Enhancing Undergraduate Research across Disciplinaries: Integration of 3-D Printing and Advanced Materials to Engage Students

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Abstract

In the last decade, there has been a dramatic increase in the efforts dedicated to involving undergraduate engineering students in research activities. Foundational topics in mechanical engineering are taught separately in most engineering programs, without emphasizing the connection among concepts and applications across topics. The advance of additive manufacturing technology provides a unique platform to integrate multiple mechanical engineering topics and courses to enhance undergraduate research and education. This paper reports the education projects and programs being developed at the University of Oklahoma to improve undergraduate mechanical engineering education integrating 3D printing technologies and advanced materials, emphasizing two core topics: (i) design and manufacturing of 3D printing systems and (ii) 3D printing and mechanical characterization of nanocomposites. The specific instructional objectives are to improve students' understanding of key materials, manufacturing, and mechanics concepts by 3D modeling and 3D printing of multifunctional polymers and nanocomposites. The integration of advanced manufacturing and advanced materials is carried out in two consequential undergraduate projects: (i) development of direct-extrusion based 3D printing system; and (ii) 3D printing and characterization of nanoparticles reinforced composites. In the first project, two undergraduate students modify filament deposition modeling (FDM) 3D printers by re-designing the material extrusion component. Fiber-reinforced composites are directly extruded to the desired location from an extrusion component installed in the 3D printer. By adjusting control parameters and print speed, materials can be printed with various spatial resolutions. The second project focuses on the development of nanoparticles reinforced composites. Thermoplastic polymers and zinc oxide nanoparticles are mixed at various weight ratios to control materials viscosity, allowing them to be 3D printed as free-standing samples for characterization and testing. 3DIn the last two years, six junior mechanical students have been recruited to the additive manufacturing related undergraduate research projects. They all decided to pursue graduate degrees after completing undergraduate research at the University of Oklahoma. This paper will also report students learning outcomes and self-assessment results.

Introduction

Undergraduate mechanical engineering education includes a broad range of fundamental concepts and abstracts, such as materials and mechanics, design, manufacturing, circuits and control, thermodynamics, and fluid dynamics. As one of the most popular engineering disciplines, most universities across the country traditionally serve to prepare many undergraduate students. Currently, this broad range of topics and courses are taught separately in most mechanical engineering programs, in most instances, without demonstrating the connection of concepts and applications [1-3]. Most undergraduate curricula of mechanical engineering programs emphasize how well students can solve textbook questions of a single topic, without deeply understanding the connection between various courses and fundamental engineering concepts. Although engineering curricula are well-designed and highly structured, a few research studies have reported that students who successfully completed the engineering education still faced challenges during the college to career transition [4, 5].

In the last two decades, significant efforts have been focused on the development, implementation, and application of novel additive manufacturing technologies. By now, the advances of additive manufacturing technologies have provided a unique platform to integrate multiple mechanical engineering topics and courses to enhance both graduate and undergraduate education. Often referred to as three-dimensional (3D) printing, additive manufacturing technologies have been well-accepted in both academia and industry as a novel manufacturing approach for fabricating a wide range of materials directly from 3D models [6-10]. Significant advantages including complex geometry, low material waste, and controllable material-parameter-process-property relationship have been well accepted. Since additive manufacturing technology was first developed by Charles Hull in 1986 using the stereolithography (SLA) method, various other 3D printing technologies have been developed including digital light processing (DLP), selective laser sintering (SLS), fused deposition modeling (FDM), direct ink writing, material jetting (MJ), and contour crafting (CC) [11-16]. Besides numerous 3D printing technologies, a broad range of materials can be employed by various additive manufacturing platforms. The most common materials include thermoplastic polymers [17, 18], continuous fiber-reinforced composites [18, 19], nanoparticles reinforced composites [20-23], ceramics [24, 25], and metals [26, 27]. In addition, 3D printing involves almost all the key elements in undergraduate mechanical engineering education, including modeling and design, materials and mechanics, and manufacturing and testing. Therefore, early introduction of 3D printing technologies to undergraduate engineering students and continuous involvement in 3D printing-related activities through in-class projects and undergraduate research projects can provide unique opportunities to improve students' understanding of abstract engineering concepts and improve problem-solving capabilities, resulting in enhanced problem-solving capability through experiential learning. Students are expected to be better prepared for the college to career transition.

In the School of Aerospace and Mechanical Engineering at the University of Oklahoma, faculty members are developing a series of projects and undergraduate research opportunities to involve undergraduate engineering students in 3D printing-related projects. Two typical projects are reported in this paper: (i) Project 1: development of direct-extrusion based 3D printing systems; (ii) Project 2: 3D printing and characterization of zinc oxide nanoparticles reinforced composites. In the first project, two undergraduate students are modifying a commercial FDM 3D printer by re-designing the material extrusion component using compressed air for extrusion of material from a syringe and in nozzle fiber impregnation for FDM. Fiber-reinforced composites with either UV curable resin or thermoplastics as the matrix can be directly printed using the 3D printers designed by the two undergraduate students. By adjusting key 3D printing parameters, such as printing speed, fiber-reinforced composites can be printed with high spatial resolutions and complex geometries. The second project focuses on the development of 3D printable zinc oxide reinforced nanocomposites. The mechanical properties, such as Young's modulus of the 3D printed materials are characterized. Each project has been created to achieve certain educational goals. The overall schematic of these approaches is shown in Figure 1. The specific instructional objective of this research is to improve students' understanding of mechanical design, mechanics, and materials and manufacturing concepts by 3D modeling and 3D printing of practical mechanical structures and products.

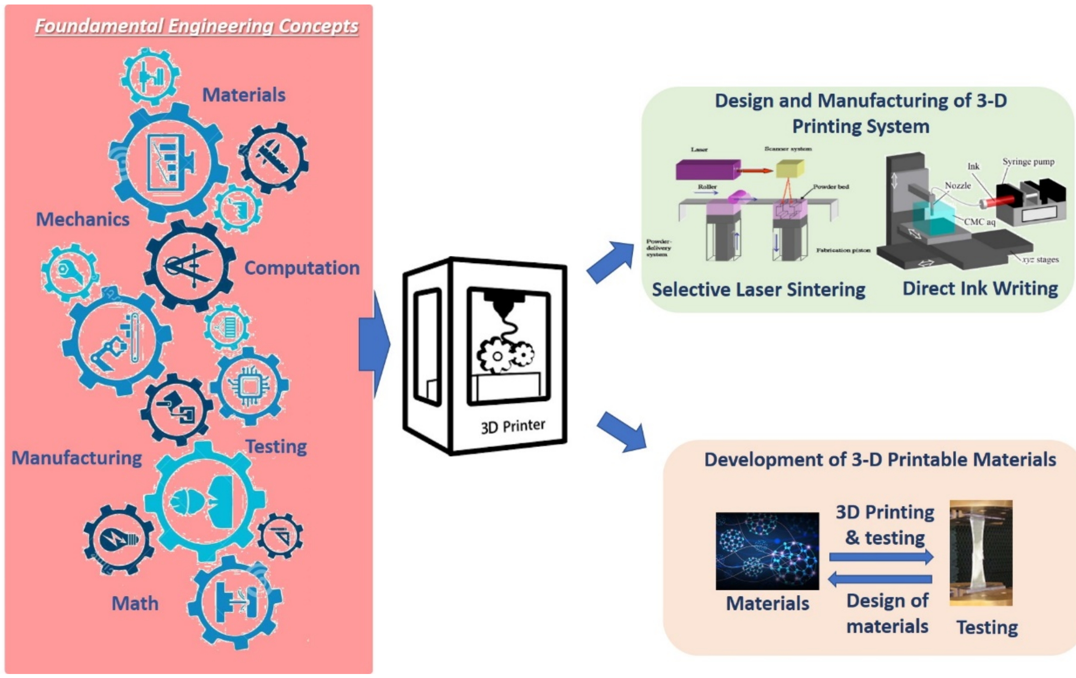


Figure 1. The schematic of mechanical engineering projects with an integrated 3D printing approach for the design of additive manufacturing systems and the development of novel materials for broad mechanical engineering applications.

Enhanced undergraduate mechanical education integrating 3D printing and design of materials approach

Materials, mechanical design, and mechanics are all critical subjects for successful undergraduate mechanical engineering education. Current curricula in mechanical engineering have provided adequate training through learning to solve textbook problems. Students are tasked with memorizing and understanding equations to know how to use the equations to solve given physics and mechanics-based questions. However, engineering practice can be dramatically different from any textbook problems. Engineers need to know how to summarize a real engineering challenge into a series of questions and prepare solutions through subtasks. Integrating materials, mechanical design, manufacturing, mechanics, and applications provide a unique opportunity for students to gain such experience. Since most engineering structures need to be built by materials, parts, and components, students can encounter real challenges when trying to use certain materials to meet the given technical requirements. Through material processing, manufacturing, and applications, they can gain real experience to understand solid mechanics behavior and their relationship with material processing procedures. In this paper, the specific learning objectives are: (i) enhance mechanical design, assembly, and validation capabilities of undergraduate students through hands-on projects; (ii) develop interdisciplinary undergraduate research projects integrating advanced materials and additive manufacturing to strengthen students' understanding of materials, mechanics, manufacturing concepts and knowledge; (iii) validate students' learning outcomes for potential improvement of the designed undergraduate in-class and research projects.

Design of direct-extrusion based 3D printing system

Two undergraduate students have been collaborating on a research project to design and testing a pneumatic driven direct-extrusion based 3D printing system. The developed 3D printer is modified from a commercial Creality Cr-10 Mini printer. Instead of using the FDM extrusion component, a pneumatic-driven syringe extrusion component and three ultraviolet (UV) lasers are installed on the printer. Compressed air first passes through a pressure regulator to vary the amount of pressure, and then through an electronic solenoid valve which the printer controls to turn the extrusion on and off. A syringe containing the resin polymers is installed inside a mount which also holds three 405-nm wavelength UV lasers aiming just below the center of the syringe tip. A small amount of compressed air is fed into a syringe to facilitate the flow of the UV curable material and fiber during printing. The lasers solidify the extruding UV resin within seconds after extrusion, resulting in in-situ curing of the materials. The in-situ curing method allows the part to adequately adhere to the bed to assist pulling the fiber at the proper rate to print complex parts. To protect operators, a small chamber is added to the 3D printer just above the syringe which holds a spool of carbon fiber and allows the pressurized air to flow through. This pneumatic-driven 3D printer allows us to manufacture continuous carbon fiber-reinforced composites and the design is shown in Figure 2.

(a) (b)

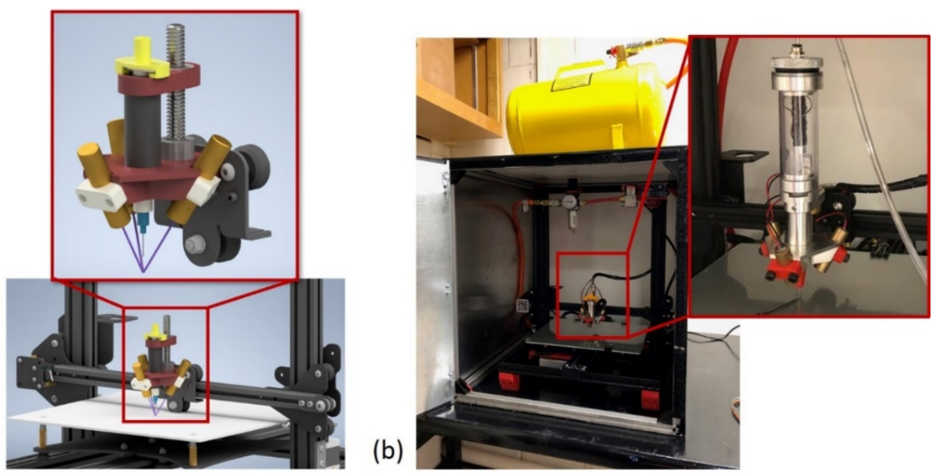


Figure 2. (a) The pneumatic driven extrusion component designed by the undergraduate students; (b) fully assembled 3D printing system with installed UV curing and extrusion components.

Currently, the printer is still in the early stages of determining the best printing parameters. It has been found that a single line of 3k fiber extruded at 15 psi and 1 mm/s provides the best results so far and creates a line approximately 1 mm in width and height. The accuracy is heavily dependent on the geometry of the print, as moving in straight lines or large radii turns is consistent, but sharp turns result in the fiber being dragged before curing enough to adhere to the substrate. Parts made thus far have been fabricated up to 50 mm in width and height, but the printer is capable of printing much larger structures (220 X 220 X 250 mm total build volume). It is also likely that the printer will be able to create parts with larger overhang angles than a typical FDM printer, as the in-situ curing of the material should make the extruding fiber and resin strong enough to support steep overhangs without support material. Samples produced so far have included 3-layer rectangular samples, a hollow cone structure, and a hollow airfoil shape, as shown in Figure 3.

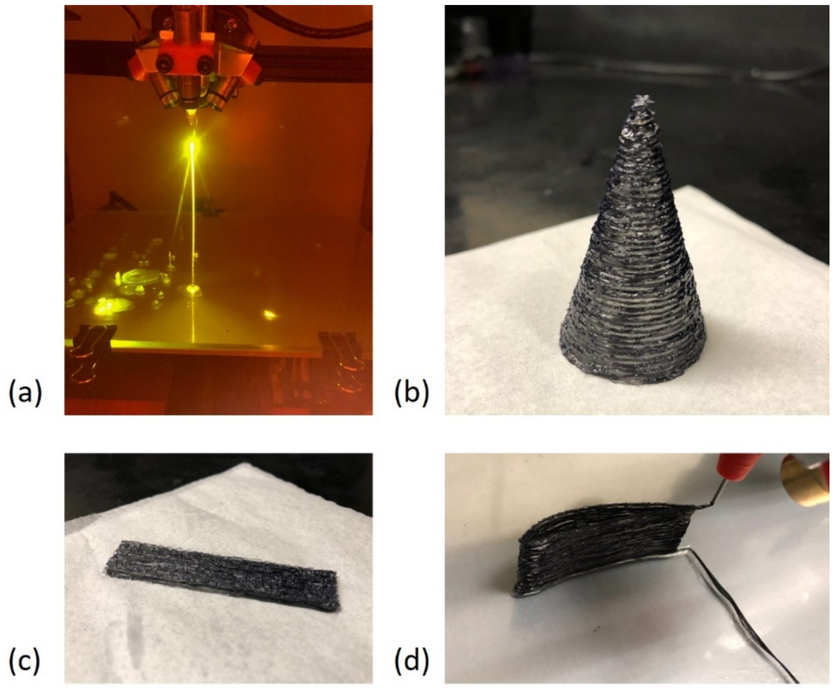


Figure 3. (a) Direction extrusion and in-situ curing of 3D printing system; (b) 3D printed cone; (c) 3D printed composite beam; (d) 3D printed air-foil shape.

Besides the pneumatic driven 3D printing system, undergraduate students also design and develop an FDM 3D printing system for continuous fiber-reinforced thermoplastic composites. For this printer, composite samples are printed with continuous carbon fiber embedded in polylactic acid (PLA). Carbon fiber with 1k tow has been used as reinforcement fibers in the printed composites. Prior to the printing process, carbon fibers are first coated with a mixture of PLA and chloroform. The PLA is mixed into the chloroform via magnetic stirring until it is entirely dissolved, resulting in a sticky and viscous solution with a PLA weight ratio of 9.5 wt.%. The carbon fiber is pulled through the solution to coat the fiber, which is then fully dried within minutes due to chloroform's high evaporation rate and assistance from a heat gun. Coating carbon fibers with the PLA/chloroform solution prevents the fiber from being frayed and breaking in the nozzle and consequently clogging the nozzle during the FDM 3D printing process, and likely improves interfacial bonding between the fiber and printed polymer.

Once the carbon fiber tow is fully coated and dried, it is then wound around a spool and mounted on a Creality CR-10 Mini 3DD printer, as shown in Figure 4. During the printing process, the carbon fiber is fed into the hot end of the printer through the heat sink to join with the PLA that is being fed through the heat sink. This occurs just above the heating block and melt pool in the heated nozzle. When the fiber and PLA pass through the heated nozzle, the fiber is impregnated with the molten PLA and extruded through a single nozzle. The fiber continues to be pulled through the nozzle by the tension of the printed composite that has cooled and solidified on the bed. Currently, the undergraduate researchers have only been able to 3D print rectangular beam samples. The print path is in an aligned rectilinear orientation. This means that the nozzle starts at one corner of the rectangle, then moves along the length (X) of the rectangle to the corner on the other side, and later travels along the width (Y)a distance of 0.9 times the extrusion width, and then moves back down the length (X) of the original edge of the rectangle. This path is repeated until the layer is complete. The speed of the nozzle in this process is 2 mm/s along the straightaways and 1 mm/s around the turns. This helps ensure that the fiber does not tear around the turns and remains centered in the filamentary extrusion.

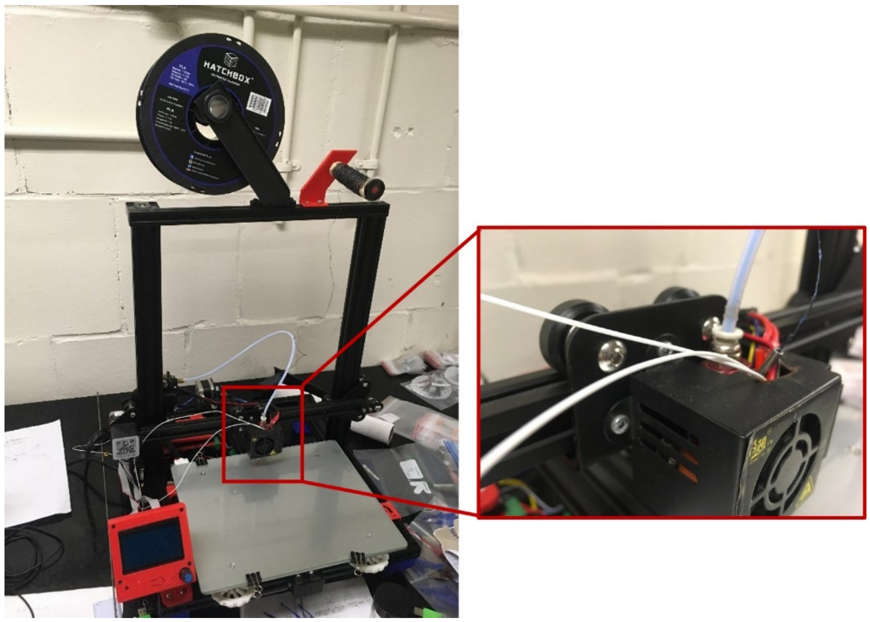


Figure 4. The developed 3D printing system for continuous fiber-reinforced composites.

The designed undergraduate research projects to develop and build a 3D printing system requires a significant time commitment. Therefore, this project can be suitable for senior undergraduate researchers, particularly for those who intend to continue into graduate study. The two undergraduate students are interested in pursuing graduate degrees in Mechanical Engineering. Both have committed to continue working on their projects and will complete their projects for their master's thesis in the future.

Design and characterization of 3D printable nanocomposite materials

The design and development of multifunctional composites have been an interesting research topic that attracts significant attention in the last decade. Three undergraduate students have been recruited in an independent research project focused on the design, development, and characterization of nanoparticles reinforced composites. The goal of this project is to help young undergraduate mechanical engineering students to gain hands-on experience in the design, manufacturing, and characterization of advanced multifunctional composites. Students are expected to enhance their understanding of fundamental concepts of materials, mechanics, CAD modeling, and mechanical testing.

In this project, students are required to investigate the appropriate method to uniformly disperse nanoparticles, in this case, zinc oxide nanoparticles, into thermoplastic polymers. Students are required to identify appropriate polymer and nanocomposite formulation so that the mixture can be manufactured as filaments for FDM based 3D printing. In addition, students need to design 3D testing models and convert the models' geometries to G-code for 3D printing. Moreover, they are asked to develop appropriate 3D printing parameters for the efficient manufacturing of testing samples. Three junior undergraduate students participated in this project in the Fall 2018 semester as their guided undergraduate research projects. The three students worked together as a team to practice their collaboration and communication skills during the project period.

The material fabrication procedure developed by the undergraduate students is shown in Figure 5. First, liquid nitrogen is used to freeze raw thermoplastic polymer pellets, including ABS and PLA. Immediately after frozen, the plastics are ground into fine powders using a commercial blender. Since the glass transition temperatures of ABS and PLA are low, liquid nitrogen efficiently cools the selected plastics to facilitate the grinding process. ZnO nanoparticles are mixed with the grounded plastic powders and extruded into a filament for manufacturing testing coupons using an in-house modified FDM 3D printing system. The student group solves several critical technical challenges during the materials preparation and 3D printing process, including (i) develop an efficient method for polymer cooling and grinding; (ii) build an FDM filament extrusion system for filament fabrication; (iii) optimize 3D printing parameters to reduce visible voids in 3D printed samples.

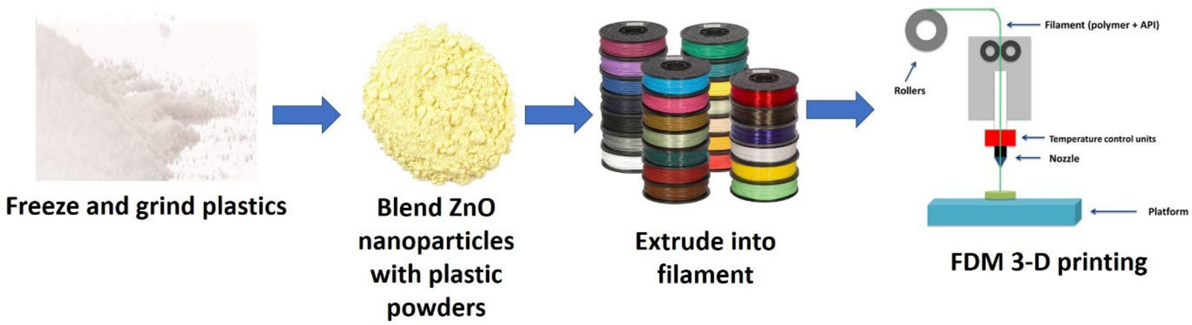


Figure 5. Schematic showing the material preparation and 3D printing process for the fabrication of nanocomposite samples

Following ASTM D638 (Standard Test Method for Tensile Properties of Plastics), the 3D printed nanocomposite samples are characterized under tensile loads. Multiple variables, including load rate, are studied to understand the true behavior of the material. The printing process is shown in Figure 6 (a). The 3D printed tensile dog bone samples using pristine PLA and ABS filaments and in-house prepared nanocomposite filaments are shown in Figures 6 (b).

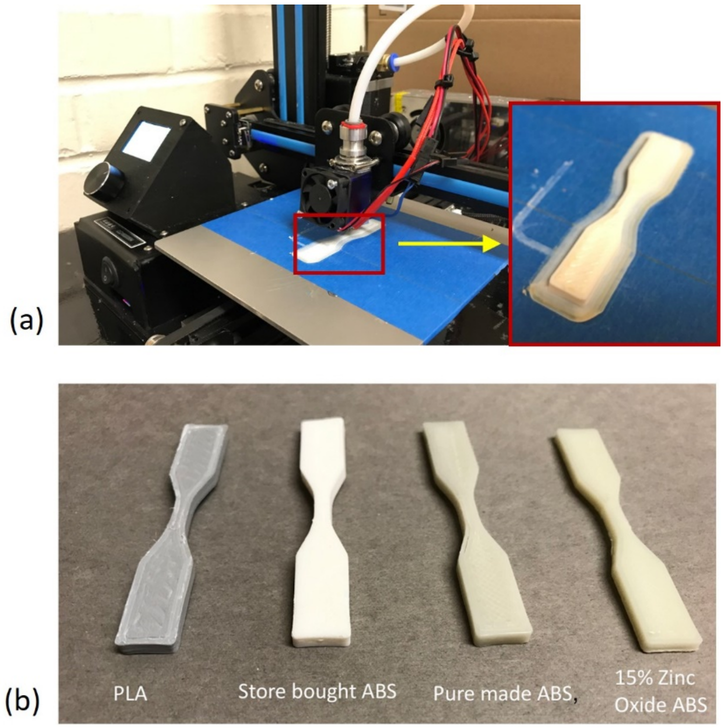
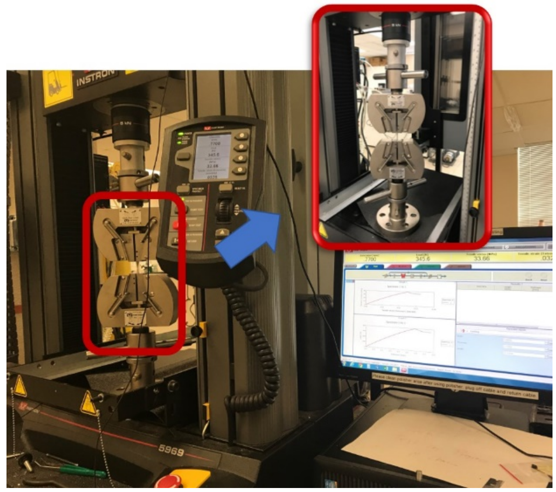
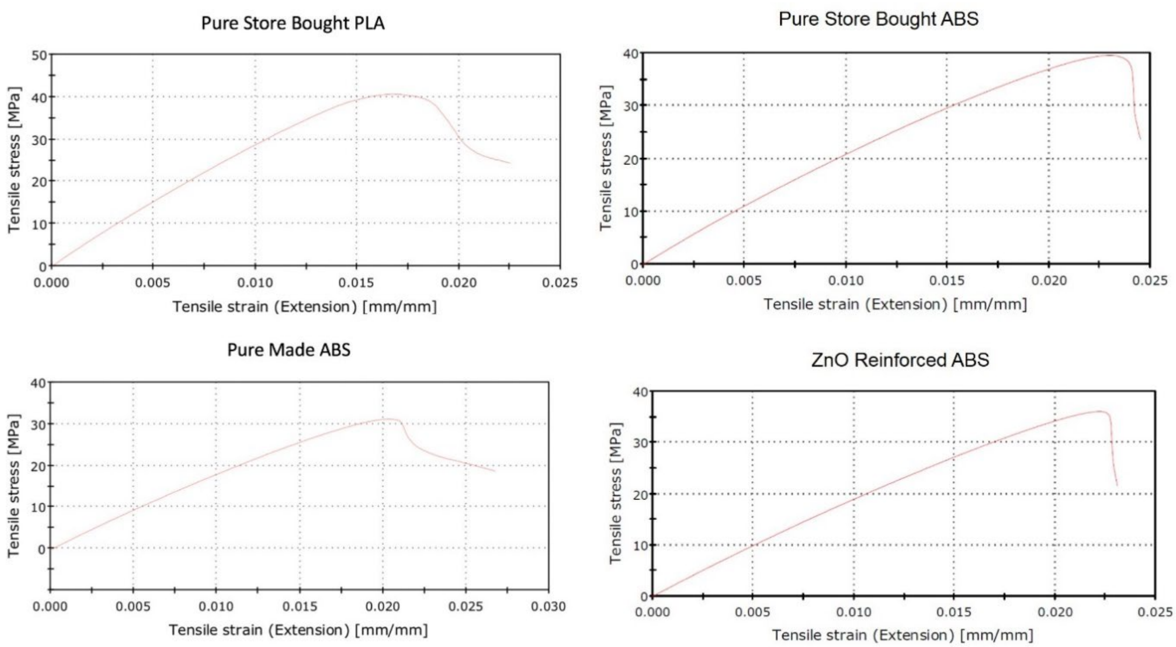


Figure 6. 3D printing of ASTM dogbone coupon: (a) 3D printing process using an FDM 3D printer; (b) 3D printed dogbone samples using pristine PLA, pristine ABS, home-made ABS, and ZnO nanoparticle enhanced ABS.

The mechanical testing and materials characterization are carried out following the selected ASTM standard. As shown in Figure 7 (a), all the tested samples are clamped in an Instron dual-column mechanical tensile fixture and tested under uniaxial tensile load until fracture. The constant load rate of 3 mm/min is used for all the quasi-static tensile tests until fracture. The mechanical behaviors of the four types of materials are shown in Figure 7 (b). Students are trained to process all the testing data by converting recorded force and displacement data into stress and strain relationships. Using their knowledge of mechanics, they can identify key mechanical parameters, such as ultimate strength, Young's modulus, and the elastic and plastic range of the 3D printed coupons. The project results are closely related to their mechanics courses, such as Solid Mechanics and Design of Mechanical Components. Therefore, positive feedback is often received from the students. More details will be discussed in the assessment of the students' learning outcome section in this paper.

(a)




(b)
Figure 7. (a) The experimental setup of 3D printed dogbone coupon; (b) Mechanical testing results of four types of 3D printed coupons.

The design and characterization of 3D printed nanocomposite materials is a suitable research project for junior undergraduate students when they study critical mechanics courses. In the last two years, the project has been carried out as independent undergraduate research projects for the senior students working in the authors' research laboratory. Under detailed guidance, the undergraduate students were able to establish a solid understanding of the 3D printing process, and the effects of nanoparticles on the overall mechanical properties of the printed parts. In addition, the experience in mechanical testing following ASTM standards emphasized the solid mechanics knowledge the students learned in their junior year. Three students have participated in the reported undergraduate 3D printing and materials testing research. Each student provided positive feedback in the final class evaluation and survey.

Assessment of student learning outcomes

Evaluation and assessment of students' learning outcomes are critical for 3D printing-related undergraduate research. Students learning outcomes should articulate the new skills the students learned during the research and training process. Although external evaluators are more appropriate, the current research and learning outcomes are still limited by internal and self-evaluation due to the lack of financial support.

All of the assessment of student learning outcomes is evaluated by using: (i) bi-weekly reports submitted by students during the entire research period; (ii) final reports provided by the students after the end of the research period; (iii) comparisons of generated experimental results with the published data and papers. Because learning objectives were given to the students at the beginning of the project, students were able to address each objective and discuss the new skills and experience they gained by the end of their project.

Conclusions

This paper presented the projects and the program being developed at the University of Oklahoma to enhance mechanical engineering education by integrating 3D printing technologies. The overall goal of this approach is to enhance students understanding of fundamental concepts in materials, mechanics, modeling, and manufacturing by providing hands-on opportunities to undergraduate students, aiming to improve their problem-solving capabilities. Two types of projects have been developed focusing on different education topics. The first type of project focused on the design of 3D printing systems. Two undergraduate students were able to independently design, assemble, and test direct extrusion-based 3D printing systems for continuous fiber-reinforced composites. Self-assessment of the learning outcomes indicated the effectiveness of this study to enhance mechanical education. Students were highly engaged in their projects and decided to pursue their graduate study after receiving their Bachelor's degree. The second type of project focuses on the integration of materials preparation, 3D printing, mechanical property characterization. Well-prepared materials were first 3D printed into standard samples following ASTM standards and then were characterized to understand materials mechanical behavior. Students were able to independently identify materials processing procedures and experimentally characterize the key mechanical properties of the 3D printed samples. Self-assessment of the students indicated that they were able to link their materials knowledge to solid mechanics knowledge and implement the relation of the two fields into their projects.

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