A DICUSSION ON THE POTENTIAL USE OF ADDITIVE MANUFACTURING FOR STRUTURAL HEALTH MONITORING

Authors: Ayranci, C.[1*] and Melenka, G.W.[1]
[1] Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada
* Corresponding author (cayranci@ualberta.ca)

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ABSTRACT

Additive manufacturing (AM) is a novel manufacturing method that can be used to produce complex, high quality components. This manufacturing method has gained increasing interest due to the advent of low cost desktop AM devices. With growing interest in AM researchers and designers are continuing to explore innovative applications that can benefit from this production technique. Structural health monitoring (SHM) is a process which integrates sensors within critical engineering components. The additive nature of AM structures lends itself to the incorporation of sensors within AM structures. Incorporating SHM within AM structures will lead to early detection of faults and defects in AM structures. SHM of AM structures will aid to increase the adoption of AM components since component failure can be mitigated with the ability to monitor damage and strain of AM components. This study presents an original methodology for incorporating SHM sensors with fused deposition modelling (FDM) AM structures. A dual extruder FDM three dimensional (3D) printer is used in order to fabricate a structure with an embedded sensor. Low cost polylactic acid (PLA) and a conductive filament Graphine-PLA filament are used to produce the AM structure and SHM sensor respectively. Preliminary results demonstrate that the conductive Graphine-PLA filament can be used to detect strain and deformation of AM structures. The methodology presented in this manuscript demonstrates a simple method for incorporating SHM in FDM fabricated components. The outcome of this work could have far reaching implications for AM structures since low-cost desktop 3D printers can be used to fabricate complex structures with embedded SHM sensors.

1 INTRODUCTION

Additive manufacturing (AM) is an advanced manufacturing process that produces components by adding layers of material to produce a final product. By contract, subtractive manufacturing operations, like milling or turning, removes material in order to form a final product. AM has grown significantly due to the advent of low-cost desktop three dimensional (3D) printers which use AM processes to produce a final component. Initially, AM processes were used to produce prototypes however this technology is more commonly being used to create functional components. A significant amount of research has focus on the characterization and improvement of mechanical properties of AM products in order to create functional products. Research is now focused on applying AM to advanced designs and structures. An emerging technology is use of AM in the construction industry to rapidly produce cement and concrete based structures [1].

The original and most general definition of additive manufacturing is adding thin layers of materials consecutively until a desired thickness and shape is achieved. All AM processes start with the design and drawing of the component/part using a Computer Aided Design (CAD) program. Then, this drawing is converted to a file format that is compatible with the particular AM machine that will be used. Finally, the part is prepared for the AM machine using a specific program that designates the different parameters during printing and sent to the printer. The very first AM technique was proposed in 1986 by Charles Hull for stereolithography apparatus which led to a patent [2]. After this, many different AM techniques have been developed such as laminated object manufacturing (LOM), selective laser melting (SLM), Laser metal deposition (LMD), and fused deposition modeling (FDM). Material Extrusion of Additive Manufacturing (MEAM), also known as Fused Deposition Modeling (FDM), is one of the most versatile and tailorable techniques in the market. MEAM machines and the materials are very affordable and versatile. These machines allow printing with more than one type of material, such as with different polymers but also with materials that are reinforced with different particles and fibers. This in return, provides tailorability of properties; such as elastic and mechanical properties and electrical and thermal conductivities.

Structural health monitoring (SHM) is a method which combines sensors with advanced engineering structures. SHM is commonly used in the aerospace and construction industries in order to monitor the integrity of advanced components. SHM commonly used in the aerospace industry to monitor critical structural components. SHM is also used in the construction industry to monitor the health of large scale structures like bridges.

Structures that are becoming increasingly larger and safety critical, of course, are also in need of advanced monitoring of structural integrity techniques, also known as health monitoring. Current health monitoring techniques that are available in the market depend mostly on strain sensing. Electrical Strain Gages (ESG), Linear Variable Differential Transducers (LVDT), Vibrating Strain Wires (VSW), Fiber optic gages (FOG) [3], Digital Image Correlation systems (DIC) are some of the systems used in health monitoring of structures. Although effective, these systems have their drawbacks. ESG and LVDT require skilled worker installation, geometry of the structures can pose challenges in installation and they also provide localized information, rather than global, which may lead to missing some critical areas in the overall structure. VSW have lower resolutions and are usually installed outside of the structures making them prone to environmental factors. FOG and DIC systems are very effective; however, they have labor intensive installation and calibration procedures and very expensive compared to the rest. As such, the AM technology, that is capable of fast-producing of shapes and structures can benefit tremendously from a health monitoring technique that is embedded into the production technique.

The goal of this manuscript is to investigate the feasibility of combining AM with SHM. Many researchers have focused on AM and SHM technologies but few have investigated the possibility of combining these two technologies. The additive nature of AM manufacturing lends itself to the incorporation of sensors within AM structures. The motivation of this manuscript is to present a novel new method for incorporating sensors within AM structures. In this work the authors present a low-cost methodology to incorporate sensors with desktop fused deposition modeling (FDM) 3D printers due to the aforementioned advantages it offers; however, the main concepts can be easily extended to other types of AM techniques as long as the demands of the design can be produced with the selected technique. One other reason behind the selection of the MEAM technique for this work is its general ability to be scaled up. Although the proof-of-concept studied here was demonstrated using a small scale MEAM machine (less than 50 cm x 50 cm x 50 cm production dimensions), recently many machines that are capable of much larger volumes (larger than 1m x 1 m x 1m) became available in the market [4]. In fact, there are a number of successful examples of similar machines that are capable of printing full concrete buildings in less than a few days. Examples of large machines capable of micro aerial vehicles, drones or small airplanes are expected to follow soon.

2 STATE OF THE ART

2.1 Structural Health Monitoring

Structural health monitoring (SHM) is an integrated sensing strategy to detect damage and failure of engineering structures. SHM is of particular interest in the aerospace industry. Many aerospace components require regular inspections using non-destructive methods like ultrasonic inspection, Bragg Grating or eddy currents [5]. Regular inspection of aerospace components can be costly and time consuming. The implementation of integrated sensors can reduce the need for costly inspections and lead to early detection of faults within in critical components.

Structural health monitoring is also important for large scale structures like bridges [6]. Health monitoring of large scale structures involves the implementation of sensors as well as the collection, processing and interpretation of sensor data. One of the major challenges with any SHM project is the collection, curation and interpretation of sensor data to make meaningful decisions regarding the safety and integrity of critical structural components. SHM of large scale structures is commonly achieved using sensors like: strain gauges, piezoelectric, fibre Bragg gratings, Microelectromechanical systems (MEMSs) [5].

Another example where health monitoring has been incorporated has been in the strain measurement of reinforced concrete [3]. A long gauge length strain measuring sensor was developed as an alternative to conventional strain measurement of concrete rebar. This project demonstrates the development of low-cost long-term measurement devices used to measure the damage and strain of concrete structures.

2.2 Additive Manufacturing

Additive manufacturing (AM) is a family of manufacturing methods that create three dimensional (3D) geometries by combining layers of material to form the final structure [7]. Example AM technologies include: stereolithography (SLA), laminated object manufacturing (LOM), selective laser melting (SLM), Laser metal deposition (LMD), and fused deposition modeling (FDM) [8]. Recently, FDM manufacturing has become increasingly popular due to the advent of low cost desktop-size AM machines. Initially, FDM and SLA printers were utilized to create prototypes and these machines were not used to create functional components. Newer FDM printers such as the MarkOne by Mark Forged create functional FDM 3D printed structures by reinforcing these components with continuous Glass, Carbon or Fiberglass fibers [9]. Other researchers are investigating the reinforcement of FDM filaments with short fibers to improve mechanical properties for functional components [10]. With the growing trend towards functional FDM 3D printed components the addition of health monitoring of these components will be of interest. An example of an FDM functional 3D printed component is shown in Figure 1. The ratchet wrench was designed and printed by NASA on the International Space Station. Since FDM and other AM products are becoming more common, an urgent need is rising for functional components that are produced with integrated health monitoring abilities. This will allow designers as well as operators to monitor the damage and failure of these components. Health monitoring of FDM components is especially important due to the laminar nature of this manufacturing process. Monitoring failures modes like delamination is necessary to ensure structural integrity.

Figure 1: Example functional 3D printed wrench manufactured using a low-cost desktop 3D printer. This wrench was designed for use on the International Space Station [11]. The ratchet wrench demonstrates the ability to create functional components using a FDM manufacturing process.

2.3 Structural Health Monitoring and Additive Manufacturing

The combination of structural health monitoring and additive manufacturing is an emerging technology. Many researchers have examined these two topics independently, however; very few researchers have attempted to combine AM and SHM. Since AM is an additive process, this technology lends itself well to the integration and embedding of sensors through various means.

SHM has been used for the monitoring of AM LMD metallic parts formed from Ti6Al4V titanium alloy [12]. Four-point bend tests and cyclic loading was used to evaluate the fatigue response of the LMD component and to evaluate the effectiveness of an integrated SHM sensor within the LMD specimen. This novel SHM system demonstrated the ability to detect faults and cracks in Ti6Al4V LMD test specimen.

Another recent study that implemented SHM with FDM parts used Acrylonitrile butadiene styrene (ABS) filament and vapor smoothing with acetone to create a water tight printed structure [13]. Structural health monitoring was achieved by embedding a capillary within the cross-section of a test sample. One major issue with this work is that the mechanical properties of ABS degrade due to acetone vapor smoothing. Combining a sensor using a conductive filament will help to overcome many of the issues of this work. A pressure sensor was used to measure pressure changes in response to strain of the test sample. Method requires the addition of a pressure sensor to measure pressure changes within the sample capillary. Using a conductive filament will overcome issues with the accuracy/ consistency of the 3D printed structure. A significant post printing process is also not required. The addition of pressure sensors or other measurement devices are not required.

The above two studies demonstrate the current work that has been performed on the integration of SHM sensors with AM materials. Work in this field is highly preliminary but will continue to grow exponentially with the wider acceptance of AM manufacturing methods.

2.4 Discussion on the future of the field

The emerging advanced materials in AM offers a unique and exciting opportunity for the advancement of SHM of AM structures. Some of the materials used in the aforementioned AM techniques require long research and development stages, such as the VAT resins. On the other hand, some AM techniques, particularly MEAM based machines; already have a wide variety of materials at designers and engineers' disposal and the available machines support successful utilization of these materials. In terms of the SHM, probably the most important factor that needs to be investigated in the filaments is the resistance of the material. Resistance is a function of the resistivity of the material and its length and cross sectional area. There are a number of conductive filaments in the market that that can be used for this purpose. Commonly used polymers for non-reinforced applications can also be found in conductive form; such as: PLA, ABS and Nylon (or Polyamide). Majority of these filaments are either graphene, carbon nanotubes or carbon black reinforced thermoplastic materials and comes with very high resistances. The resistances are in the range of 4,000 ohms for a 1 m length of 1.75 mm filament, such as the one used for this work.

3 METHODS

Samples were printed using a low-cost but very reliable FDM desktop printer (Ultimaker3, Ultimaker, Geldermalsen, Netherlands). The Ultimaker3 was selected for this study for its dual extrusion capability. Test samples were printed using 3D printer slicer software (Cura 2.4, Ultimaker, Geldermalsen, Netherlands). Two filaments were used with the dual head 3D printer polylactic acid (PLA) (1.75mm PLA filament, Ultimaker, Geldermalsen, Netherlands), and a conductive filament Graphine-PLA filament (Conductive Graphine PLA Filament GRPHN-PLA, Black Magic 3D, Calverton, NY). The sample geometry was designed using a computer aided design software package (SolidWorks 2016, Dassault Systems, Waltham, MA). The external dimensions of the test specimen were 20mm width by 5mm thick with an overall length of 60mm. The internal Graphine-PLA section had a cross-section of 4mm by 2mm. A schematic of the sensing device that is the ultimate goal of this manuscript is shown in Figure 2. Figure 2 demonstrates that a quarter-bridge Wheatstone circuit could possibly be used with FDM printed samples with and embedded sensor. This figure purports that conventional strain measurement circuit could be used in conjunction with FDM printed samples with embedded sensors.

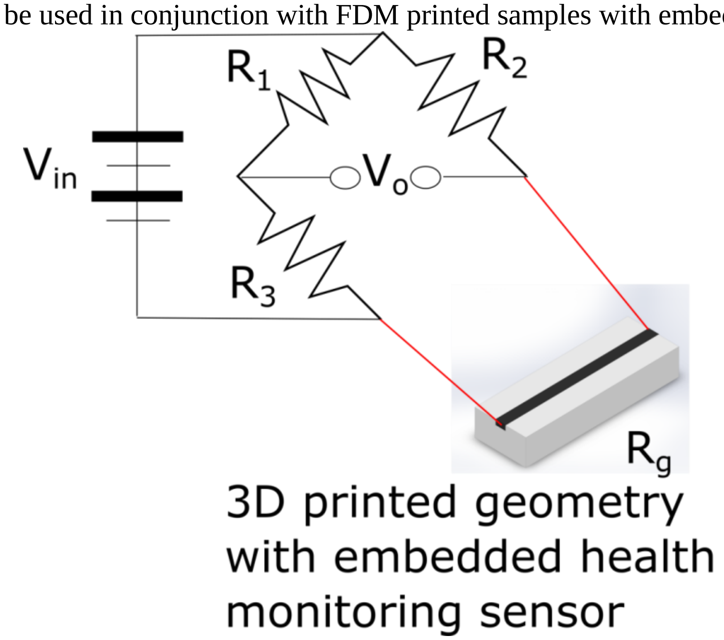
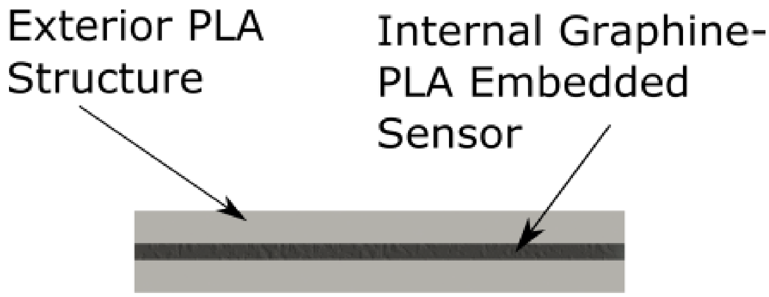


Figure 2: Schematic of a health monitoring sensor embedded within a FDM 3D printed structure

An example of the FDM printed geometry used in this study is shown in Figure 3. Figure 3 (a) shows a cross-section of the FDM printed sample. Figure 3 (b) shows the final printed specimen with the conductive Graphine-PLA filament shown in black.



(a)

(b)

Figure 3: Structural health test specimen (a) Longitudinal Cross-section of test specimen. Exterior PLA structure is shown as well as the internal conductive Graphine-PLA embedded sensor. (b) Printed specimen showing the external PLA structure and internal conductive filament used as an embedded sensor.

The resistance of the conductive ayer was measured using a multimeter (HHM14 Digital Multimeter, Laval, Quebec). The connection between the FDM printed sample and the multimeter leads were improved using a two part silver epoxy (Silver Conductive Epoxy 8330S-21G, MG Chemicals, Surrey, B.C., Canada). A weight set (ASTM Class 6 Weight Set, Ohaus, Dundas, Ontario, CA) was used to apply loads to the FDM samples. The test sample and multimeter used to measure the sample resistivity is shown in Figure 4.

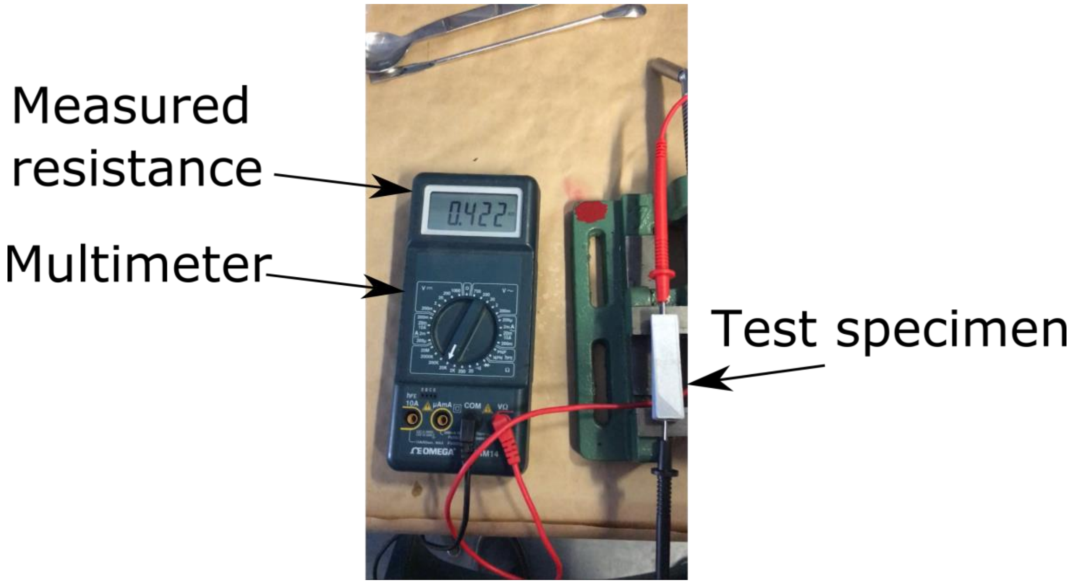


Figure 4: Example preliminary experimental setup to examine the ability to use conductive filament for health monitoring

3.1 *Preliminary Work and a Case Study*

A preliminary test was performed to determine if a change in test sample resisitivity could be recorded. As shown in Figure 4, the initial resistivity of the test sample without an applied load was found to be 0.422kΩ. Using the experimental setup shown in Figure 4 a load was applied to the mid-span of the test specimen. A maximum recorded change in resistance of 7Ω was recorded after applying a load to the mid-span of the test specimen. The initial test results demonstrate the feasibility of using a conductive Graphine-PLA filament as a structural health monitoring sensor within a PLA 3D printed structure. More extensive testing will be required to ensure that the method of using a dual extruder 3D printer with a conductive Graphine-PLA filament will be required to ensure this method can be effectively used for SHM.

3.2 *Future Work*

This study presents preliminary work on the SHM of FDM structures using a dual extrusion manufacturing process. A simplistic geometry was utilized in order to detect changes in sample resistance due to an applied load. The next step with this project will be to perform standard mechanical tests on FDM samples. A gamut of potential mechanical tests include: tension, compression, torsion, three-point and four-point bending and shear tests. Optimization of sample geometry and conductive filament sensor structure will be required for each of the prescribed mechanical testing producers. Validation of strain measurement with the conductive filament structure against conventional strain measurement methods like strain gauges, extensometers or digital image correlation will also be required to gain further confidence in the dual extrusion SHM approach outlined in this manuscript.

After validating SHM of FDM structures using conventional strain measurement techniques SHM can be implemented for FDM manufactured structures. Potential FDM structures that would benefit from SHM include:

3D printed prosthesis or 3D printed quadcopter drones. Both of the aforementioned structures could benefit from SHM.

Investigation of the adhesion of the dual extrusion materials is also required. Optical microscopy can be used to investigate the bonding of the external PLA structure with the internal sensing Graphine-PLA structure. Proper bonding between the conductive Graphine structure with the external sample structure will be necessary in order to obtain accurate strain or damage data.

Finally, investigation into the configuration and geometry of the internal SHM sensor structure is required. A concept embedded Graphine-PLA sensor is shown in Figure 5. This figure demonstrates a possible geometry that can easily be created due to the additive nature of FDM printed geometries. A "scissor" type internal sensor structure like the one shown in Figure 5 can easily be produced due to the FDM manufacturing process. Investigation into possible internal SHM sensor geometries and the benefits of these geometries will also be explored.

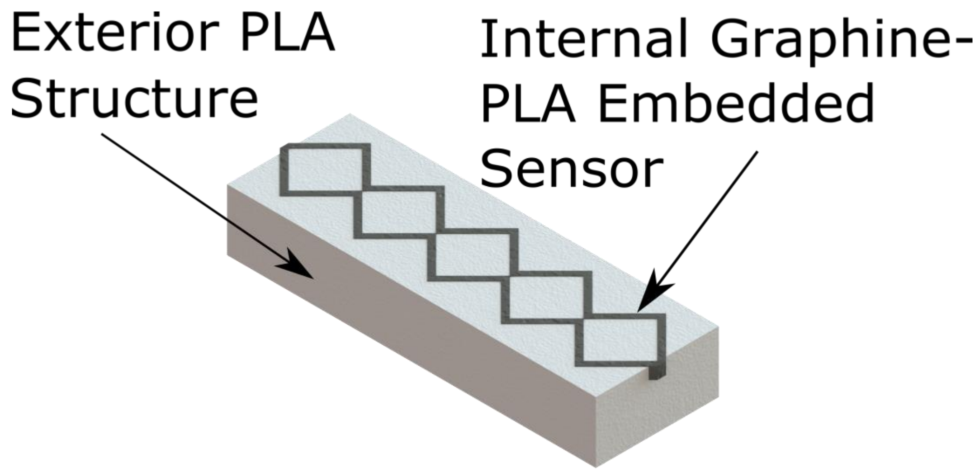


Figure 5: Concept SHM sensor configuration for a FDM printed structure.

Other important areas that will require research before using of the AM/SHM concept are calibration and characterization of the response of the sensors in non-uniform and not-straight geometries, such as corners. As stresses in corners and different radii are higher than the nominal stresses in a system, thorough calibration for these geometries are required. It is also equally important to address the post-yield characteristic of the sensors. In metallic wires, the gage factor of the sensors change dramatically once the yield point is passed due to the effect of increased dislocation density on the movement of the electrons. This portion in the polymeric conductive 3D materials needs to be well characterized to be able to assess the severity of loads/strains absorbed in damaged –but not failed- structures. Finally, of course, the temperature effect on the sensors needs to be investigated.

4 CONCLUSIONS

This study demonstrates a novel methodology for implementing SHM in FDM manufactured structures. Much work was been done in the fields of AM and SHM; however, few researchers have attempted to combine these two advanced technologies. In this work a conductive Graphine-PLA filament was used to form a small conductive cross section within a PLA structure using a dual extrusion 3D printer. Preliminary results demonstrate that the conductive Graphine-PLA filament can be used to measure resistance changes in response to an applied load. The methodology presented in this manuscript potentially has far reaching implications for low-cost desktop 3D printers since SHM sensors can easily be embedded within functional components using this approach. The approach outlined in this work can easily be implemented in order to introduction health monitoring into FDM manufactured structures.

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