of GaInSn also lead to an increase in possible discharge paths, increasing dielectric loss and lowering PDIE. The relatively high cost of GaInSn limits the economic viability of LMPCs, particularly at higher concentrations of GaInSn.

Due to its high conductivity, ready availability, and low cost, iron (Fe) has been investigated as a substitute for part or all of the liquid metal in LMPCs [6], [7]. Due to its high conductivity, however, increasing the volume concentration of Fe would compromise the dielectric quality of the composites in a similar manner to GaInSn. In addition to its high conductivity, the geometry of individual solid Fe particles can vary widely. While this means that particle size and shape is more readily tunable for Fe than for liquid metals such as GaInSn, certain particle geometries could have dramatic effects on the electrical integrity of Fe-polymer composites. Previous work has found that the incorporation of Fe degrades the dielectric reliability of LMPCs due to electric field enhancements occurring around the sharp edges of the Fe particles [6]. However, research on the effects of particle geometry in such composites is lacking. With the goal of determining the effects of particle geometry on the electric field and dielectric failure characteristics of Fe-polymer composites, this study investigates the differences in partial discharge inception electric field (PDIE) and breakdown electric field (E_{bd}) of PDMS-Fe composites fabricated with fine Fe filler with mostly spherical particles and coarse Fe filler with sharp, irregularly shaped particles. The experimental results were qualitatively compared to finite element analysis (FEA) models that estimate the electric field distribution in each type of PDMS-Fe composite.

II. Composite Fabrication

Two types of Fe filler were used in the fabrication of the PDMS-Fe composites. Scanning electron microscopy (SEM) was used to determine the average particle size and shape for each type of Fe filler. SEM images of both Fe filler type are shown in Fig. 1. The Fe fillers were found to have distinct particle size with the Fe in Fig. 1(b) being several times larger than the Fe in Fig. 1(a) on average. The Fe particles shown in

Fig. 1(a) were found to be approximately spherical, while the Fe particles in Fig. 1(b) were found to be irregular in shape with sharp, jagged edges.

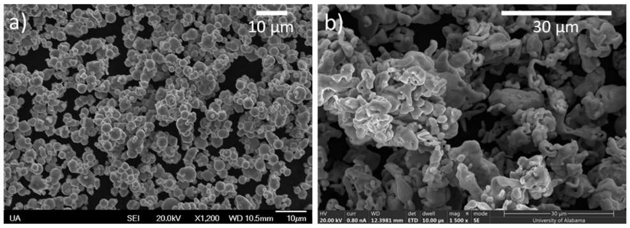

Fig. 1. SEM images of (a) spherical Fe particles and (b) irregular Fe particles.

To form the composites, a 10 vol% concentration of each type of Fe filler was mixed into a 1:1 volume ratio of vinyl-terminated and trimethyl-terminated PDMS. Each formulation was mixed using a high torque overhead stirrer at 1,800 rpm for 2 hours. After 2 hours, the catalyst, platinum-cyclovinylmethylsiloxane, and the cross-linker, tetrakis (dimethylsiloxy) silane, were added to the dispersion, and the dispersions were stirred for an additional 30 seconds. The final dispersions were then poured into 1.9 cm diameter circular polytetrafluoroethylene (PTFE) molds and cured for 72 hours at 82°C.

III. Partial Discharge and Breakdown Measurement

A. Testbed Design and Methods

Partial discharge (PD) and dielectric strength measurements were taken using the testbed shown in Fig. 2 [6]. Each PDMS-Fe composite sample is placed in the container and submerged in transformer oil to suppress surface flashover and surface discharge. The container was designed with an aluminum bottom so that the bottom surface of the sample would make an electrical connection to the ground plate. The testbed was configured to ensure firm contact between the high voltage electrode, sample, and ground plate without deforming the sample.

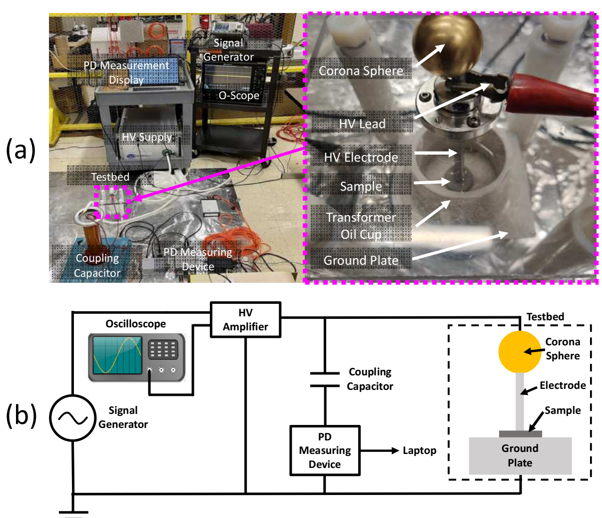

Fig. 2. (a) Testbed for conducting PD and breakdown measurements and (b) circuit diagram of testbed. (Note: Coupling capacitor and PD measuring device are not used for breakdown measurements.) [6]

For both PD and dielectric strength measurements, the electrode was connected to a high voltage amplifier, and a 60 Hz sinusoidal signal was applied. For the PD measurements, the voltage was slowly increased until PD was detected by the measurement system, and this voltage—the partial discharge inception voltage (PDIV)—was recorded. The PDIV was then divided by the thickness of the sample to derive the PDIE. For the dielectric strength measurements, the coupling capacitor and PD detector were disconnected, and the voltage was slowly increased until the voltage signal collapsed to zero, indicating dielectric breakdown. The breakdown voltage (V_{bd}) was then recorded and divided by the thickness of the sample to derive E_{bd}. Three PDIE and three E_{bd} measurements were taken for each type of sample.

B. Experimental Results

PDIE and E_{bd} measurements for each type of PDMS-Fe composite are shown in Fig. 3. The PDIE of the composite containing irregularly shaped Fe particles is approximately 40% higher than that of the composite containing the same volume of spherical Fe particles. The E_{bd} of the composite containing irregularly shaped Fe particles was just over 20% higher than that of the composite containing the same volume of spherical Fe particles. The lower PDIE and E_{bd} for the spherical Fe is possibly due to electric field enhancements caused by the smaller radii of the spherical Fe particles [6].

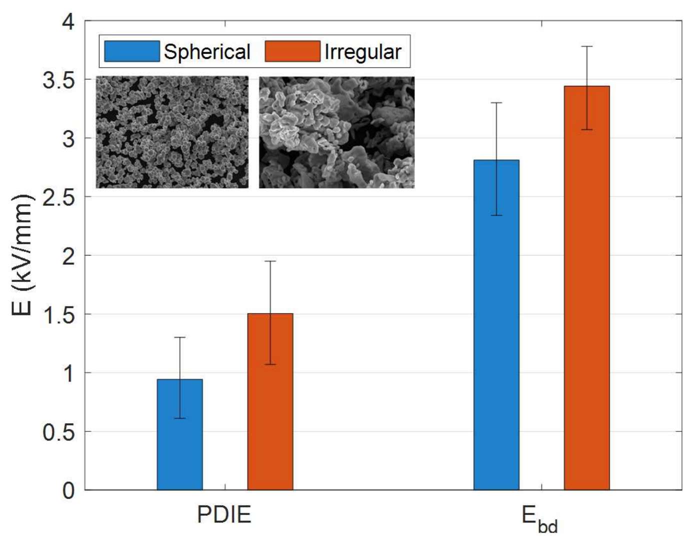

Fig. 3. PDIE and E_{bd} of PDMS-Fe composites composed of Fe at 10 vol% concentration

IV. Finite Element Analysis

To gain a better understanding of the effect of each type of Fe filler on the electric field distribution within the composites, FEA models of each type of composite were developed. To facilitate modeling, the irregularly shaped Fe particles were simplified to ellipsoids to account for the sharp edges. Also, to account for the larger particle size of the irregular Fe, the cross-sectional area of each ellipsoid was multiplied by a factor of 10 compared to the cross-sectional area of each of the spheres. Two-dimensional models were used to represent a cross sections of the samples, where the cylinders are represented by rectangles, spheres are represented by circles, and ellipsoids are represented by ellipses. The properties of Fe (conductivity of

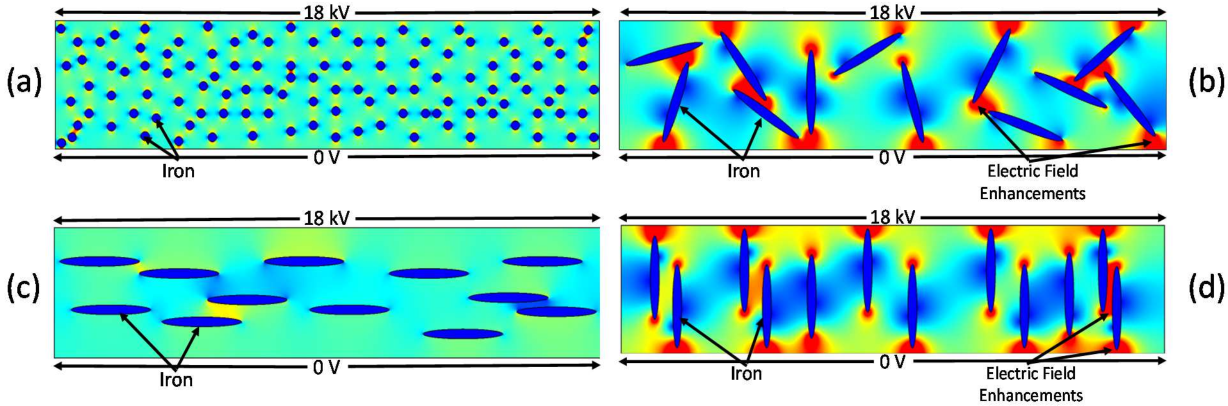

Fig. 4. Electric field distribution under voltage stress of 18 kV, 60 Hz. (a) Spherical Fe, (b) randomly oriented ellipsoidal Fe, (c) horizontally oriented ellipsoidal Fe, and (d) vertically oriented ellipsoidal Fe.

10^7 S/m and relative permittivity of 1 were applied to the circles and ellipses while the properties of PDMS (conductivity of 10^{-13} S/m and relative permittivity of 2.86) were applied to the spaces in between the fillers. An 18 kV, 60 Hz sinusoidal voltage was applied to the top edge of each sample, and the bottom edge was set to 0 V. Because the ellipsoidal particles may affect the electrical field distribution differently based on orientation, they were modeled at random, vertical, and horizontal orientations.

Plots of the electric field distribution of each sample are shown in Fig. 4, and the average electric field in the PDMS for each model is shown in Fig. 5. Based on these models, vertically oriented ellipsoidal Fe particles produce the highest electric field in the PDMS, and horizontally oriented ellipsoidal Fe particles produce the lowest electric field. Assuming random particle orientation and arrangement, the average electric field in the ellipsoidal Fe composite is approximately 10% higher than that in the spherical Fe composite due to the sharp edges on the ellipsoids near the voltage and ground edges [6].

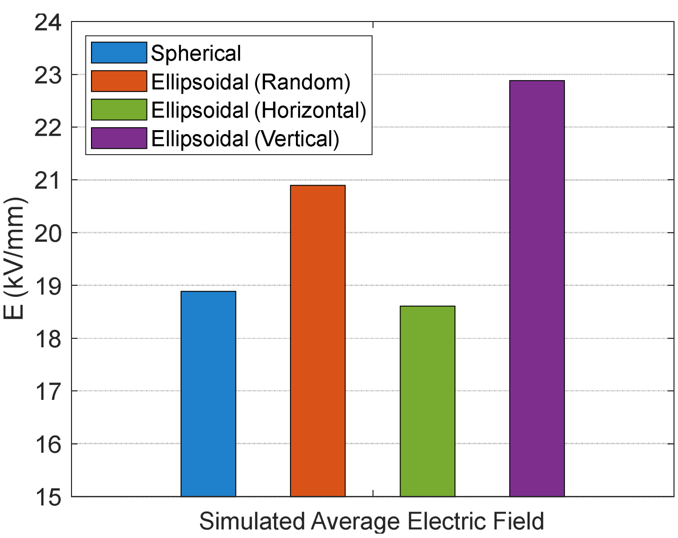

Fig. 5. Average electric field within the PDMS derived from FEA models shown in Fig. 4.

V. Discussion

In this study, PDIE, E_{bd}, and electric field distribution in PDMS-Fe composites were found to be highly dependent on the geometry of the Fe particles. While PDIE and E_{bd} are lower for the composites containing spherical Fe particles, FEA models predicted the randomly-oriented large ellipsoidal Fe particles to enhance electric field greater than small spherical Fe particles due to their sharp edges and greater surface area [6]. Because higher electric field in a dielectric at a given voltage is correlated to lower PDIE and E_{bd} [8], the trend of the simulation is in direct opposite with that of the experimental results. The discrepancy suggests either 1) ellipses are not the accurate representation of the irregularly shaped Fe particles, or 2) the horizontal alignment of the ellipses is the true representation of the samples used in the experiment. Because irregularly shaped particles are difficult to model accurately, the viability of FEA modeling of electric field distribution predicting the PDIE and dielectric strength of metal-polymer composites containing irregularly shaped metal particles is limited. Furthermore, metal fillers used in the formulation of metal-polymer composites should be of uniform size and regular shape to avoid variability in PDIE and dielectric strength.

VI. Conclusion

In this work, PDMS-Fe composites were fabricated using small spherically shaped Fe particles and large irregularly shaped Fe particles. Both composites were characterized using PD and breakdown measurements and FEA electric field distribution models. The results of this investigation suggest that PDIE, E_{bd}, and electric field distribution are highly dependent on filler geometry. Composites formulated with small spherical Fe particles have a lower PDIE and dielectric strength than those formulated with large irregular Fe particles. Furthermore, this study supports the necessity of accurate FEA modeling of filler particles in metal-polymer composites and suggests that highly simplified FEA models of metal-polymer composites with irregularly shaped fillers are of limited viability.

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