6-1-2017

Development of a Laboratory Module in 3D Printing

Spencer Kim
Rochester Institute of Technology

Development of a Laboratory Module in 3D Printing

Dr. Spencer Seung-hyun Kim, Rochester Institute of Technology (CAST)

Dr. Spencer Kim is an Associate Professor in Mechanical and Manufacturing Engineering Technology Department (MMET) at RIT, and serves as Associate Director of American Packaging Corporation Center for Packaging Innovation at RIT. He previously worked in the semiconductor industry. Dr. Kim, as a PI or Co-PI, received grants and sponsorship from NSF, SME, SPE, universities, and industries. In 2009 and 2013, he was nominated for the Eisenhart Award for Outstanding Teaching, RIT's premiere teaching award at RIT. Dr. Kim has directed numerous undergraduate research projects and several students won the first place in the undergraduate and graduate research competitions at the 2012 and 2013 GPEC (Global Plastics Environment Conference; Division of Society of Plastics Engineers).

Development of a Materials Laboratory Module in 3D Printing

Abstract

The goal of the study was to develop a laboratory module in the mechanical and thermal characterizations of the 3D printed specimens by the ASTM standard test-methods in order to improve an undergraduate materials laboratory course utilizing Extrusion Material (EM) technique. A small-scale-low-cost EM printer was used as a default-test-printing machine to produce the test-specimens for the ASTM standards of D6110 (Charpy impact test), D638 (tensile test), and D648 (heat deflection test), respectively; these test specimens were printed using a filament material (Polylatic acid (PLA)) and were evaluated according to the ASTM standards designated. The results of the mechanical and thermal tests for the 3D printed specimens were contrasted to the published data for comparison. In addition, the study presented the survey results of intended learning outcomes (ILOs) in the laboratory course designed by POGIL (Process-Oriented Guided Inquiry Learning) approach for active learning in undergraduate materials education.

Introduction

3-D printing has witnessed significant improvements since its inception. The terms “3D printing” and “additive manufacturing (AM)” are sometimes used interchangeably, as this process enables economical and rapid prototyping of various product designs within a very short time period. 3D printing is a process of producing three dimensional (3D) objects from digital models in which the solid objects are made by laying down successive layers of various types of materials: such as polymers, metals, ceramics, and composites.[1,2,3] In contrast, traditional machining techniques are considered to be a “subtractive process” technique, which the products or parts are mostly machined out from stock materials.[3]

The recent technical advancement in 3D printing managed to scale down the size of printing machine and the complexity of process, where it is a more affordable technology for hobbyist, educators, engineers, researchers and scientists. Various 3D printing techniques are used in many professional fields in automotive, architect, construction, jewelry, education, dental and medicine, consumer and industrial design, geosciences, and others.[1-4] Despite the advances made in 3D printing technology, it is still far from where it could commercially provide new opportunities for more complex and flexible applications. Furthermore, due to the nature of the current techniques, materials are one of the most limiting factors in the advancement of 3D printing technologies.[5]

The primary goal of the paper was to develop a laboratory module in 3D printing for undergraduates to present a methodology in the characterization of the mechanical- and thermal-properties for the 3D printed specimens by the ASTM standard testing, using material extrusion technique. The open-source-based 3D printers in material extrusion (i.e. fused deposition modelling (FDM)) are readily available to the public at low costs in the market. In the development of a material laboratory session, a small-scale-low-cost material extrusion printer was used as a default-test-printing machine to produce the standard-specimens for the ASTM testing of D6110 (Charpy impact test), D638 (tensile test), and D648 (heat deflection test), respectively; these test specimens were printed using the current filament material (e.g. Polylatic acid (PLA)) with a default setting of process parameters, and were evaluated according to the ASTM standards designated. Additionally, the results from the ASTM mechanical and thermal tests were compared to the published data for the analysis. In the paper, we report the experimental results of the 3D printed specimens by the ASTM standard tests and present findings from the assessment and evaluation of the laboratory session developed for a materials laboratory course for undergraduate programs.

Material Extrusion (EM) in 3D Printing Processes

3D printing encompasses a wide range of additive manufacturing technologies. There are many different printing technologies on the market today, ranging from desktop 3D printers that produce jewelry, toys, and small parts to industrial sized 3D printing-machines that create products ready for actual uses. Recently, with synthetic-biology and nanotechnology, 3D printing has shown a promise to radically transform from research studies to design, processes and production in variety of medical applications.[6,7] ISO/ASTM 52900-15 ("Standard Terminology for Additive Manufacturing – General Principles – Terminology") defines seven categories of 3D printing (i.e. additive manufacturing) processes within its meaning: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo polymerization.[8] The 3D printing techniques used vary significantly, but all start with a computer aided design (CAD) model or a digital scan. This is then processed by "slicing software" that divides the object into thin cross sections that are printed out one on top of the other.[1-5] In the 3D printing process, a solid (or semi-solid) object is printed in successive layers that are typically about a 0.1 mm-thin layer.[2,3] Figure 1 shows a typical 3D object printed by material extrusion method. "Material Extrusion (EM)" method is also called "Fused Deposition Modeling (FDM)" or "Fused Filament Fabrication (FFF)." [4,5]

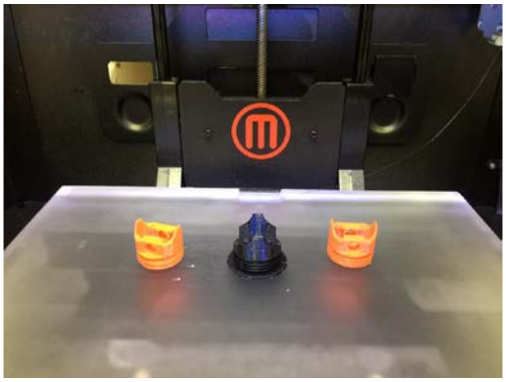


Figure 1: 3D objects printed by material extrusion method

The 3D printing processes use a wide range of engineering materials that include thermoplastics, thermoplastic composites, pure metals, metal alloys, ceramics, and various types of chemical compounds including foods.[1-5] In the current additive manufacturing market, polymer-based materials account mostly for uses in the vast majority of 3D printing machines, because polymers represent the greatest market penetration and user accessibility to compare with other types of engineering materials. Various forms of polymeric materials (such as powder, filament, and sheet) are utilized in polymer-based 3D printing processes and photo-sensitive resins are used in active polymerization 3D printing processes. "Material extrusion (EM)" uses a nozzle to extrude a semi-liquid material to create successive object layers in 3D printing (Figure 2). This 3D printing process is analogous to conventional extrusion or injection molding except that mold is unnecessary. Most build materials in material extrusion are thermoplastic polymers; such as acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA), high-density polyethylene (HDPE), PC/ABS, polyphenylsulfone (PPSU), and high impact polystyrene (HIPS).[9] In general, the polymer is converted into the form of a filament (diameter of 1.75 mm or 3 mm) fabricated from a virgin resin using plastics extrusion process. In the material extrusion (fused deposition modeling (FDM)) machines, printing materials are restricted mostly to acrylonitrile butadiene styrene (ABS) or poly (lactic acid) (PLA). However, additional efforts are required to further the research and development of new materials for the advancement of 3D printing technologies.

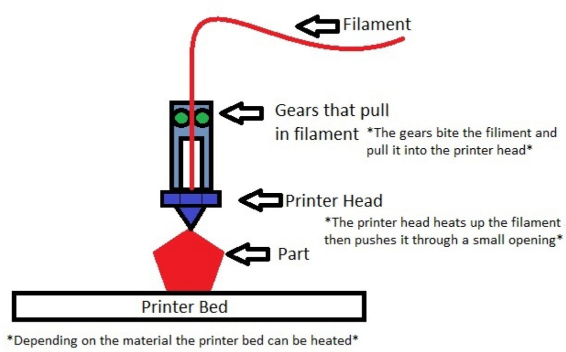


Figure 2 Schematic diagram of material extrusion method (FDM or FFF): heated nozzle extrudes semi-solid filament in the layer-by-layer building on the printed bed

The material extrusion (EM) technique is somewhat restricted in the variation of shapes that may be fabricated. For example, the material extrusion technique usually cannot produce stalactite-like structures, since they would be unsupported during the build. This 3D printing method produces somewhat greater anisotropy in terms of mechanical properties compared to the Stereolithography Apparatus (SLA) and Selective Laser Sintering (SLS) 3D printing methods.[10-12] Also, many studies found that processing parameters in the material extrusion method resulted in different properties and accuracy in printing.[3,10,13,14]

Experiment

1) **Specimen Preparation and Extrusion Material Printing**

Extrusion material (i.e. FDM) creates a 3D object using a computer aided design (CAD) model; a STL file of the CAD model is converted to a G-code file using a slicer software. The slicer software cross-sections the CAD model to be read by the 3D printer. Figure 3 shows the sliced model of the notched specimen to prepare a specimen for the ASTM D6110 testing (i.e. Charpy impact test).

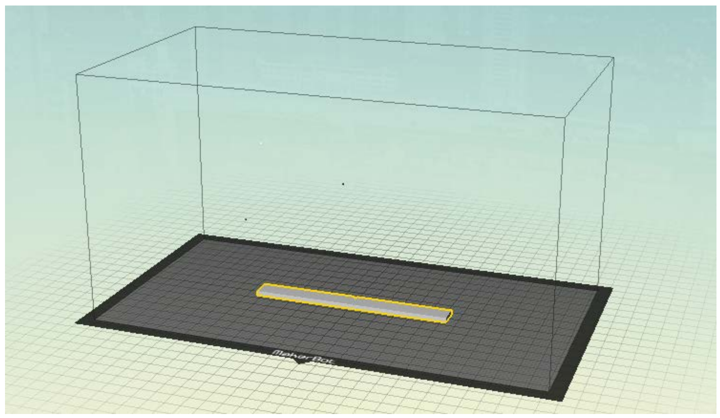


Figure 3: Sliced model of notched specimen for Charpy impact test (ASTM D6110)

For the study, the filament was a generic brand of polylatic acid (PLA), and a low-cost FDM machine (Makerbot Replicator 2) was used to create all test specimens. In material extrusion printing, the PLA-filament (1.75 mm diameter) was fed by two drive-wheels where the filament was melted and extruded through a heated nozzle on the printer bed (or build platform) shown in Figure 2. The layers of the semi-liquefied polymer were deposited on to the printer bed on the motions of the x-y-z directions by the controlled processing parameters in printing. A set of the processing parameters, as a default setting of the printing, was used to print all ASTM specimens for the study. The 3D printing parameters are shown in Table 1.

Table 1: 3D processing parameters for the study

Description	Parameters
Material	PLA
Quality	High/no raft/no support
Layer height	0.10 mm
Infill	15%
Number of cells	2
Extruder temperature	230°C
Printer bed temperature	Room temperature

2) ASTM Standards, Test Methods, and Printing Specimens

The 3D models of the ASTM standard-specimens for the study were created by CAD software (Solidworks) and exported in STL format: the geometries and dimensions of the 3D printed test-specimens (ASTM D6110, D638, and D648) are shown in the ASTM standards (Table 3). These STL models were imported to produce the G-code models using a slicer software. Each of the G-coded models was then printed to produce a type of the ASTM-test-specimens by the FDM machine with the default-processing parameters. Figure 4 shows the dimensions and geometry of Tensile Specimen Type I (ASTM D638).

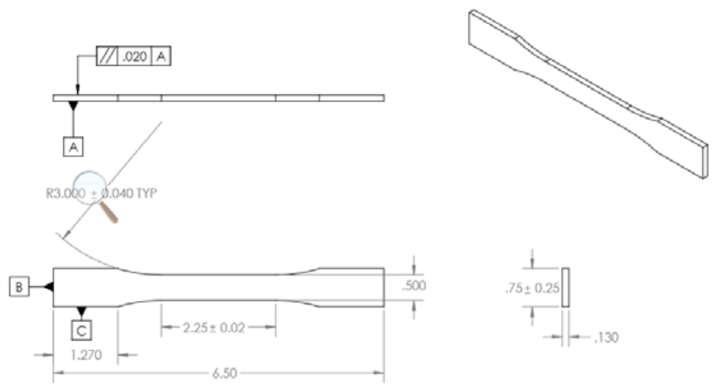


Figure 4 CAD drawing of tensile Type I-specimen (ASTM D638)

Each specimen was created individually on flat-print-position at the center of the printer bed in order to produce all specimen as similarly as possible (Figure 3). A total of five specimens in each type of the ASTM standard tests were created for testing. Therefore, the slice height, extrusion width, air gap, printer environmental temperature, build temperature, nozzle type and size, and raster angle were held to constant values to print the specimens in order to study the properties of 3D printed materials for the comparison of the data from the results of the tests. In the study, all printed specimens were tested according to the ASTM testing procedures (ASTM D6110, D638, and D648) listed in Table 2. One of the tension specimens (Type I) printed is shown in Figure 5.

Table 2: ASTM standards for the study

Title of ASTM Standard	Designation Number
Standard Terminology for Additive Manufacturing – General Principles – Terminology	ISO/ASTM 52900
Standard Specification for Additive Manufacturing File Format (AMF)-Version 1.2	ISO/ASTM 52915
Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics	ASTM D6110

Standard Test Method for Tensile Properties of Plastics	ASTM D638
Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position	ASTM D648

Figure 5: Tensile specimen of Type I printed by material extrusion (FDM)

Testing Results and Discussion

The five specimens of each of the sample batches were prepared for the tensile testing, Charpy impact testing, and heat deflection temperature testing, respectively. These testing results were compared to the published data to investigate the characteristics of the material (i.e. PLA) printed by the material extrusion method. Table 4 summarize the results of the ASTM tests and present the nominal values of the material's (PLA) properties for the data comparison and evaluation; the material's data (i.e. general purpose PLA) in the study was referred to CES-Edpack 2016.[15]

Table 4: Summary of the ASTM testing results and nominal values of the published data of PLA

ASTM Testing	Experimental results of 3D printed PLA (average values)	Published data of PLA (general purpose)
D638	• Tensile strength at maximum load: 18.85 MPa • Young's modulus (tangent): 237 MPa • Elongation: 0.084	• Tensile strength: 47-70 MPa • Young's modulus: 3.3-3.6 GPa • Elongation: 0.025-0.06 (strain)
D6110	• Charpy impact strength (notched): 1.64 J/m	• Izod impact strength (notched): 1.3-2.8 kJ/m^2
D648	• HDT at 0.45 MPa: 54.7 °C • HDT at 1.8 MPa: 53.2 °C	• HDT at 0.45 MPa: 51-56 °C • HDT at 1.8 MPa: 48.5-53.2 °C

In tensile testing, each specimen of the batch sample of the printed PLA was tested at 50.8 mm/min with a static load cell (capacity of 10 kN) in a laboratory environment. The tensile testing was utilized with a software to control the machine and record all data for the analysis. The test results show that the tensile strength, Young's modulus, and tensile elongation were 18.85 MPa, 237 MPa, and 0.084 (strain), respectively. The typical stress-strain curve for the printed specimen is shown in Figure 6.

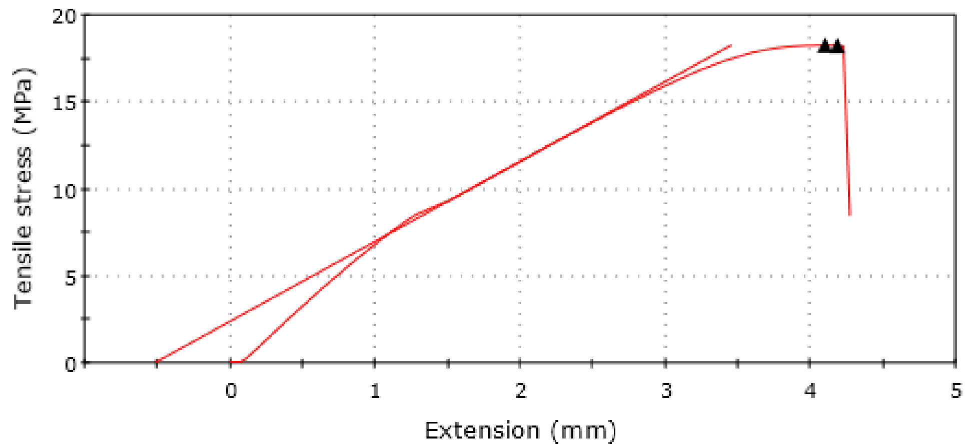


Figure 6: Typical stress-strain curve of a 3D printed PLA specimen

The test results indicated that the printed specimens showed a brittle characteristic in tension; all five specimens were broken with a clean break as shown in Figure 7.

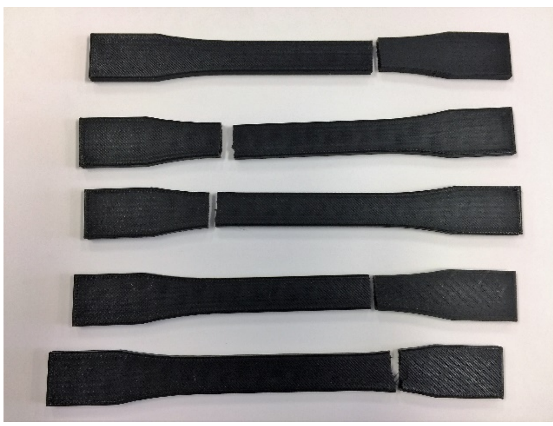


Figure 7: Clean-break of the fractured PLA specimens in tension

In the data comparison, some tensile properties, such as the averages of tensile strength and Young's modulus, are relatively low (18.85 and 237 MPa) to compare with the published data, whereas the average of tensile elongation is somewhat high (8.4%). The difference of the properties is directly related to the fabrication method; the specimens for the study were created by material extrusion, whereas the specimens for the published data were mostly produced by injection molding. Also, it is known that the specimens printed by the material extrusion method (i.e. FDM) show an anisotropic characteristics and are sensitive to the process parameters.[10-14]

Impact test method is used to determine the resistance of plastics to breakage by flexural shock. The notch of the Charpy impact specimen produces a stress concentration which promotes a brittle, rather than a ductile, fracture. The results of the impact test method are reported in terms of energy absorbed per unit of specimen width (J/m). The average of impact resistance of the printed specimens was 1.64 J/m. The impact results indicated that all specimens resulted in a complete-break by impact loading and thus, showed a typical brittle behavior of the printed PLA (Figure 8).

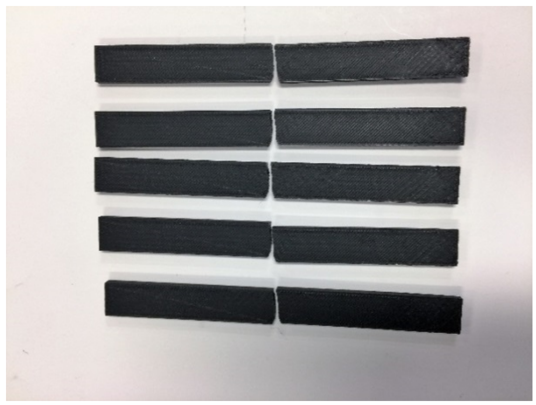


Figure 8: Complete-break of the PLA specimens by Charpy impact test

The HDT test method covers the determination of the temperature at which an arbitrary deformation occurs when specimens are subjected to an arbitrary set of testing conditions. The test results showed that the averages of heat deflection temperatures at 0.45 MPa and 1.85 MPa are 54.7 °C and 53.2 °C, respectively. The experimental results of the HDT were close to the published data and indicated the low resistance of PLA to heat; the low HDT of PLA is one of the limitations in applications. Figure 9 shows the printed specimens deflected under the loads of 0.45 and 1.85 MPa in the HDT test.

Figure 9: Two printed specimens after the deflection in the HDT testing

Development of Undergraduate Materials Laboratory by POGIL Approach

1) Laboratory Contents and Delivery

The laboratory course, "Characterization of Non-metals," studies plastics testing fundamentals in the American Society for Testing Materials (ASTM) and the ISO standards testing methods; various types of polymers, including green polymers, and composites are evaluated and characterized for polymers selection and product design. This lab course is a core-required course that provides key concepts of the characteristics of polymers to the lower level of undergraduate students (i.e., 2^{nd} year status) in the manufacturing and mechanical engineering technology programs at the Rochester Institute of Technology (RIT). On the basis of the ASTM and ISO standards, the emphasis is placed on analyzing experimental results and preparing professional-quality laboratory reports in the characterization and testing of various polymers. Also, the laboratory course emphasizes the skills and knowledge needed in engineering tasks, such as teamwork and problem solving for the design of manufacturing products. Table 4 shows the laboratory topics delivered during the semester period. A new laboratory session in 3D printing was added into the current topics.

Table 4: Materials Laboratory Topics

	Topics
1.	Introduction to Plastics Testing: • Lab Introduction, Safety Rules, Care of Equipment, Team Assigned, and Tour of the Lab. • Teamwork and Teamwork • Resources and Materials Database for Polymers
2.	ASTM/ISO Standards and Materials Specification
3.	Polymers, Types, Classification, and Polymerization
4.	Plastics Tensile Testing: Temperature and Strain Rate and Environment Effects
5.	Plastics Impact Tests: Charpy Impact Testing and Izod Impact Testing of Polymers
6.	Melt Flow Rate
7.	Hardness Testing in Polymers and Plastics: Rockwell Hardness Testing and Durometer Hardness Testing
8.	Water Absorption in Thermoplastics
9.	Heat Deflection Test
10.	Additive Manufacturing (Term Project)

POGIL (Process-Oriented Guided Inquiry Learning) is a student-centered strategy; students work in small groups, with individual roles assigned to ensure that all students are fully engaged in the learning process.[16-17] POGIL adapts guided inquiry approach, which is composed of a learning cycle of exploration, concept invention, and application in learning.[16-17] The guided inquiry approach uses carefully designed materials to guide students to construct new knowledge.[16-20] Particular approaches in POGIL may be suitable to the students' and audience's specific characteristics, facilities, instructional goals, personal preferences, and educational resources.[18-20]

POGIL (Process-Oriented Guided Inquiry Learning) was implemented for the pedagogic strategy that developed the laboratory course structure.[21,22] We developed the contents and practices of a materials laboratory course in which the instructional design is to be utilized by cognitive development and a team learning environment. In the POGIL laboratory, students work together in small groups (four students per group) at the laboratory; each group begins a lab work recognizing the need of a material (or a set of materials) for a specific product. The lab-instructor only serves as a facilitator, working with student groups if they need help during the lab-activity. Students within the team are encouraged to discuss and explain observed differences between the experimental and published values for the need recognition of the material(s) tested and, thus, they can examine the validity of theoretical concepts as well as uncertainties resulted from a laboratory process. Students working with the team members were finally required to write a paper on the laboratory exercise after the completion of the lab experiment. We have reported the results and findings in the development of POGIL based-materials and manufacturing curriculum in the ASEE conferences, the Materials Symposia, and other professional meetings.[21-26]

2) Results of the Student Survey in POGIL-based Materials Laboratory Course

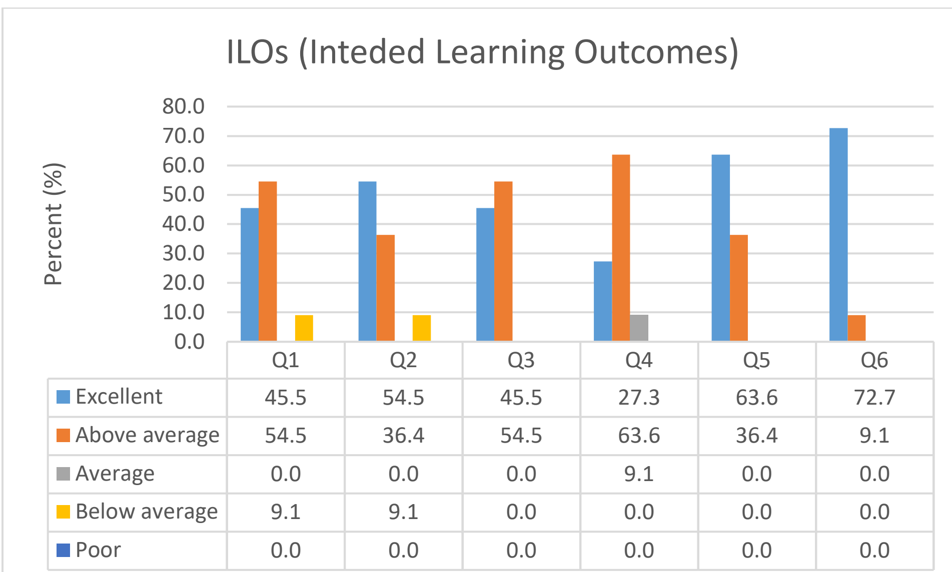
This new laboratory module in 3D printing, as a term project, emphasizes the needs to give students proper preparation in additive manufacturing (AM), so that they can deal with inevitable changes in the fields of science, engineering and technology. Some concerns reflected on the development of a laboratory module are to enhance knowledge in advancements of engineering materials and manufacturing, to develop laboratory skills by the ASTM/ISO standards, and to synthesize the course goals utilizing the POGIL approaches. The purpose of the student survey was to investigate how students felt about their experiences (e.g. Intended Learning Outcomes) after the completion of an undergradute materials laboratory course work in fall 2016. However, the survey results of ILOs did not indicate the impact of the new lab module of Extrusion Materials (EM) technique developed on the current materials laboratory course.

The survey questions for intended learning outcomes are listed in Table 5. The survey results were summarized to understand the outcomes of the lab course for the continuous improvement for materials education by the implications of the POGIL format (Table 6).

Table 5: Survey for Course Intended Learning Outcomes (ILOs)

No.	Questions
1.	Are you able to perform laboratory techniques in testing and characterization of non-metals?
2.	Are you able to characterize the properties of non-metals for design needs?
3.	Are you able to identify and select proper materials for design using materials data and technical resources?
4.	Are you able to analyze the lab experimental results and to write technical laboratory reports following ASTM testing (or ISO method)?
5.	Are you able to organize ideas in a logical way to report the work and to present a solution for problem solving?
6.	Are you able to work within the team and to complete the assignment through team learning?

Table 6: Summary of Intended Learning Outcomes (ILOs) Survey



The survey questions Q1-Q5 were to assess and evaluate the effectiveness of the laboratory modules for students to study major principles in polymeric materials testing. The survey results indicated positive responses to the lab learning environment implemented to practice the lab techniques and skills including a new lab module in 3D printing, although there were disagreements.[19-22] For example, strong agreement responses (i.e., excellent) in Questionnaires 1, 2, 3, and 4 were 45.5% and 54.5%, 45.5%, 27.3%, and 63.6%, respectively. Agreement responses (i.e., above average) were 54.5%, 36.4%, 54.5%, 63.6%, and 36.4%, respectively. Neutral responses (i.e., average) to the question 4 was 9.1% and negative responses to the questions Q1 and Q2 were both 9.1% in the survey. Negative responses were to be considered in Questionnaires 1 and 2 which could measure a level of the comprehension of the laboratory modules developed by the POGIL lab approaches.[21-26]

Question 6 shows the collaborative learning in classroom, which provides students one of the key elements to appreciating the active learning environment in the undergraduate materials laboratory course. In the result of the survey, the strong agreement responses (i.e., excellent) was 72.7% and the agreement responses (i.e., above average) 9.1%. These positive responses reflect that the team learning environment played an important role to successfully implement an active learning model for the development of the course content and delivery.[21-26]

Conclusions

The primary goal of the paper was to develop a laboratory session in 3D printing for undergraduates to present a methodology in the characterization of the mechanical- and thermal-properties for the 3D printed specimens by the ASTM standard testing, using material extrusion technique. A new material laboratory session was developed using a small-scale-low-cost material extrusion printer as a default-test-printing machine to produce the standard-specimens for the ASTM testing of D6110 (Charpy impact test), D638 (tensile test), and D648 (heat deflection test). The results from the ASTM mechanical and thermal tests were compared to the published data for the analysis. The results of the assessment and evaluation indicated positive responses to the lab learning environment implemented to practice the lab techniques and skills including a new lab session, although there were disagreements. We found that the team learning environment played an important role in successfully implementing an active learning model, developing the course content and delivery in materials education.

Bibliography

1. Robert Bogue, " 3D printing: the dawn of a new era in manufacturing? ", Assembly Automation, Vol. 33 Issue 4, pp. 307-311, 2013.
2. Kaufui V. Wong and Aldo Hernandez, “A Review of Additive Manufacturing,” International Scholarly Research Network, ISRN Mechanical Engineering, Volume 2012, Article ID 208760, 10 pages doi:10.5402/2012/208760.
3. Ian Gibson, David Rosen, and Brent Stucker, “Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing,” 2nd Edition, ISBN 978-1-4939-2112-6, Springer, New York.
4. http://explainingthefuture.com/3dprinting.html
5. Joseph T. Belter and Aaron M. Dollar, “Strengthening of 3D Printed Fused Deposition Manufactured Parts Using the Fill Compositing Technique,” PLOS ONE, DOI:10.1371/journal.pone.0122915, April 16, 2015
6. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4189697/
7. C. Lee Ventola, “Medical Applications for 3D Printing: Current and Projected Uses,” P&T®, Vol. 39, No. 10, pp.704-711, October, 2014.
8. http://www.iso.org/iso/catalogue_detail.htm?csnumber=69669
9. Aaron M. Forster, “Materials Testing Standards for Additive Manufacturing of Polymer Materials: State of the Art and Standards Applicability,” http://dx.doi.org/10.6028/NIST.IR.8059.
10. Mukesh K. Agarwala, Vikram R. Jamalabad, Noshir A. Langrana, Ahmad Safari, Philip J. Whalen, and Stephen C. Danforth, "Structural quality of parts processed by fused deposition", Rapid Prototyping Journal,” Vol. 2, Iss 4, pp. 4 – 19, 1996.

11. Sung-Hoon Ahn, Michael Montero, Dan Odell, Shad Roundy, and Paul K. Wright, "Anisotropic material properties of fused deposition modeling ABS", Rapid Prototyping Journal, Vol. 8, Iss 4, pp. 248 – 257, 2002.
12. C.S. Lee, S.G. Kim, H.J. Kim, and S.H. Ahn, “Measurement of Anisotropic Compressive Strength of Rapid Prototyping Parts,” Journal of Materials Processing Technology, 187–188, 627–630, 2007.
13. B.H. Lee, J. Abdullah, Z.A. Khan, “Optimization of Rapid Prototyping Parameters for Production of Flexible ABS Object,” Journal of Materials Processing Technology, 169, 54–61, 2005.
14. C.W. Ziemian, P.M. Crawn III, "Computer Aided Decision Support for Fused Deposition Modeling", Rapid Prototyping Journal, Vol. 7, Iss 3, pp. 138 – 147, 2001.
15. Granta Design, 2016 CES Edupack, http://www.grantadesign.com/
16. POGIL, http://www.pogil.org/
17. David M. Hanson, Instructor’s Guide to Process Oriented Guided Inquiry Learning, POGIL Project, May 2009. (http://new.pogil.org/downloads/pogil_ig.pdf)
18. Prince M., “Does Active Learning work? A Review of the Research,” J of Eng. Edu., 1-9, July 2004.
19. Mohamed, A., “Effects of Active Learning Variants on Student Performance and Learning Perception,” International J. for the Scholarship of Teaching and Learning, Vol. 2, No. 2, July 2008.
20. Elliot P. Douglas and Chu C. Chiu, “Implementation of Process Oriented Guided Inquiry Learning (POGIL) in Engineering,” Advances in Engineering, ASEE, Winter 2013.
21. Spencer Kim and Betsy Dell, “Transforming Materials Education in Mechanical Engineering Technology,” 2012 Faculty Institute on Teaching and Learning, RIT, May 30-31, 2012.
22. Spencer Kim, “Materials Education for Green Plastics Manufacturing Technology (GPMT), 2012 Annual Conference for ASEE, San Antonio,” Texas, June 10-13, 2012.
23. Spencer Kim, “Transforming Curriculum for Workforce Development in Green Plastics Manufacturing Technology (GPMT),” 2013 CCLI/TUES Conference, Renaissance Hotel, Washington DC, Washington, District of Columbia, Jan. 21-22, 2013.
24. Spencer Kim, “Green Plastics Laboratory by Process Oriented Guided Inquiry Learning (POGIL),” 2014 ASEE Annual Conference, Indianapolis, Indiana, June 15 - 18, 2014.
25. Spencer Kim, “Materials Laboratory Designed by Process Oriented Guided Inquiry Learning (POGIL),” 2015 N American Materials Education Symposium, Ohio State U., Columbus, OH, March 25-27, 2015.
26. Spencer Kim, “Transforming Curriculum for Workforce Development in Green Plastics Manufacturing Technology (GPMT) for STEM: Lesson Learned,” 123rd ASEE Annual Conference & Exposition, New Orleans, LA, June 26 - 29, 2016.