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STRUCTURAL HEALTH MONITORING OF 3D PRINTED STRUCTURES

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Abstract

3D printed parts are used in industry for both tooling application and smaller parts in assembled structures. Articles made through polymer based additive manufacturing are anisotropic and may have defects throughout the part. For instance, the layer to layer interactions are weaker than the in-plane printing which can cause delamination of the layers. Identifying when and where the cracks form can be very difficult if the cracks are inside the structure This paper introduces an innovative patent-pending method to monitor polymer-based 3D printed structures for internal failures by printing a highly sensitive conductive material into the part itself. When a section of the conductive material inside the part is damaged or split, the resistance across the conductive pathway increases which will indicate that the article has been damaged. We present several small printed circuits and observations that show as a crack is introduced to the structure, the resistance measured increases which alerts users that a crack has formed/propagated.

Introduction

Rapid advancements in the field of Additive Manufacturing (AM) has led companies to produce both large-scale and small-scale printers varying in size and feedstock material options. This facilitated the expansion of AM to cover a wide variety of applications ranging from small demo articles to large tools and dies for composite manufacturing [1]. One of the most common polymer AM methods is Fused Filament Fabrication (FFF) or extrusion deposition where the printed part is built by extruding melted plastic layer by layer until the desired structure is achieved. Small scale printers have a limited build size of about 929 cm^2 and are relatively slow in speed, 100 mm/sec. Small scale printers use low-cost feedstock materials that come in a filament form such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) [2]. On the other hand, printers that are mid-scale (i.e. 5574 cm^2) such as Stratasys F900 or large-scale in size (i.e. 46,652 cm^2) such as Big Area Additive Manufacturing (BAAM) can print feedstock materials with high melting point such as polyetherimide, polyphenylsulfone (PPSU) or polyphenylene sulfide (PPS) [1]. FFF systems can be used in several applications that ranges from dental implants [3], to prototypes designs for small scale [2], and up to large scale applications such as molds, trim tools, and dies [1].

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Structures printed through FFF methods have anisotropic properties, and a good understanding for the materials rheological and thermal properties is needed in order to fabricate a minimal defect structure. There are several types of defects can be formed during the FFF process, such as voids, porosity, and cracks [4]. Defects such as micro-cracks and layers desponding could lead to a catastrophic failure to the printed structure. These defects occur due to several factors such as uneven heat profile during the print, porosity in the feedstock material, small clogs in printing nozzle, etc. Printed structures are 10-25% weaker for neat materials such as PLA or ABS in the Z-direction (i.e. Direction perpendicular to the deposition direction) [5], and 75-90% weaker in the same direction, Z-direction, when these materials are reinforced with carbon fiber [5]. When external loading is applied, in case of the presence of micro cracks, the printed part will fail far below the designed loading conditions. Researchers have investigated several quality control and inspection methods for metal-based AM [6]; however, limited efforts were conducted on polymers and composites AM [7]. Non-Destructive Test/ Evaluation methods (NDT/E) are quite challenging when performed on polymer and composite materials [8]. A common and standard NDT and inspection method is Ultrasound Testing (UT) [7]. The technique is used to detect several types of defects in polymeric material such as voids, cracks, and delamination [4]. One of the limitations of using UT inspection for 3D printed structures is the topography of the printed surface. In UT inspection scanning surfaces should be flat to avoid noise and deflection of the waves. Moreover, polymers are highly attenuative materials and scanning thick parts for micro cracks (i.e. < 200 μm) could be a challenge. Another common method is X-ray inspection. X-ray has a limitation for scanning polymer and polymer reinforced materials as thickness increases. Most of these techniques are localized techniques that require disassembling of the desired part (i.e. leading for operation/service down time), accessibility for the articles scanning surfaces, long inspection time, and in some cases expensive equipment. In this paper we propose an innovative structural health monitoring method that is based on resistivity properties of conductive materials that can be integrated to the structure during the printing process itself.

Conductive Material Monitoring (CMM) Method

In this process (patent pending [9]) a conductive feedstock material was used to integrate a customized conductive toolpath within a non-conductive FFF polymer printed structure. This custom toolpath is designed and fabricated to form a circuit in which the resistance can be measured, analyzed, and correlated to the internal changes of the printed structure. The resistance of the printed circuit can be expressed as

$$R = \frac{\rho L}{A} \ (1) \qquad \text{Eq. (1)}$$

where ρ is the resistivity, L is the length of the printed circuit and A is the cross sectional area of the circuit. The design freedom of the AM process provides a lot of possibilities for different circuit designs. The circuits can be strategically located at the points of interest where the fracture is likely to occur or the places where fracture should be immediately reported. Figure 1 shows a schematic for a design of an integrated parallel circuit printed within an AM structure. In case a crack propagates in a nonconductive section of the print, parallel circuits can be used to find crack location and crack length. Parallel circuits use contributions from the resistance of every branch in a structure to create an effective resistance. As branches in the circuit fail, the effective resistance changes according to the branches that remain undamaged in the circuit to create a new effective resistance. By controlling each individual branches' resistance by controlling the area and length of each branch, the change in effective resistance as each branch is broken by crack propagation can be determined to better understand how large the detected crack is. In similarity, by using varying resistive values for each branch, the change in effective resistance will correspond to each individual branch allowing users to identify crack location. Common prints where cracks occur such as compression molding tools, autoclave tools, large scale structures, etc. need structural integrity to fabricate final parts for industry. Identifying when these molds break allows for the operator to understand when their molds need to be replaced before their products are created saving time and money for the company.

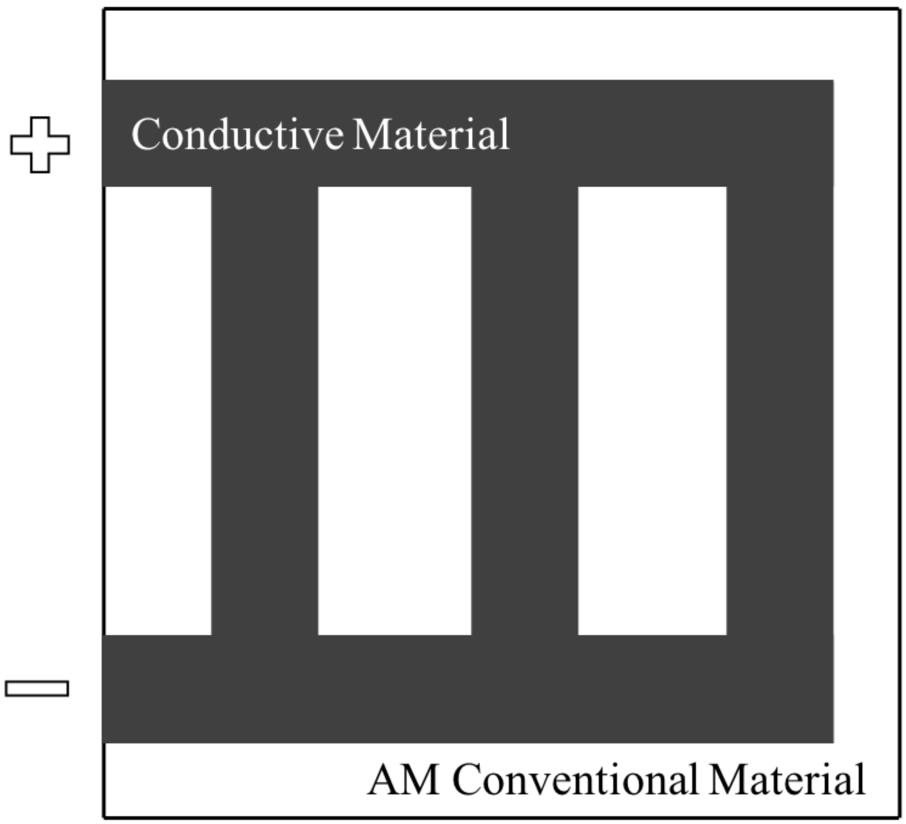

Figure 1: Schematic for a parallel embedded 3D printed circuit design

Experimental Setup

Sample Fabrication and Preparation

Neat PLA filament from Matterhackers was used for printing the AM structure. A graphene filled PLA with a resistivity of 0.6 Ω.cm was used as a feedstock material for printing the integrated circuit. The graphene filled PLA from Black Magic 3D has a graphene content of 5% by weight. A Makergear M2 with a dual extruder was used to print the sample. A printing speed of 60 mm/sec and a melting temperature of 215 ºC were used during printing of the sample. Figure 2 shows a g-code preview for the sample showing a 0º infill pattern used to print the sample. The infill pattern was carefully chosen to represent the layer to layer interactions observed in the out of plane direction. Since the out of plane direction in FFF printing is the weakest direction [1], most of the structures failure should start between the printed layers. To predesign the delamination failure mechanism, the structure should be printed in an orientation that the crack will propagate in the Z-direction during testing. However, printing tall structures with relatively thin bases is challenging due to the low stability during the build process. To overcome this challenge, the 0º infill pattern (see Figure 2) was chosen to represent the weakest axis. In order to control the location of crack propagation, the specimens were designed for fracture toughness tests with a designed notch at the middle of the sample to initiate the crack. Four samples where printed with a single circuit path. Figure 3 shows an actual printed sample with the integrated 3D printed parallel circuit design (i.e. graphene filled PLA "black in color") for structural health monitoring.

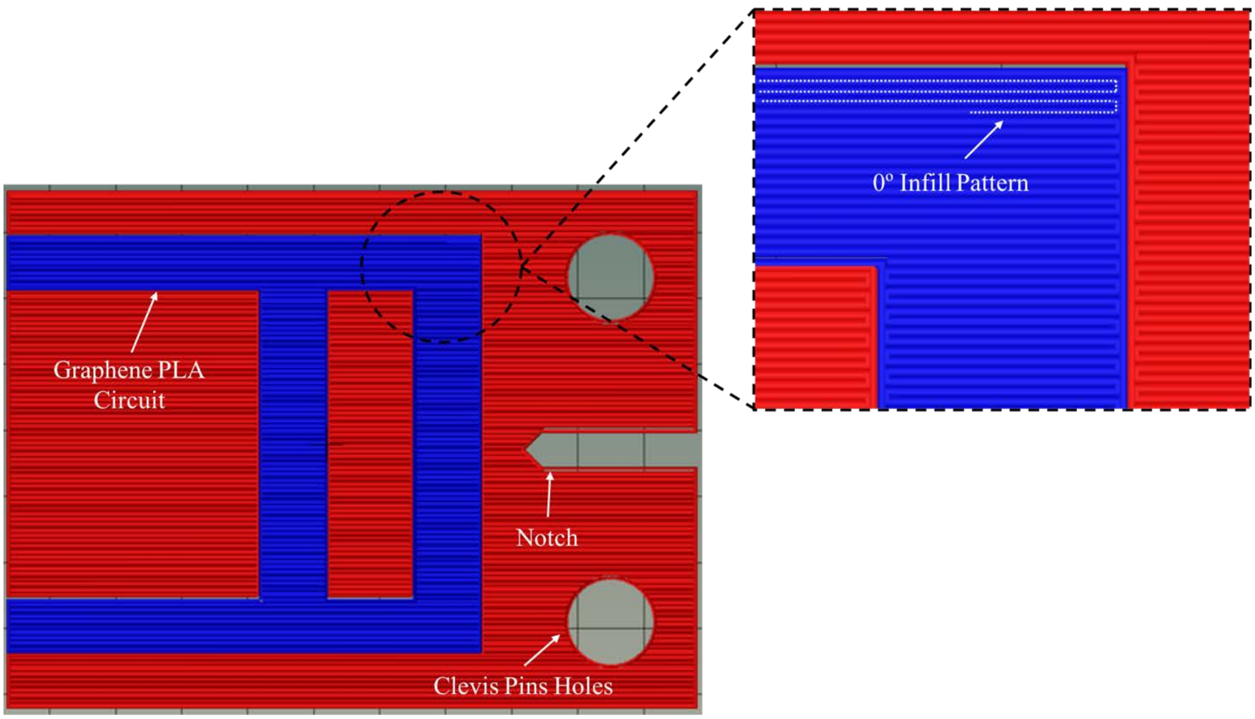

Figure 2: Schematic showing PLA printed sample with integrated 3D printed circuit design for structural health monitoring; the zoom-in area shows the 0º infill pattern

Integrated 3D Printed Circuit Testing and Evaluation

Since the printed structure has a rough surface, taking resistance measurements from the surface fluctuates over time will provide an inaccurate data. To reduce the measurement noise and fluctuations when the electric wires were attached to the sample, we melted the wire ends and the surface of the sample so that the wire and the sample fused together (see Figure 4). Melting wires into the conductive material allows for stable readings across the structure that are difficult to achieve with the rough surface area caused during the printing process. The samples were tested under tensile loading using a universal testing machine (MLP-500) with a rate of 10 mm/min. A digital multi-meter (Fluke 87 III) was used to acquire the resistance measurements. A reading every 5 seconds was acquired and plotted versus tensile force and time during the duration of the test until fracture.

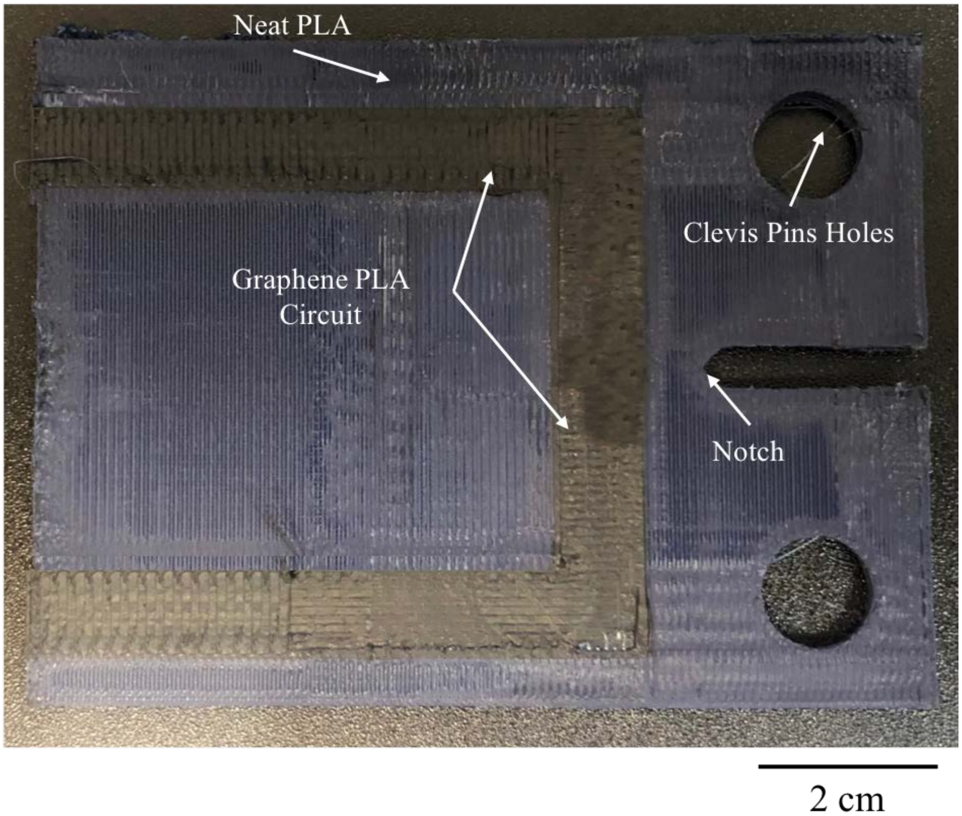

Figure 3: Actual printed PLA sample with integrated 3D printed circuit design (graphene filled PLA) for structural health monitoring

Results and Discussion

Figure 5 shows the resistance measurement in relation to the force applied to the sample. The graph can be separated to three distinguished regions. The first region shows the resistance measurement for a healthy (i.e. no defects) sample was 0.2 KΩ. Change in this value will indicate a change in the state of the internal structure. It can be noticed that loading the sample resulted in a crack propagation initiated at the notch area in a controlled manor (see Figure 4). In region two, the resistance measurement starts to increase to 20 KΩ when the crack propagated through the circuit. It was noticed that in region three, the resistance measurement spiked up to ~250 KΩ as an indication of the crack propagation throughout the entire printed circuit leading to a complete circuit failure. As the contact area used in sensing (i.e. conductive material) decreases, the overall resistance increases. The resistance is inversely proportional to the contact area as it can be observed in (Eq. 1). In theory, the resistance should go to infinity, materials themselves have a base resistance, and other factors contribute to a reading still being measured after complete circuit failure has occurred. The difference between resistance readings in each stage (i.e. healthy sample = 0.2 KΩ, damage = 20 KΩ, and fail = 250 KΩ)) is very distinguishable and can be used for monitoring defects formation in the printed structure. We have tested another sample and obtained a consistent trend (healthy sample = 0.3 KΩ, damage = 10 KΩ, and fail = 300 KΩ).

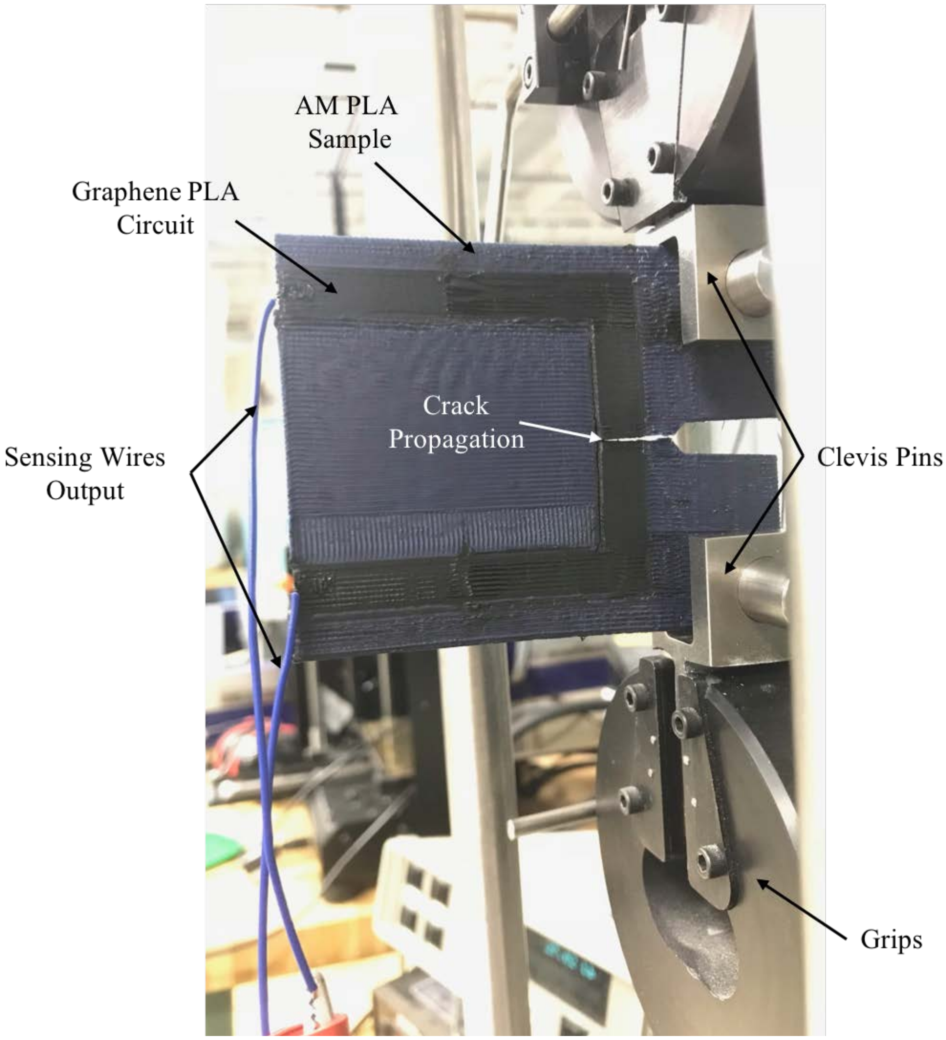

Figure 4: Experimental test setup

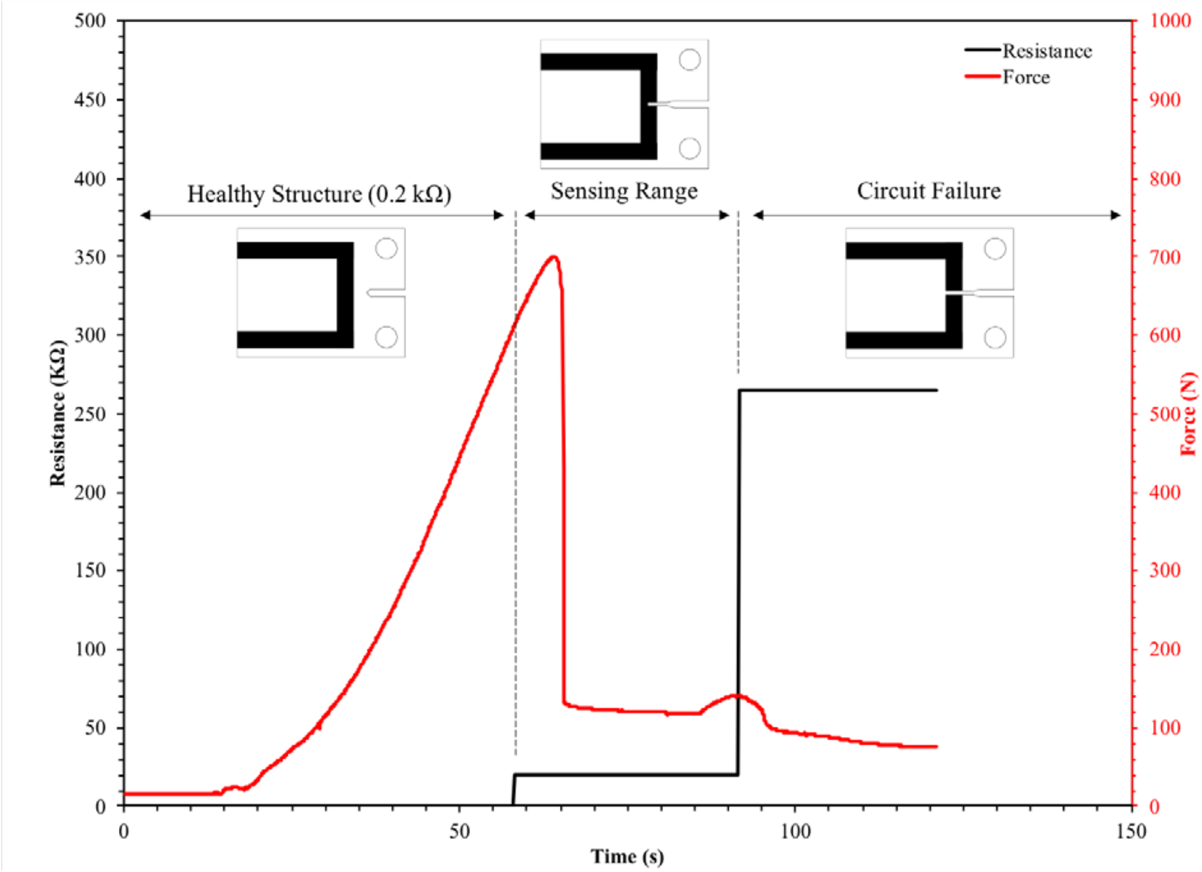

Figure 5: Resistance versus tensile force and time during the duration of the test and until full failure of the 3D printed circuits

Conclusion

Structures made through standard polymer-based AM process could contain different defects such as micro-cracks and voids that degrade mechanical properties and cause failures throughout the part. Detecting defects inside the structures is challenging using traditional NDT/E methods. Integrating self-sensing material to the printed structure showed that that internal defects such as crack propagation during service loading can be detected in early stages before catastrophic failure of the printed structure. Results showed that the resistivity change can be correlated to different stage of failure. Efforts on correlating the crack size and location to the acquired measurements are being investigated. Future studies should include the effect of inserting conductive circuits on the overall structural integrity of a part, the effect of different conductive materials, and methods to optimize the printed circuits within the FFF structure.

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