Mechanical Properties of 3D Printed Polylactic Acid Parts under Different Testing Conditions

Neville Tay[1], Xiu Jie Low[1], Vinay Patil[2], and Eylem Asmatulu[2,*]
[1]Department of Aerospace Engineering
[2]Department of Mechanical Engineering
Wichita State University
1845 Fairmount St., Wichita, KS 67260
*Email: e.asmatulu@wichita.edu

Abstract

3D printing has been gaining much attention worldwide because of its capability and ease of use for different industries. Based on somebody's imagination and creativity, new parts can be created in a shorter time with cost effective ways. This study mainly focuses on the mechanical properties of 3D printed polylactic acid (PLA) parts exposed to UV light, and moisture and kerosene bath, and compares the changes of mechanical strengths with the original samples. Tensile test studies indicated that mechanical properties of the 3D printed parts could be drastically reduced when the prepared samples were exposed to UV light, and moisture and kerosene bath. After proper training, two undergraduate engineering students were involved in these studies and gained enormous hands-on research experience on the 3D printing process and degradation mechanisms of those parts under different conditions. These students also used these hands-on activities for their Engineer of 2020 requirements in the College of Engineering at Wichita State University.

Keywords: 3D Printing, Polylactic Acid, Environmental Degradation, and Tensile Strength.

1. Introduction

Three-dimensional (3D) printing, also known as additive manufacturing and rapid prototyping, refers to a process used to create a 3D object where layers of polymeric and metallic materials are formed on top of each other to manufacture 3D objects. The size and shapes of the 3D parts can vary substantially. 3D printing technologies have been improving continuously worldwide. One of the earliest technologies in this field is called rapid prototyping technologies developed in the 1980s. The rapid prototyping enables engineers to reduce the time of manufacturing more complex parts, and also provide more time to design specific materials. Charles Hull has the privilege to have the first patent for stereolithography apparatus (SLA) in this field. In the year 2000s, SLM technology has been introduced to the market because many commercial opportunities were available for the 3D printer [1].

A lot of experimental studies use Acrylonitrile-Butadiene-Styrene (ABS) and Polylactic Acid (PLA) for 3D printing, but other polymeric materials (e.g., nylon, polycarbonate, polyurethane, etc.) have not been experimented much. When compared ABS to PLA filament, ABS plastic is more ductile and less brittle, so it can also be post-processed with acetone to provide a glossy finish in the final product. Cantrell et al., 2016 conducted a research study on mechanical properties of 3D printed ABS and polycarbonate parts. The experiments have been performed using tensile and shear tests to determine the different properties with various directions of materials. Dog bone shape specimens were printed and tensile tests were conducted on the specimens to measure the strain. Yield strength, ultimate tensile strength, Young's modulus, Poisson's ratio, and breaking strength data have been collected and analyzed. The test results indicated that the shear yield strength and shear modulus has been considerably increased [2,3].

PLA is a promising candidate for industrial applications because of its low cost, decent properties and biocompatibility [4]. This polymer is also approved by FDA for biomedical and manufacturing studies. Traditional polymer processing technologies would be suitable for many polymers; however, PLA has a special behavior of shear thinning during the manufacturing [5]. PLA is durable and suitable for the short and long-term manufacturing options.

3D printed materials are being widely used nowadays in many industries, such as aircraft, energy, automotive, defense, electronics, medical and pharmaceutical. According to Kampker et al., 2015 using PolyJEt 3D printing in e-mobility interior and exterior components reduced the production costs considerably. The technical report summarizes that this technology does offer many advantages compared to conventional tools and technologies. Also, the initial production of molding tools are very costly and time consuming process. By 3D printing, its help save time and reduce the cost of making prototypes in light weight manner [6].

According to Zhang and Miyamoto, 2014, there have been increasing demands on nanoscale satellite launch systems, so it is stated that 3D printing process can offer a practical solution to this increasing demand [7]. 3D printed materials can also be used to develop new sets of Unman Aerial Vehicles (UAV) for different applications. Banfield, et al., 2016 studied the infill density, pattern, and orientation on the structural properties of 3D printed airframe components. 3D printing enables complex geometry replication and rapid fabrication which allowed them to produce an airplane part within 24 hours. The study concluded that the infill density had the greatest impact on strength of the 3D printed airplane for a stable and consistent flight [8].

A study by Tymrak et al., 2014 was performed to investigate the mechanical properties of components fabricated via open-source 3D printer systems under realistic environmental conditions [9]. This study quantifies the basic tensile strength and elastic modulus of printed components using realistic environmental conditions for standard users. The study reports some mechanical properties, such as tensile strength and the modulus of elasticity of the ABS and PLA printed parts. The test results indicated that the parts printed with tuned, low-cost, open-source RepRap 3D printers could be considered as mechanically functional in tensile applications.

Zhang et al., 2013 conducted a research on developing a new process for PLA composting. PLA can replace some of the petroleum-based plastics because of its comparable cost and properties [10]. The authors assessed the effectiveness of UV light on the degradation of the PLA. The PLA samples were exposed to UVC light for 30, 60, and 90 minutes. The amount of PLA degradation was measured by mass loss as well as molecular weight analyses. Based on the experimental results, UV light significantly shortens the time of PLA degradation in comparison to the current process of hydrolysis. The authors stated that their new process for PLA composting would significantly shorten the existing process time from days to hours. This three-step new process involves mechanical chopping, UV treatment and disposal in a compost facility.

3D printing is considered to be beneficial to print food for space missions. According to Terfansky et al., 2013 [11], there has been ongoing research to develop proper foods for astronauts. Using a 3D printer to print food and food containers, one can make the food more attractive and satisfying for the human senses and promote happiness that will maintain nutritional balance. Based on the study of Barsotti and Straub, 2017, producing parts with 3D printer is very convenient, so this technology can be used for in-space applications [12]. The in-space 3D printer will be able to print spacecraft components, structures, and potentially in the longer term, the whole spacecraft. Companies such as “Made in Space” (MIS) have recently sent a 3D printer to the International Space Station (ISS) that can successfully print tools for use onboard of the ISS. However, this technology is developing, and much work need to be done both in the hardware and software sides of the systems.

3D printing process can be implemented in bone tissue engineering in accordance with Bose et al., 2013 [13]. With the advent of additive manufacturing bone tissue engineering is advancing rapidly with new technologies. Among the different other technology options, 3D printing is becoming popular due to the ability to directly print porous scaffolds with designed shape, controlled chemistry, and interconnected porosity. Some of these inorganic scaffolds are biodegradable or biocompatible and have proven for bone tissue engineering. The ability to locally print almost any designable object would have strong consequences across the modern society [14].

2. Experiment

2.1 Materials

Polylactic acid (PLA) filaments were provided by the 3D printing company and used without any further modifications for the 3D printing process.

2.2 Methods

Using the CATIA model, a dog-bone shape was drawn for the 3D printing following the dimensions of the ASTM D638 TYPE I specifications. Figure 1a shows the schematic view of tensile test specimen. PLA filament was placed into the 3D printer unit (MakerBot; https://www.makerbot.com), and bog-bone shape PLA specimens were printed. To carry out all the tests, 40 dog-bone specimens were printed using the MakerBot device. Prior to the tensile testing, the prepared samples were immersed into DI water and kerosene for 0, 5, 10 and 20 days. The same 3D printed samples were also exposed to the UV light (UVA-340 lamp) for 0, 5, 10 and 20 days. The UVA-340 provides the best possible simulation of sunlight in the critical short wavelength region between 365 nm and 295 nm. The highest peak emission is at 340 nm, which is very destructive to the polymeric materials. Figure 1b shows the tensile test unit (MTS Criterion model 45) employed in these studies. In addition to the mechanical tests, water contact angle tests were conducted on the specimens before and after the UV exposure tests. For each test, at least three samples were tested and the test results were averaged. The PLA samples were used by the engineering students during the tests to determine property changes of the 3D printed materials.

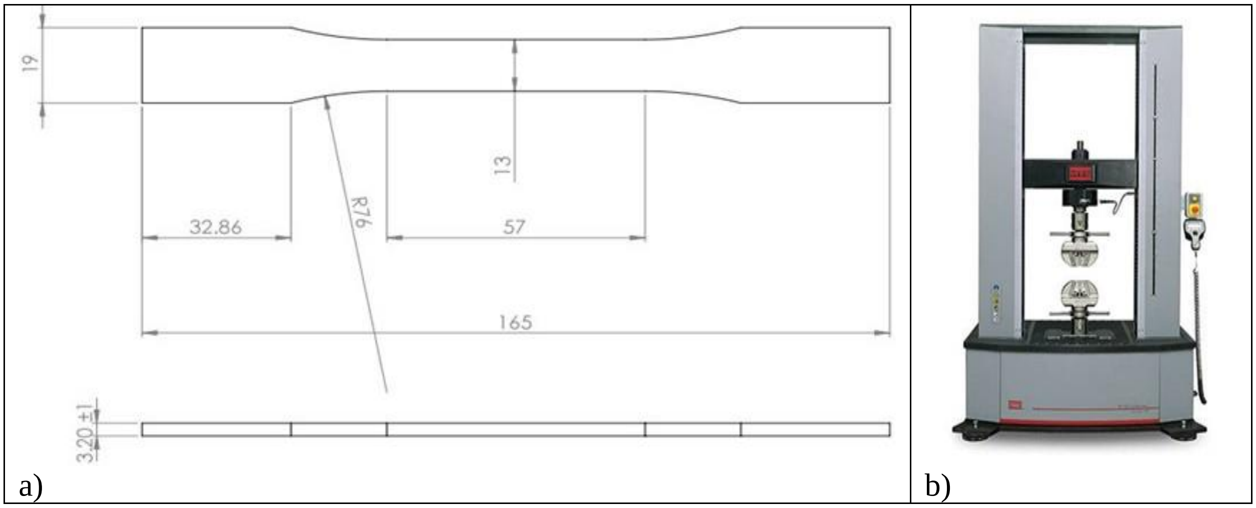

Figure 1: a) The schematic view of tensile test specimen based on ASTM D638 TYPE I, and b) MTS Criterion model 45 for tensile tests. All dimensions are in mm.

3. Results and Discussion

Figure 2 shows the ultimate tensile stresses of the 3D printed PLA samples immersed into DI water for 0, 5, 10, and 20 days. At 0, 5, 10 and 20 days of DI water immersions, average ultimate tensile stress values of the 3D printed PLA samples are 25.0, 14.5, 14.2 and 13.5 MPa, respectively. Most of the degradation in water takes place within the first 5th days, and then it mainly leveled off. Similar observations were seen in other studies (15, ra5). The reason behind this behavior is that when the polymeric materials absorbs the water molecules in its structure, polymers get soften and lose the stiffness and strengths.

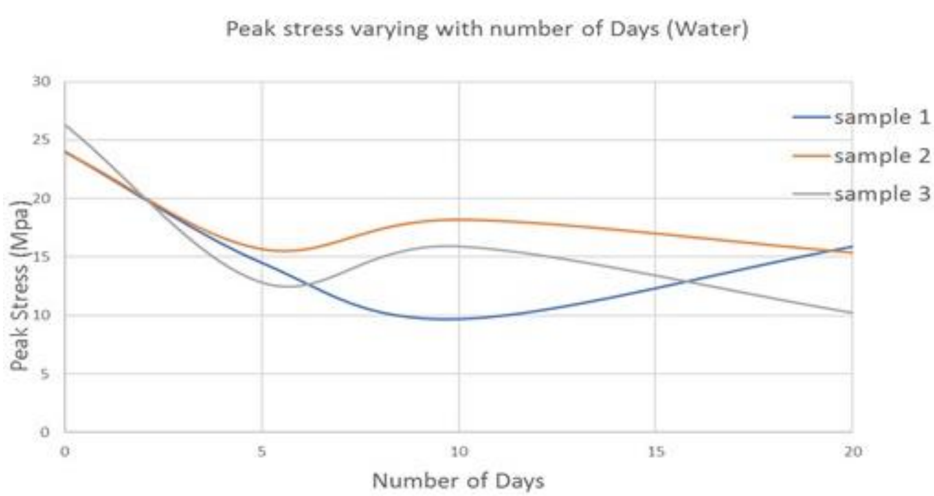

Figure 2: The ultimate tensile stresses of the 3D printed PLA samples immersed into DI water for 0, 5, 10, and 20 days.

Figure 3 shows the ultimate tensile stresses of the 3D printed PLA samples immersed into kerosene as a function of time. The tensile test studies indicated that the average ultimate tensile strengths of the PLA samples are 25.0, 7.2, 7.1, 6.5 and 6.2 MPa, correspondingly. As can be seen, the ultimate tensile strengths of the kerosene soaked samples drastically reduce the mechanical properties of the PLA samples. When compared to the water immersed samples, the samples immersed into kerosene got more distractive damages. This may be because of the fact that the kerosene molecules can easily get into the PLA structure, and substantially reduce the mechanical strengths.

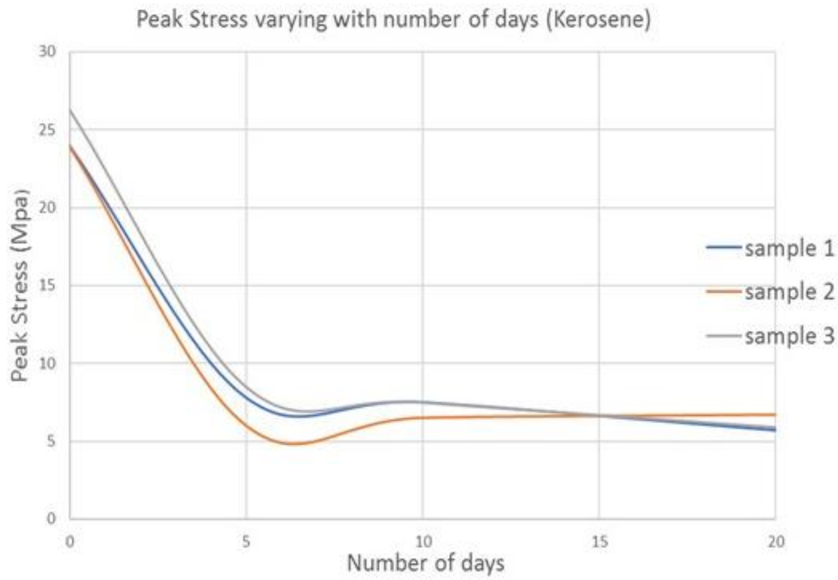

Figure 3: The ultimate tensile stresses of the 3D printed PLA samples immersed into kerosene for 0, 5, 10, and 20 days.

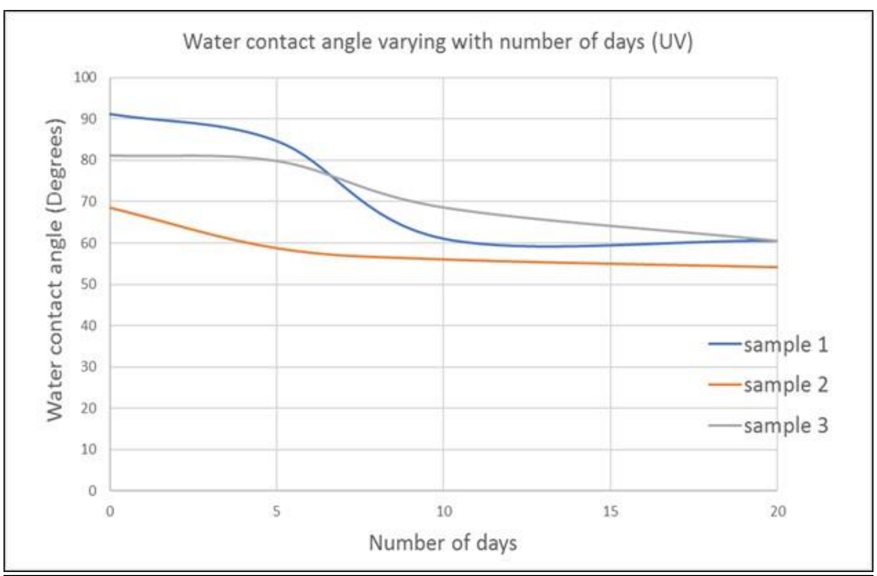

Figure 4: The water contact angle values of the 3D printed PLA samples exposed to the UV light for 0, 5, 10, and 20 days in a UV chamber.

Figure 4 shows the water contact angle values of the 3D printed PLA samples exposed to the UV light for 0, 5, 10, and 20 days in a UV chamber. Average water contact angle values of the samples at 0, 5, 10 and 20 days of exposures are 80.1, 72.0, 63.4, and 58.4°, respectively. Increasing the UV exposure on the surfaces of 3D printed samples considerably reduce the water contact angle values. UV light has mainly rays and photons. The rays of UV light likely break the polymeric chains of the PLA, while photons donate their energy to the broken chains to cross-link or oxidize them further. In both cases, the polymers lose their strengths substantially [16].

Figure 5 shows the ultimate tensile stresses of the 3D printed PLA samples exposed to the UV light for 0, 5, 10 and 20 days. The ultimate tensile strengths of UV exposed samples are 26.5, 18.3, 15.2, 14.8 and 14.7 MPa for 0, 5, 10 and 20 days UV light. These test results are closely in agreements of the water contact angles. High UV exposures on the surfaces changed the chemical structures of the PLA samples and drastically reduced the mechanical properties. These data may be useful for designing the new sets of 3D printed parts for different industries [10].

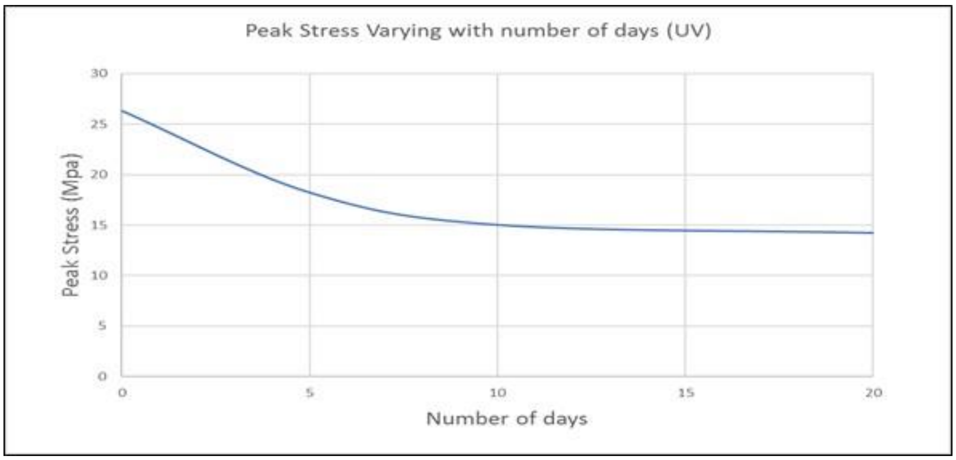

Figure 5: he ultimate tensile stresses of the 3D printed PLA samples exposed to the UV light for 0, 5, 10 and 20 days.

4. Hands-on Experiences for Engineering BS Students

The 3D printing enables engineers to reduce the time of manufacturing complex objects, and also provide more time to design specific materials for different industrial applications. Because of the various advantages compared to the other conventional technologies, 3D printing technologies have been growing faster. Collage of Engineering at WSU has over 2500 undergraduate students and a big portion of them are considering hands-on engineering experiences during their studies. Mr. Neville Tay and Mr. Xiu Jie Low, two of the BS students in the Department of Aerospace Engineering, were involved in the present study, learned many new techniques and gained a lot of new skills and knowledge about 3D printing, biodegradability, environmental effects on polymeric structures, their mechanical properties, and other related technologies and techniques. These students have used these research activities as their own Engineer of 2020 requirements in the College of Engineering at WSU. Both of them are also co-authors of the present study and made a lot of contributions during the experiments [17-21]. We believe that the hands-on research experiences can enhance the knowledge of many BS engineering students to perform more detail studies in the future.

5. Conclusions

3D printed PLA samples were immersed into DI water and kerosene, and also exposed to UV light for 0, 5, 10 and 20 days in order to find out the changes in the mechanical and surfaces properties of these samples. Specimens that were immersed into water and kerosene lost most of their strengths within five days. Effects of kerosene is more detrimental than the DI water on 3D printed objects. The UV exposure studies indicated that the PLA samples were sensitive to the UV light as well because water contact angle was reduced to 58.4 from 80.1° after 20 days of UV light exposure. The reduction in water contact angle is closely related to the reduction in the mechanical strengths. Two of the engineering students, also authors of this study, designed, developed and performed these tests on the 3D printed specimens. The BS students have used these research activities for their Engineer of 2020 requirements. Overall, these studies greatly benefit undergraduate engineering students for their future academic studies in different institutions.

Acknowledgements

The authors greatly acknowledge the Wichita State University for the financial and technical supports of this study.

References

[1] Cantrell, J., Rohde, S., Damiani, D., Gurnani, R., Disandro, L., Anton, J., Young, A., Jerez, A., Steinbach, D., Kroese, C., and Ifju, P. (2016). "Experimental Characterization of the Mechanical Properties of 3D Printed ABS and Polycarbonate Parts," Advancement of Optical Methods in Experimental Mechanics, Volume 3 Conference Proceedings of the Society for Experimental Mechanics Series, pp. 89–105.
[2] Davis, J. R. (2004). "Tensile testing," Materials Park, OH: ASM International
[3] Rankouhi, B., Javadpour, S., Delfanian, F., and Letcher, T. (2016). "Failure Analysis and Mechanical Characterization of 3D Printed ABS with Respect to Layer Thickness and Orientation," Journal of Failure Analysis and Prevention, vol. 16, pp. 467–481.
[4] Ingenia magazine "Articles - Rapid Prototyping," Royal Academy of Engineering (06/13/2017) <http://www.ingenia.org.uk/Ingenia/Articles/233>
[5] Hamad, K., Kaseem, M., Yang, H. W., Deri, F., and Ko, Y. G. (2015). "Properties and Medical Applications of Polylactic Acid: A review," Express Polymer Letters, vol. 9, pp. 435–455.
[6] Kampker. A., Deutskens.C., Kreisköther. K., Reinders.C. (2015). "Reducing Production Costs of E-mobility Interior and Exterior Components by Using PolyJet 3D Printing for Direct Tooling," 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference
[7] Zhang.T., and Miyamoto.C.M. (2014). "3D Printing: A Cost Effective and Timely Approach to Manufacturing of Low-Thrust Engines," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014.
[8] Banfield.C., Kidd.J, and Jacob.J. (2016). "Design and Development of a 3D Printed UAV", 54th AIAA Aerospace Sciences Meeting

[9] Tymrak, B.M., Kreiger, M., Pearce, J. M. (2014). “Mechanical Properties of Components Fabricated with Open-Source 3-D Printers Under Realistic Environmental Conditions,” *Materials & Design*, 58, pp. 242-246
[10] Zhang,C., Rathi,S., Goddard,J., Constantine,K., and Collins,P.(2013) “The Effect of UV Treatment on the Degradation of Compostable Polylactic Acid”, Journal of Emerging Investigators
[11] Terfansky,M., Thangavelu,M., Fritz,B., and Khoshnevis,B.(2013). “3D Printing of Food for Space Missions”, AIAA SPACE 2013 Conference and Exposition
[12] Barsotti.R.E., and Straub.J. (2017). “Development of Command and Control Software for an In-Space 3D Printer and Small Satellite Test Mission,” AIAA Information Systems-AIAA Infotech @ Aerospace
[13] Bose,S., Vahabzadeh,S., and Bandyopadhyay.A.(2013). “Bone Tissue Engineering Using 3DPrinting,” *MaterialsToday*, Volume 16, Issue 12, Pages 496-504
[14] Campbell,T., Williams,C., Ivanova,O., and Garrett.B.(2011). “Could 3D Printing Change the World?” Atlantic Council, Strategic Foresight Initiative
[15] Gendey,R. (2005). “Tensile Testing Basics, Tips and Trends” Quality Magazine, 4 p.
[16] Yuan.Y., and Lee, T.R. (2013). “Chapter 1 Contact Angle and Wetting Properties” Department of Chemistry, University of Houston, 4800 Calhoun Road, Houston, TX 77204-5003, USA
[17] Mallonee, E., Barkley, J., and Asmatulu, R. “Training Renewable Energy Systems to Midwestern College Students for Engineering Education and Improved Retention Rates," *Transactions on Techniques in STEM Education*, 2016, Vol. 2, pp. 4-10.
[18] Chinni, G., Belachew, I., and Asmatulu, R. “Hands-On Training the Engineering Students on Biodisel Production Using Waste Vegetable Oils," *Transactions on Techniques in STEM Education*, 2016, Vol. 1, pp. 37-45.
[19] Hughes, S.M., Pham, A., Nguyen, K.H., and Asmatulu, R. “Training Undergraduate Engineering Students on Biodegradable PCL Nanofibers through Electrospinning Process," *Transactions on Techniques in STEM Education*, 2016, Vol. 1, pp. 19-25.
[20] Alarifi, I., Alharbi, A., Alsaiari, O., and Asmatulu, R. “Training the Engineering Students on Nanofiber-based SHM Systems," *Transactions on Techniques in STEM Education*, 2016, Vol. 1, pp. 59-67.
[21] Hughes, S.M., Alamir, M., Neas, B., and Asmatulu, R. “Effects of Heath Treatments and UV Exposures on Mechanical Properties of 3D Printed Acrylonitrile Butadiene Styrene Specimens,” SPIE Smart Structures/Non-destructive Evaluation Conference, Portland, OR, March 25-29, 2017, 6 pages.

Biographical Information

Neville Tay

Neville Tay is a BS student in the Department of Aerospace Engineering at WSU. He has worked on different projects, such as building a lightweight emergency relieve unmanned vehicle and also carried out a study to determine the feasibility of a submergible aircraft.

Xiu Jie Low

Xiu Jie Low is a BS student in the Department of Aerospace Engineering at WSU, and transferred from Malaysia to this university. He is planning to join graduate school and work on 3D printer technologies.

Vinay Patil

Vinay Patil is pursuing his Master's degree in Department of Mechanical Engineering at WSU and working as a Graduate Teaching Assistant in the same department. He is currently studying on "enhancing the rate of evaporation of salt water using nanoparticles, flotation of superhydrophobic particles and nanofuels".

Dr. Eylem Asmatulu

Dr. Asmatulu is currently an Engineering Educator in the Department of Mechanical Engineering at WSU and actively involving in teaching, research, and scholarship activities in the same department. She received her PhD degree from the Department of Industrial and Manufacturing Engineering at WSU in May 2013, which was mainly focused on the "Life Cycle Analysis of the Advanced Materials". Prior to the WSU, she also worked in the Environmental Health and Safety at WSU and Composite Manufacturing Laboratory at NIAR of WSU. Throughout her studies, she has published 7 journal papers and 23 conference proceedings, authored 7 book chapters, presented 8 presentations, and reviewed several manuscripts in international journals and conference proceedings. Dr. Asmatulu is currently conducting research on "e-waste recycling, active carbon processing, algae based biofuel productions and CO_2 capturing".