EFFECT OF POROSITY ON ELECTRICAL INSULATION AND HEAT DISSIPATION OF FUSED DEPOSITION MODELING PARTS CONTAINING EMBEDDED WIRES

Kazi Md Masum Billah*, Jose Luis Coronel Jr*, Ryan B. Wicker *, and, David Espalin*

*Department of Mechanical Engineering, The University of Texas at El Paso, El Paso, TX, USA, 79968
*W.M. Keck Center for 3D Innovation, El Paso, TX, USA, 79968
Corresponding email address: kbillah@miners.utep.edu

Abstract

While the effects of porosity on the mechanical strength of fused deposition modeling (FDM) parts have been thoroughly investigated, there exists a need for evaluating electrical and thermal properties. This work describes the method of determining the effect of porosity that resembles 3D printed electronics. In addition to mechanical strength, determination of desirable limit of electrical insulation and heat dissipation will allow the additive manufacturing community to fabricate power electronics components with reduced cost and improved performance. For experimentation, three different sets of coupons were fabricated using Polycarbonate (PC) thermoplastic with embedded bare copper wire. Characterization included high electrical stresses and thermal testing to determine the effect of porosity on insulation and heat dissipation, respectively. During electrical characterization, higher wire density resulted in reduced breakdown strength. In thermal test, the comparisons between as fabricated and heat-treated specimen showed that heat dissipation increased by an average of 30 % to 40 %.

Introduction

In the polymer material extrusion additive manufacturing (AM) community, there is an immense interest in the fabrication of multifunctional parts by incorporating two or more manufacturing processes. An example of these processes is machining which is used to improve the surface finish of fused deposition modeling (FDM) built substrate, enhancing the quality of the part. Both operations could be done as post-processing. Printing and interrupting the build is a luxury one has with an FDM system as it allows the manufacturer to introduce new component as well as conventional machining if necessary. The pausing advantage can be taken in a continuous AM process by incorporating a second manufacturing platform that will allow the further customization on fabricated parts. For this type of component integration platform, the Multi^{3D} foundry system is a prime example [1]. The foundry system includes the introduction of an electrical component, a pick and place, machining, and embedding circuitry elements within the printed parts. For example, wire embedding on the fused deposition modeling (FDM) part is one the processes of increasing the part functionality such as electrical, mechanical, and thermal.

While the improvement of mechanical properties of FDM built parts is taking a continuous effort in designing new materials, and the development of process parameters, porosity remains as an inherent challenge for many applications. Several factors such as resolution, the temperature of the printing environment, and thermal gradient within the rasters are responsible for the formation of voids. Although tissue engineering application was the primary focus, authors in [2] showed that the raster gap size has a dominant effect on the porosity, pore diameter, and the mechanical strength of the part. For example, ABS specimen with 0.1 mm raster gap had a compressive strength of 14 MPa and doubling the raster gap to 0.2 mm reduced the strength to 8 MPa. On the contrary, 30 % porous (vol.) ABS specimen had compressive strength 17 MPa, while the specimen with 60% porosity had a value of 8 MPa. In a separate design experiment, it showed that every 20 % (vol.) increasing of porosity within ABS specimen was reducing the mechanical strength by 5 MPa [3]. Therefore, it is obvious that changing printing parameters is not enough to avoid the porosity within parts; improvement of the mechanical properties requires further post-processing procedures.

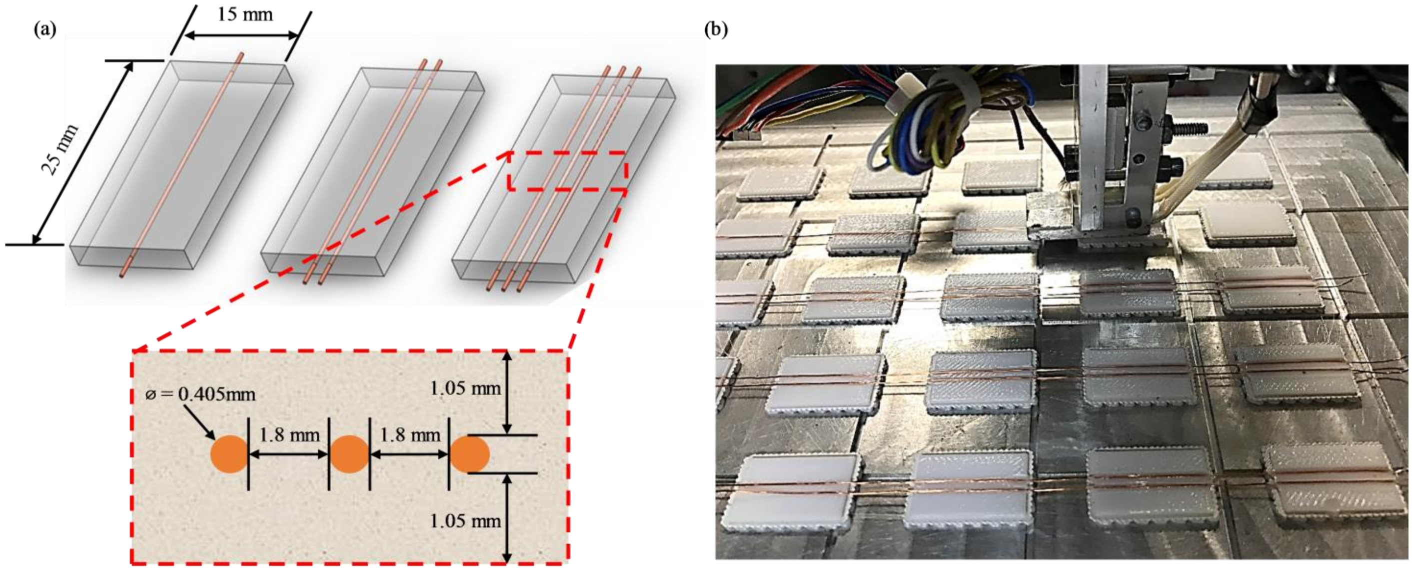

Figure 1. (a) CAD for fabricated coupon and (b) fabrication of wire embedded coupon using thermal wire embedding tool

Knowing the presence of voids in printed part, tremendous effort is being made to increase the application-based AM, specifically for 3D electronics fabrication, however, the effect of porosity remains unexplored. One of the major challenges of porosity on electrical parts is the failure of breakdown strength. Breakdown strength, also known as high electrical potential (hipot), is the ability to withstand sudden rise of voltage of an insulating material. For example, in medium voltage application (300~1000V), breakdown strength is an essential parameter to ensure the reliability of the manufactured part. Another challenge of the porosity is the decrease in thermal conductivity of a printed part. Within the part, air has a conductivity value of 0.02 W/m/K, and plastic varies from 0.18~0.22 W/m/K. Using Voigt's rule, the increase of the porosity results in a lesser amount of combined thermal conductivity in the part. Knowledge of heat dissipation on FDM parts will explore a new dimension in 3D electronics fabrication with advanced and efficient thermal management.

Although the mechanical properties are heavily demonstrated by myriads of article in past, this research was aimed to investigate the effect of porosity on electrical and thermal properties of an FDM built parts. Particularly in 3D electronics fabrication and characterization, the necessity of knowing the effect porosity has on breakdown strength and heat dissipation is undoubtedly essential to explore new product development and production. Additionally, the findings of this research would help to improve the thermal management plan, electrical safety, and operational reliability. To accomplish these specific set of goals, coupons were fabricated using polycarbonate (PC) with material extrusion AM and embedding bare copper wires followed by characterizations: high potential insulation testing and thermal testing including heat treated and untreated test specimens. Lastly, it was anticipated that findings from these experiments can aid in designing future hybrid additively manufactured power electronics (such as stators, inductors for a wireless charger, or embedded transformers).

Fabrication

To investigate the effect of porosity in electrical and thermal performance of FDM parts, three sample sets, each containing fifteen specimens, of wire embedded coupons were fabricated. In each sample set, ten specimens were chosen and had either one, two, or three wires embedded within each specimen. Of the ten specimens within each group, five were tested in an as-fabricated condition while the other five specimens were heat treated before testing. The heat treatment consisted of placing the specimens in an oven for two hours. The oven temperature was set at 165 ºC, which was above the glass transition temperature of PC (161 ºC), to promote polymer chain mobility and reduction of voids while limiting temperature induced dimensional changes, which were more pronounced above 165 ºC. The 3D printing was accomplished by using a Multi^{3D} foundry system which can be read in details at [1].

In this research, a FDM Fortus 400Mc machine (Stratasys, Eden Prarie, MN, USA) in Multi^{3D} foundry system was used to deposit polycarbonate (PC) (Stratasys, Eden Prarie, MN, USA) and embed a series of 26 AWG (Ø = 0.405 mm) bare copper wires (Arcor Electronics, Niles, IL, USA) in an automated fashion. The embedding of bare copper wire within the PC was accomplished in following steps (i) dispensing PC material to produce a substrate, (ii) transferring the workpiece via the six-axis robot to the CNC machine where wire embedded using a cartridge heating wire embedding tool, and (iii) transferring the workpiece back to the FDM printer to dispense PC onto the substrate. **Figure 1** (a) is a computer-aided design (CAD) representations for each of the three sample groups. The 3D printing layer thickness was set at 0.254 mm (0.010 inch). The coupon was fabricated by stacking six PC layers before embedding the copper wire, which was embedded within the sixth PC layer and occupied approximately half the thickness of the fifth PC layer. In **Error! Reference source not found.** (b), wire embedding on PC substrate at CNC router is shown. A build interruption in FDM printing was made to transfer the build platform to CNC router and embedded the wire.

Experimental Methodology

Three characterization techniques were used to determine the effect of porosity including (i) hipot testing using AC or DC, (ii) thermal testing, and (iii) cross-sectional micrograph analysis.

Hipot testing

According to IEEE Std. 1995 1995 [6], both AC and DC hipot testing was done in this work. AC hipot testing voltage was chosen by the following equation:

$$V_{Test} = \left(2 \times V_{Operational} + 1000\right) \qquad \{1\}$$

In the case of DC hipot testing, the test voltage was chosen using the following equation:

$$V_{Test} = \left(2 \times V_{Operational} + 1000\right) \times 1.7 \qquad \{2\}$$

A HiPot-3870 Tester with device under testing (DUT) enclosure (Associated Research Inc., Lake Forest, IL, USA) was used to conduct the experiment. The conductive copper wire was connected to the high voltage electrode while the insulating polycarbonate was connected to the low voltage electrode of the hipot tester where "Test" and "Operational" are the expected and end-use operating voltage, respectively. During AC hipot test, the considered $V_{operational}$was 2,000 V (ramp 0.1s) and dwell time of the test was 10 s. The DC test was performed similarly to the AC test by considering $V_{operational}$ as 970 V, which resulted in a V_{Test} of 5 kV. In the DC test, the ramp was 5 s and total dwell time was 1 minute.

Thermal testing

The steady state surface temperature of the printed thermoplastic was determined by simulating the Joule heating effect within the embedded wire using ANSYS steady state thermal module (ANSYS, Inc., Canonsburg, PA). Boundary conditions in the modeling included using a convective heat transfer coefficient (*h*) of 12, 15, and 15.27 W/m^2/°C for all six sides of the one-, two-, and three-wire thermoplastic coupon respectively, an effective conductive heat transfer coefficient (*K*) of 0.182 W/m/K (using Voigt's model)

Thermal testing was performed using the Joule heating principle to generate heat within the embedded copper wire (26 AWG or Ø = 0.405 mm) by supplying current (5 A) from a DC power supply (BK PRECISION 9115, B&K Precision Corporation, Yorba Linda, CA, USA). Two K-type thermocouples were placed on the top and bottom surface of the specimen to collect the surface temperature. Data acquisition unit NI – cDAQ 9426 (National Instruments, Austin, TX) was used to measure temperature. Data were acquired every second for a total duration of two hours. For each test specimen, three separate tests were performed at different times to verify the repeatability of the experimental data.

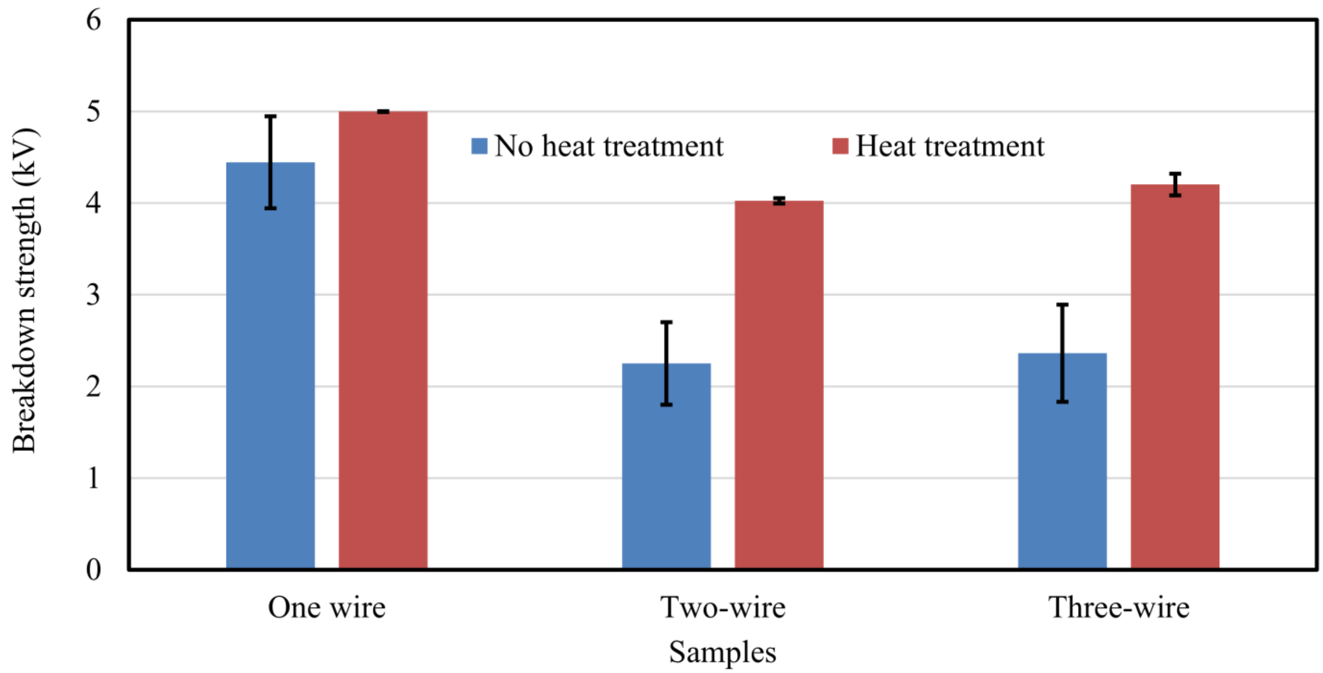

Figure 2. AC hipot testing before and after heat treatment of wire embedded coupons

Results and discussion

Electrical characterization

As it mentioned earlier that electrical breakdown strength was measured in both AC and DC test. AC hipot testing of the coupons containing embedded wires was designed to test the ability to withstand low and medium voltages. To keep in mind that, it was not the goal to determine the dielectric strength of the PC material, rather it was to observe the effect of voids in insulating materials. **Figure 2** shows the average breakdown strength (AC hipot testing) from five measurements for each group before and after heat treatment. The measured breakdown strength ranged for one-, two-, and three-wire untreated specimens (with constant thickness of PC at 2.5 mm) were 4 - 4.8 kV, 1.98 - 2.6 kV, and 2 - 2.8 kV, respectively. It was expected that breakdown strength of coupons would decrease with increasing number of wires, which was found in one-wire and two-wire specimens, however, the comparisons of the two-wire and three-wire specimens did not agree with the expectation. It was assumed that supper position of electric field is responsible for lowering the breakdown strength.

Breakdown strength of heat-treated specimen was increased as shown in **Figure 2**. Among the 5 tests, four of the one-wire breakdown strength was above 5 kV. In the case of the two- and three-wire specimen, average breakdown strength was 4 – 4.03 and 4.15 – 4.3 kV, respectively. During DC hipot testing, all the specimens from the three sample groups passed (i.e., did not breakdown) when subjected to 5kV in both the heat-treated and untreated condition.

Thermal characterization

The steady-state substrate surface temperature of one-wire specimens was simulated 51 °C **Figure 3**(a). The empirical surface temperature for the same specimens without heat treatment was measured as 38°C. After the heat treatment a steady state surface temperature of 51 °C was observed as shown in **Figure 3**(b). While the heat-treated surface temperature was in close agreement with the simulated temperatures, the non-heat-treated surfaces was substantially lower. The mismatch is attributed to the inherent porosity of printed parts, which influences the conductive heat transfer coefficient.

In the case of two-wire and three-wire specimens shown in **Figure 3**(c) to (f) the simulated and empirical substrate surface temperatures had close agreements. Since the number of wire increased, relatively higher temperature was measured on the PC surface. Besides the PC surface temperature, a sound agreement of analytical

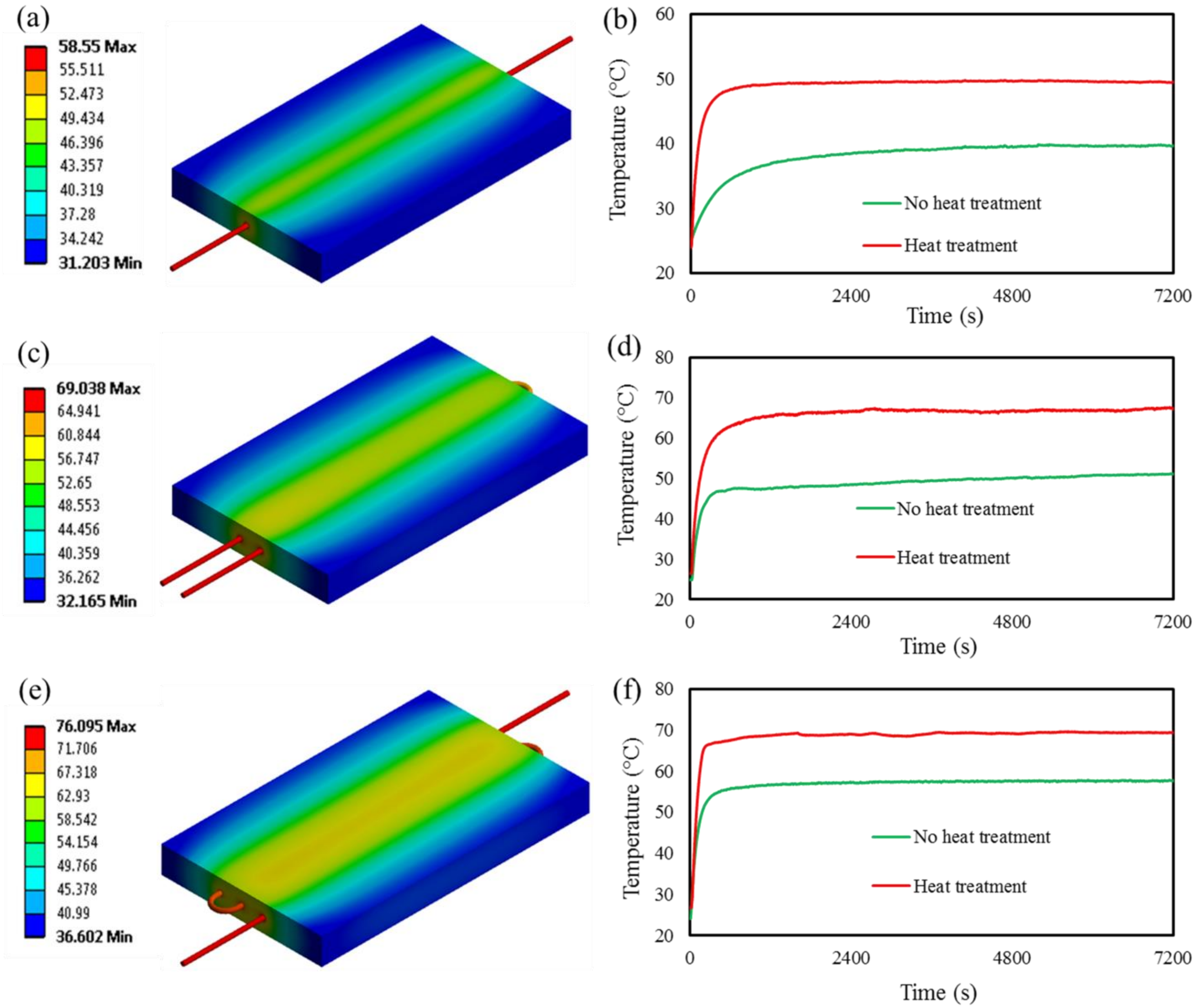

Figure 3. Temperature contours and experimental temperature plot of wire embedded coupons.

and simulated temperature of the embedded conductor surface was found. All sets of thermal testing results showed agreement of temperature difference between heat-treated and untreated specimens as well as with the analytical temperature. Now it is obvious that porosity reduction increases the heat conductivity because air has a lower thermal conductivity (0.02 W/m·K) which was filled up by the expansion of each rod of PC during heat treatment.

Micrograph analysis

To further confirm the reduction porosity and subsequent effect on breakdown strength and heat dissipation of heat-treated specimen, micragraph analysis was performed. Scanning Electron Microscopy (SEM) images of heat-treated and untreated 3D printed specimens revealed reduction of porosity. For example, thermal testing of untreated specimen confirmed that the presence of porosity reduces the heat dissipation whereas the heat-treated specimen having less porosity also had higher heat dissipation. The higher heat conduction was the result of reduced voids by the expansion of PC rod and ultimately the bulk of PC. In **Figure 4** the presence of porosity is in heat treated and untreated specimen is shown. Therefore, the main finding was the reduced porosity led not only the higher heat dissipation but also increased the breakdown strength.

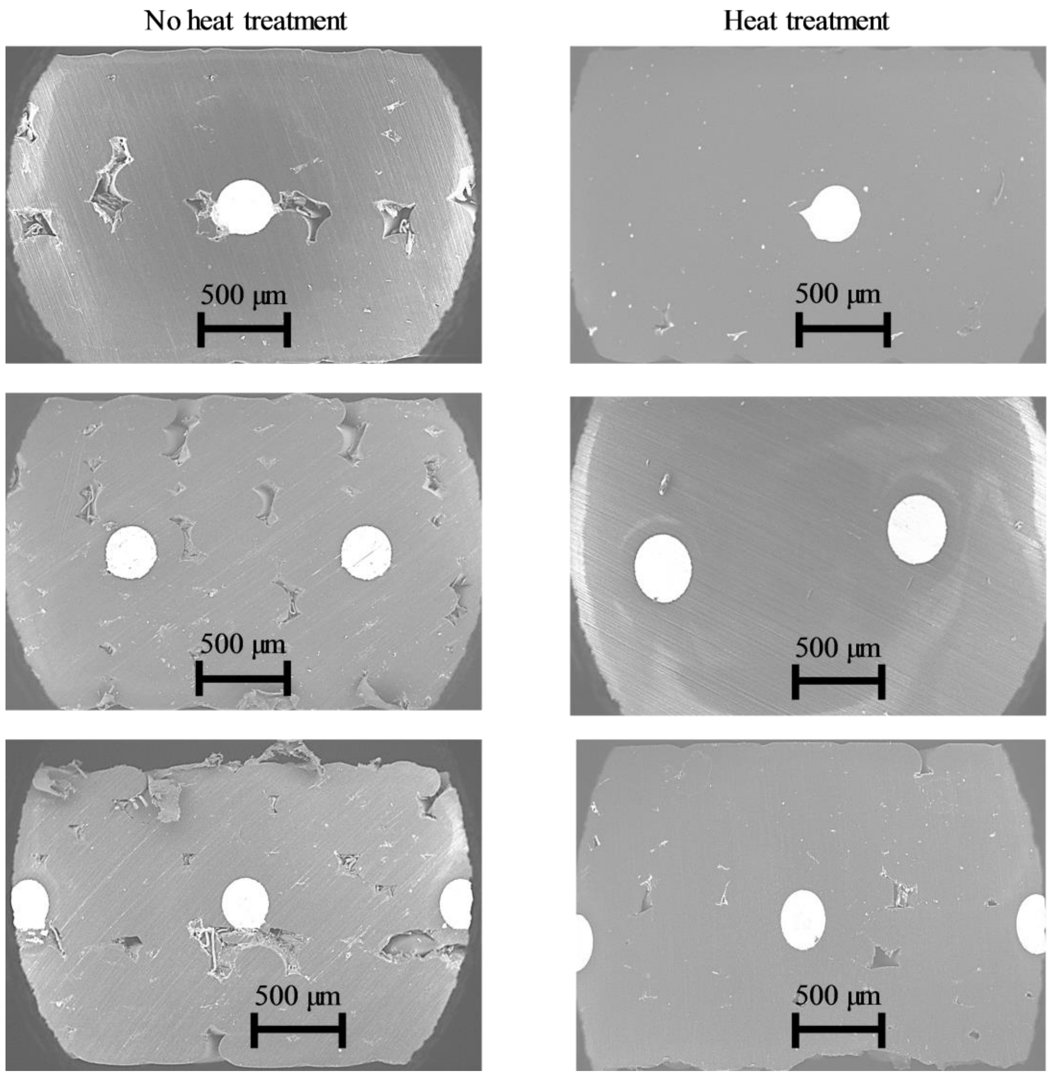

Figure 4. SEM image of cross sectioned specimen before heat treatment (a) one-wire, (b) two-wire, (c) three-wire and after heat treatment (d) one wire, (e) two-wire, and (f) three-wire.

Conclusion

This research paper described the effect of porosity in electrical and thermal performance of material extrusion 3D printed parts containing embedded solid conductor. Test coupons containing PC substrate material and embedded bare copper wire were fabricated using an automated hybrid additive manufacturing process via the Multi^{3D} system. Through experimental testing of wire embedded coupons that has voids, the ability to withstand at high electrical stress was determined. Thermal testing was conducted to confirm the hypothesis of improving the porosity by heat treatment. Following three conclusions were made from the present studies to strongly support the claim of effect of porosity on electrical insulation and heat dissipation of 3D printed parts:

1. Heat treatment of wire embedded specimen increased the breakdown strength of each group. For example, two-wire untreated specimen had average AC breakdown strength 2.4 - 2.8 kV while after heat treatment it was 4 – 4.2 kV. Therefore, the effect of porosity was found in breakdown strength by conducting tests before and after the reduction of voids in printed parts.
2. Untreated specimen had inherent porosity that led the lower heat dissipation. Heat treated specimen had higher heat dissipation. This was quantified in each case such as the three-wire coupons were substrate temperature increased from 56°C to 71°C after reducing porosity by heat treating. Additionally, simulated and empirical data had good agreement in terms of surface temperatures of each group.

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