Independent Study on Creating Conductive 3D Printed Polymers and Improving their Strength

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Abstract

An independent study class was introduced to students from Mechanical Engineering Department for investigating possibilities to create conductive 3D printed polymers and for improving the 3D printed polymers strength for harsh environmental conditions performance. Students planned their experiments and worked under the professors' guidance using advanced manufacturing and testing equipment to complete the task. The 3D printed polymer specimens were manufactured by fused deposition modeling and their mechanical properties were tested using Mark-10 flexural testing equipment. In order to create conductive structures, metallic coatings were deposited using DC high vacuum magnetron sputtering technique. The uncoated and coated 3D printed specimens were sequentially exposed to UV radiation, high temperature and moisture (ASTM G154 standard) using a Q-Lab QUV accelerated weathering system. The metallic thin films created conductive materials and improved the mechanical behavior of samples exposed to accelerated environmental conditions. After performing the required experiments and measurements, students worked on data collection, analysis and organized the information for future technical conferences.

Keywords

Independent study, 3D printed polymers, metallic coatings, weathering test, conductive polymers

Introduction

The study class was proposed to junior and senior students from the Mechanical Engineering Department, for a group consisting of maximum three students and involved research that was performed over few semesters. Students worked together as a "team for establishing the goals, plan tasks, meet deadlines, provide leadership and create a collaborative and inclusive environment" in conformity with Outcome 5 (ABET). The class initially involved performing literature search in order to help students understand the present situation in the given field of study. Students gathered knowledge from national and international published journals in the area of 3D printed polymers, with the focus on the electrical and mechanical performances. They applied the new knowledge to create conductive polymers, enhance their strength and environmental behavior (Outcome 7, ABET).

The predominant way of 3D printing is currently the fused deposition modeling in which a thermoplastic polymer filament is heated and then extruded to form the final object after it cools down. The ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) are among the most common polymer materials used in fused deposition modeling. Both ABS and PLA have high electrical

resistance and are susceptible to damage during exposure to ultraviolet (UV) radiation, high temperature and moisture. The use of thin metallic films for coatings is a topic of interest for enhancing the electrical and mechanical properties of 3D printed polymers while the resulted structures have reduced weight and volume. Magnetron sputtering technique offers a good coating possibility using low temperature conditions (room temperature). The metallic coatings (e.g. copper and silver) are providing protection, enhancing the wear, erosion, and degradation resistance of polymer-based substrates [1-10]. They possess high ductility, adherence to the substrate, high thermal expansion coefficient and good corrosion resistance. The research examines the conductivity of polymers after applying metallic coatings and the weathering effects of UV radiation and moisture on coated and uncoated 3D printed polymers.
The independent study class is a three credits class and has fix and flexible components. Each week there is a fix one-hour meeting time for literature search discussions and progress report while there is flexibility granted to students for performing the experiments, taking measurements and data analysis.

Methods

The Dimension SST 1200es 3D Printer (Stratasys) was used in order to produce the ABS and PLA based 3D printed structures of standardized dimensions (ASTM D790 standard [11]). Samples were cleaned with water and soap followed by ultrasonically cleaning in isopropyl alcohol (99%) before coating. Samples were placed for coating on a circular plate and loaded in a high vacuum DC magnetron sputtering chamber. Both sides of the specimens were metallic coated with one micrometer thickness. The base pressure in the chamber was monitored using an ion gauge and it was established at 1×10^{-3} Pa. The 6575 Agilent DC power supply was used to apply one-volt potential to the metallic coated samples and observe their electrical conductivity after performing the coating and after exposure to harsh environmental conditions. Samples were then placed in the controlled environmental chamber and exposed to cyclic weathering conditions: UV radiation, moisture and high temperature. The exposure was conducted in a Q-Lab QUV/basic accelerated weathering tester according to ASTM G154 standard [12]. The coated and uncoated specimens were examined using a Keyence VHX 6000 digital microscope. The flexural properties of specimens during environmental aging were measured using three-point bending test performed with Mark-10 testing equipment at the intervals of 300, 600, and 1200 h of exposure. The required steps for manufacturing and testing samples are schematically represented in Figure 1.

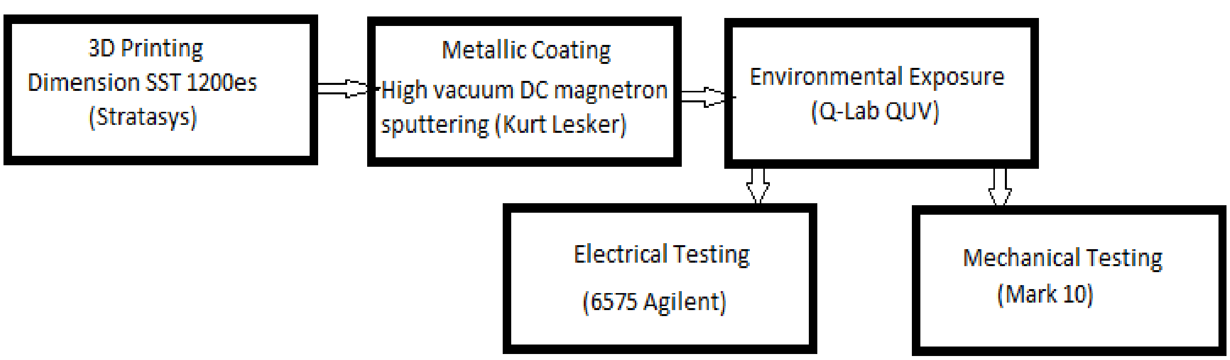
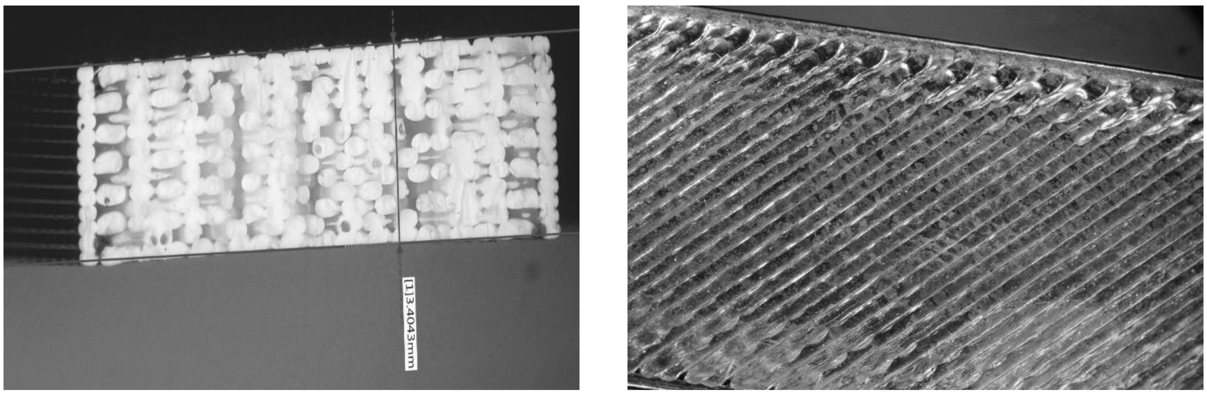


Figure 1. Manufacturing and testing procedures for 3D printed samples

Discussion

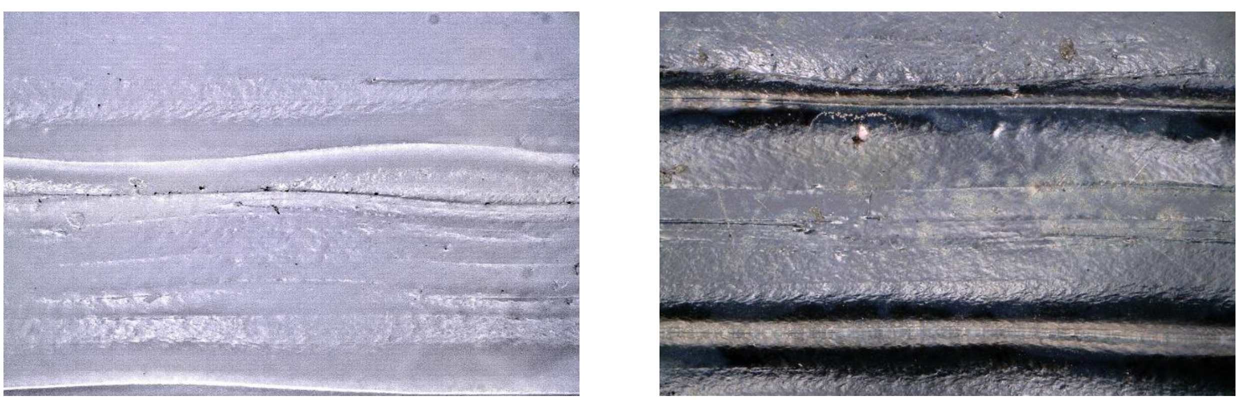
Students designed the required experiments and actively participated in performing the experiments and taking measurements for electrical and mechanical evaluations. The coated and uncoated structures were initially investigated using optical and digital microscopy. Figure 2 shows the optical microscopy image (20 X magnification) of one-micron metallic coated ABS sample cross section fracture (a) and surface (b). In the cross-section picture, it is observed that the printing pattern has alternating angles (i.e. periodic -45°/+45°) of layer deposition to ensure the isotropic mechanical properties. Samples were manufactured with dimensions in conformity with the ASTM D790 standard and a minimum of five samples were used for each experiment.



(a) (b)

Figure 2. Digital microscopy picture of a metallic coated 3D printed standardized ABS sample cross section (a) and surface (b) (20X magnification)

The digital microscopy images of the surface of uncoated (a) and silver coated (b) ABS specimens (300 X magnification) are presented in Figure 3. The images are taken before the exposure to harsh environmental conditions.



(a) (b)

Figure 3. Digital microscopy of the surface of the (a) uncoated and (b) silver coated 3D printed ABS sample (300 X magnification)

The electrical conductivity of specimens (ABS and PLA) was evaluated on a 90 mm standardized sample length after performing the silver coatings (0 hours) and after the exposure to the environmental aging at the intervals of 300, 600, and 1200 h of exposure. Figure 4 presents the general trends of the changes in the electrical current [Amps] under the application of 1 [V] potential for silver coated ABS and PLA. The graph values are obtained as average after performing measurements on 20 ABS and 20 PLA samples. It is observed that all structures are conductive after coating (0 hours of exposure) and their conductivity remains unchanged during the following 300 and 600 hours of exposure. While the conductivity of the ABS sample is slightly increasing after the 900 and 1200 hours of exposure, the conductivity of the PLA samples is decreasing due to the PLA degradation in harsh environmental conditions exposure and metallic coating delamination.

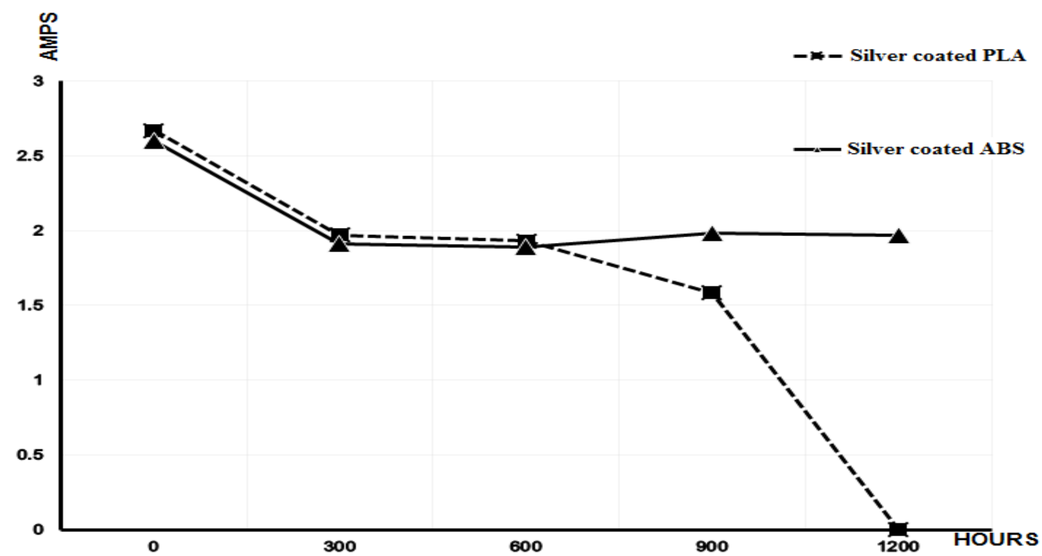


Figure 4. Changes in the electrical current (Amps) on silver coated ABS and PLA after 0, 300, 600, 900 and 1200 hours of exposure.

The mechanical properties of the uncoated and coated polymers were tested using the Mark-10 flexural testing equipment and standardized conditions (ASTM D790) and minimum five samples were used for each testing. Figures 5 represents general trends for the mechanical properties of uncoated and metallic coated ABS specimens: ultimate tensile strength (a), Young's Modulus (b), fracture strain (c), and flexural toughness (d). It was observed that the uncoated specimens gradually lost their flexural strength over the course of exposure with a maximum reduction of 59 % after 1200 h of environmental aging. The failure strain of uncoated specimens decreased significantly during exposure time with a maximum reduction of 68 % after 1200 h of environmental aging. However, the flexural strength and failure strain were preserved for metallic coated specimens (e.g. for failure strain the maximum decrease was 19 %). It can be observed that flexural toughness is the most susceptible mechanical properties of uncoated 3D printed ABS specimens to the environmental exposure with a maximum reduction of 92 % after 1200 h of environmental aging. The metallic coated ABS specimens significantly retained their flexural toughness during environmental aging as compared to uncoated specimens.

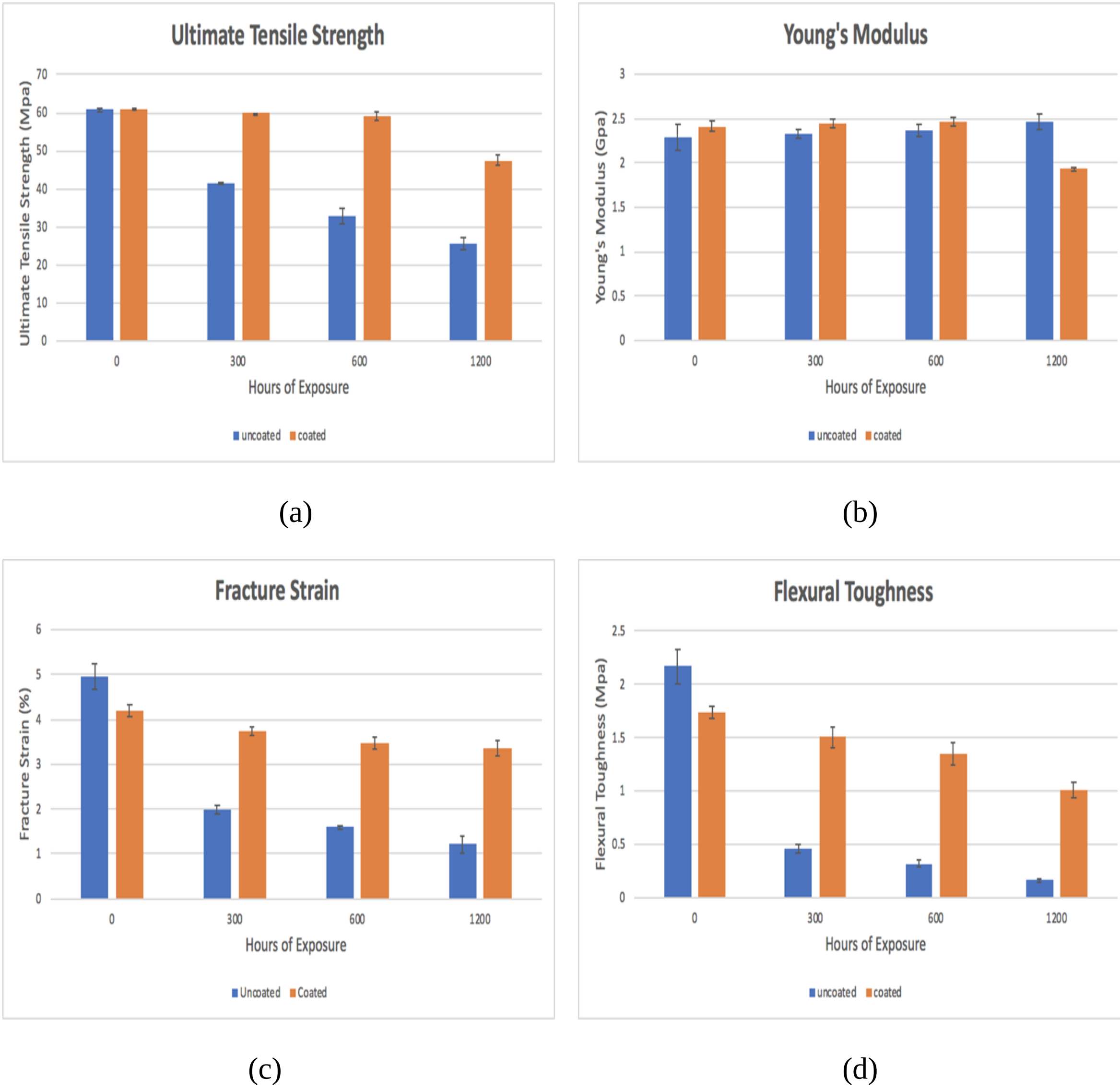
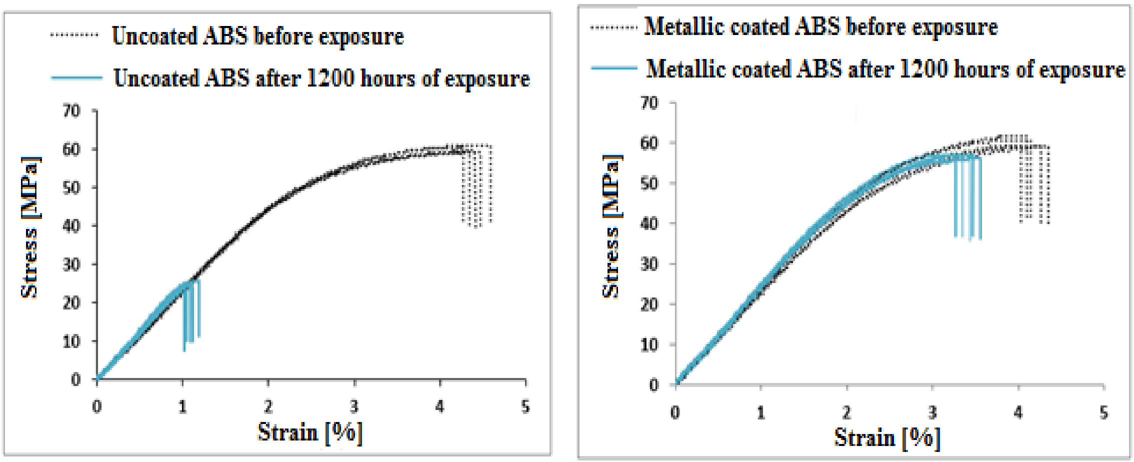


Figure 5: Flexural properties of uncoated and metallic coated 3D printed ABS samples during exposure to UV radiation and moisture a) Ultimate Tensile Strength b) Young's Modulus c) Fracture Strain d) Flexural Toughness

Accordingly, flexural modulus of ABS specimens was relatively unchanged during the environmental exposure. A ductile mode of failure was observed for both environmentally aged and unaged copper coated 3D printed ABS specimens. Extensive microcracking was observed using digital microscopy on the surface of the uncoated specimen after 1200 h of environmental exposure while no microcracks were observed on the surface of the metallic coated specimen after prolonged environmental aging. The stress-strain curves for uncoated and metallic coated ABS specimen is represented in Figure 6 for pristine samples (before exposure) and after 1200 hours of environmental exposure. Five specimens were examined per each condition. It is observed a change in the failure mode from ductile failure before the environmental exposure to brittle failure after 1200 hours of environmental exposure.



(a) (b)

Figure 6. Stress-strain curves of (a) uncoated and (b) metallic coated 3D printed ABS specimens before and after 1200 h of environmental exposure (five specimens per condition)

During the research-oriented independent study class, students improved their ability to develop and conduct appropriate experimentation, analyze and interpret data and use engineering judgement to draw conclusions (Outcome 6, ABET). Students are collecting and analyzing data, preparing posters and presentations for students and professional technical conferences. The independent study class offered students the possibility to "apply engineering design to produce solutions that meet specified needs" with consideration to global and economic factors (Outcome 2, ABET).

Conclusions

The independent study class aimed to involve students in research and "hands on" activities enabling them to use advanced equipment. Students investigated the possibility of creating conductive polymers and experimented the effects of synergistic exposure to UV radiation, high temperature and moisture on the mechanical and electrical properties of 3D printed polymers. They planned and conducted appropriate research using the 3D printing equipment, physical vapor deposition system, environmental accelerated exposure chamber, electrical and mechanical testing equipment. Electrical measurements showed good conductivities for metallic coated ABS structures that were preserved during the environmental aging. The metallic coated ABS specimens effectively retained their flexural strength, ductility and toughness over the course of exposure while uncoated samples significantly lost their mechanical properties even after short term environmental aging. The independent study class foster students the ability to present their research to technical conferences and communicate effectively to a large range of audiences (Outcome 3, ABET).

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