Development of Hands-on Additive Manufacturing Course

Abstract

In this paper, developmental effort toward an Additive Manufacturing (AM) senior elective course for undergraduate mechanical engineering students is presented. To develop the next generation of engineers with digital manufacturing skill sets, the AM course offers unique opportunities for undergraduate engineering students. A senior elective in the AM course was developed based on the seven different process categories of AM. There are three parts to this course: (a) introduction to seven different AM process categories (b) generative design for AM, and (c) design-manufacturing-testing project. Early in the semester, students were introduced to material extrusion AM and the generative design module of Fusion 360 CAD software. In parallel to the regular in-class meeting for seven different AM processes, students were tasked with self-paced generative design for AM-based course modules. In the mid-semester, a comprehensive guideline and rubric of design, manufacturing, and testing (DMT) based projects was provided to the students. Due to the availability of low-cost material extrusion 3D printers, students were tasked to identify load-bearing parts for real-life structural applications. Example parts including L-Bracket, Engine Mount, Engine Bracket, Electric Motor Mounting Bracket, etc. were identified by students. All these example parts are traditionally made by compression molding, metal casting, and machining operations. A justification was required for each team to answer the questions: (a) how AM will overcome the challenges of traditional manufacturing? and (b) what are the benefits of AM? By providing the appropriate justification each team developed their part geometry using the Fusion 360 generative design module. Imported digital parts from Fusion 360 software were then processed within the Fusion 360 slicing software module to implement the design and processing for manufacturing. The sliced, i.e. generated tool path of the generative design part, was then used in several benchtop thermoplastics-based 3D printing machines. After successfully fabricating the parts, each team tested their parts for tensile loading. Tested results were compared with the legacy part which is also a 3D printed part with no change in the original design. Throughout the course of DMT and regular lecture presentations, high enthusiasm was observed within the class. In addition to the active engagement of students in this course, an essential skillset of digital manufacturing was developed. In the future, this effort will be translated to other AM process categories thus enhancing student engagement and developing the next generation of mechanical and manufacturing engineers.

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, is a process of fabricating a three-dimensional object in a layer-by-layer fashion using computer-aided design parts as opposed to the subtractive manufacturing process such as milling operation [1]. The development, preparation, and processing of the files are completely done digitally. For instance, the three-dimensional modeling using computer-aided design (CAD) software, slicing the object, generating the tool path, and processing parameter selections, are all performed digitally. The digital processing of AM reduces many processing chains thus, yielding faster adoption in many engineering and educational applications [2]. In addition to the digital processing of AM, the decentralized nature also enables faster and cleaner energy production of the prototype parts compared to the traditional manufacturing process thus helping in environmental sustainability.

As an example, the GE Aircraft Engine Bracket is traditionally manufactured by machining of Titanium stock and the part weight is 4 lb. as shown in figure 1(a) [3]. This part does not play an active role during the operation of the engine; however, the primary function of this part is to support the weight of the cowling during engine service. When it was recognized that the part could still meet all the functional requirements at a lower weight, an optimized design with reduced weight would reduce the overall carbon footprint during manufacturing. Recognizing the potential of a crowdsourcing-based design challenge, GE solicited a design competition to reduce the weight while still maintaining functionality by providing some specifics to the loading conditions. The design challenge was not limited to any particular manufacturing process. Almost 700 designers were signed up for the competition to design the part and perform the loading analysis with optimized structures. As shown in Figure 1(b), an optimized structure was designed with 80% less weight of bracket without sacrificing the load-bearing capacity. This optimized design was then fabricated using the metal AM process as shown in Figure 1(c). It is possible that the optimized design can be manufactured in traditional machining operations such as milling, however, the cost of manufacturing would be relatively higher due to the cost of fixtures and tooling. This example certainly presented the AM community with an example of how parts could be produced with highly optimized geometry for light-weighing applications.

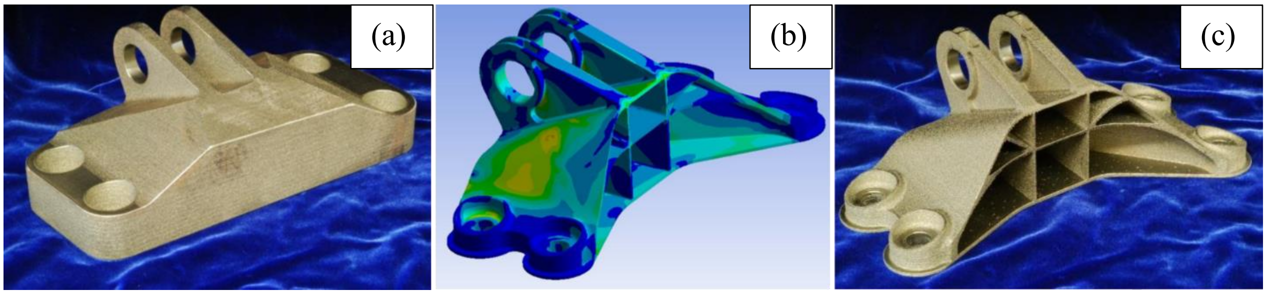

Figure 1: GE Engine Bracket crowdsourced challenge [3]: (a) legacy part of GE Engine Bracket that is machined from Titanium bar and weight of 4 lb. (b) example optimization of the structure by the design challenge participants, and (c) example of winning bracket design for 1st place.

It is evident that AM is well-positioned in producing complex geometry parts with mass customization and a high degree of agility. Therefore, the use of certain AM technologies is increasing in the industry, which is creating a demand for a skilled engineering workforce [4]. Realizing the advantages of AM processes and the demand for a skilled workforce, many educational institutions developed and offered AM-related courses for both undergraduate and graduate levels [5-9]. The University of Houston–Clear Lake (UHCL) is relatively new to offering AM courses for undergraduate Mechanical Engineering program. The Department of Engineering at UHCL has offered a Bachelor of Science in Mechanical Engineering since the Fall of 2018 and received the ABET accreditation in the Fall of 2021. With an effort to develop advanced manufacturing research and a rapid prototyping-based teaching laboratory, material extrusion and material jetting-based AM machines were acquired. The overall goal of this initiative is to support design and manufacturing-based educational activities and create opportunities to engage undergraduate students in research. However, there were no such formal course offerings on the AM that would allow students to learn and engage in the full spectrum of the AM process such as 3D design with optimization in mind to hands-on experience in manufacturing and testing of these designs. In Spring 2023, a senior elective on AM was offered for the first time in the Mechanical Engineering Program. In order to fulfill the growing demand for a skilled workforce, this course is designed by considering the hands-on aspect of the AM utilizing low-cost and readily available material extrusion-based 3D printing machines and Autodesk Fusion 360 software.

This paper primarily describes the details of the AM course offering such as the development of the lab, contents for the course, approach to develop the hands-on aspect of the course, and student engagement throughout the semester. The learning outcomes of this course are listed here.

Learning outcomes:

i. Develop a comprehensive understanding of the fundamentals of AM.
ii. Cultivate a "Design for Additive Manufacturing: DfAM" skillset by combining computer-aided design (CAD) and computer-aided manufacturing (CAM).
iii. Understand the various software tools, processes, and techniques that enable AM and on-demand/personal fabrication.
iv. Fabricate parts using an available AM technology.
v. Execute a design-manufacturing-testing (DMT) project that demonstrates the superiority of AM over the counterpart traditional manufacturing processes.
vi. Understand the latest trends and business opportunities in AM, distributed manufacturing, and mass customizations.

2. Overview of AM Laboratory at the University of Houston – Clear Lake

The Additive Manufacturing Laboratory at the University of Houston – Clear Lake is designed to foster innovation and hands-on learning experiences for students by engaging through course projects and research. This lab is equipped with cutting-edge technology, including the Gigabot 3+ Material Extrusion 3D printer, Raise3D E2, Sovol 3D printer, Einscan Pro 3D scanner for reverse engineering, FLIR thermal imaging camera, and other relevant equipment and tools as shown in figure 2. This lab offers students a conducive environment to work on materials extrusion and materials jetting based AM and prototyping. Students gain practical experience in designing, creating, and analyzing components using extrusion-based AM techniques by active engagement in the semester projects and research. The establishment of this lab was made possible through support from state and federal research grants, reflecting a commitment to advancing STEM education and research at the university. The lab also serves as a hub for interdisciplinary collaboration, where students and researchers can explore the limitless possibilities of AM while addressing real-world challenges and pushing the boundaries of innovation.

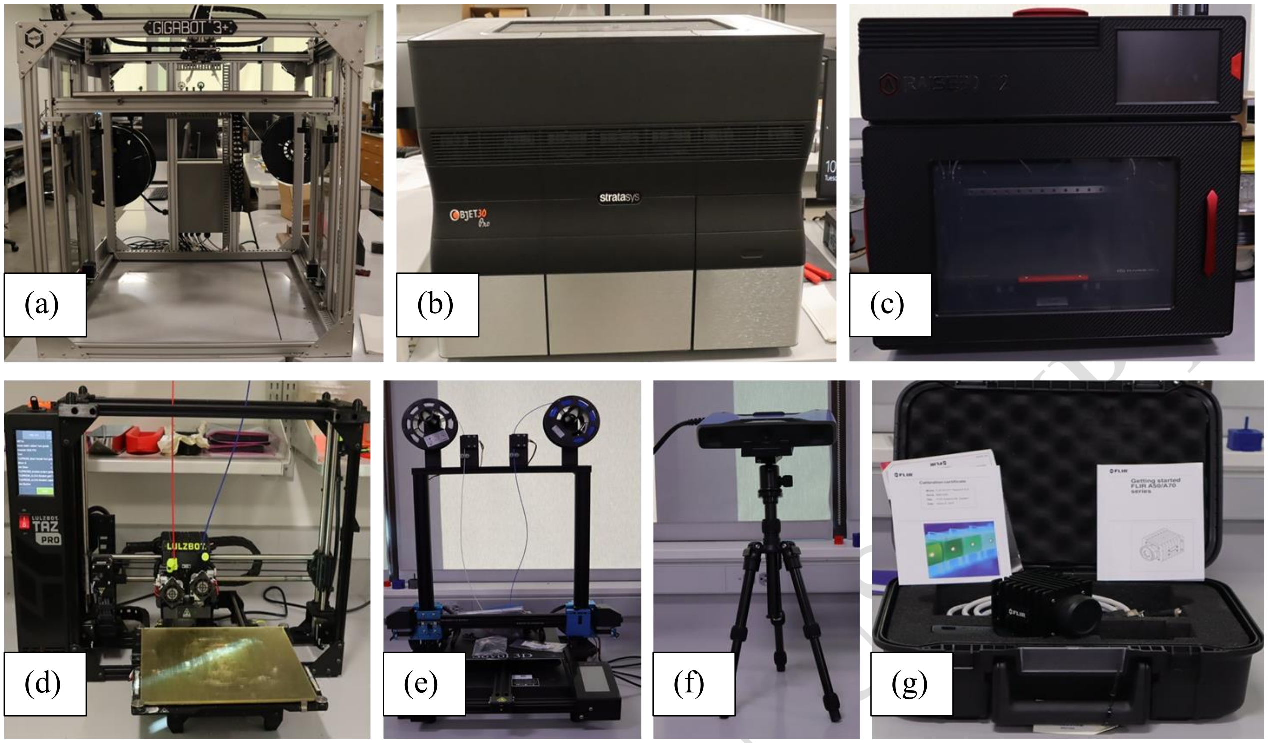

Figure 2: Machines and equipment in AM Laboratory at UHCL: (a) A Gigabot 3+ FFF 3D printer, (b) Material Jetting 3D printer, (c) Raise3D E2 3D printer, (d) Lulzbot Taz Pro 3D Printer, (e) Sovol 3D printer, (f) Einscan 3D scanner, and (g) FLIR thermal imaging camera.

3. Structure of the Course

The Additive Manufacturing course was designed to provide the opportunity to engage in hands-on activities throughout the semester. In Table 1 the structure of the course is provided. It was a fourteen (14) week-long course and two class meetings per week. In week 1, students are introduced to the course materials and learning outcomes, tour the AM lab, and access the Fusion 360 student version. Every week, lecture modules were delivered in the class via PowerPoint presentation lectures. In parallel, students were required to work on developing the team and project ideas. By realizing the importance of mass customization and shape optimization opportunities in AM, a generative design module was introduced. During the teaching and discussion of the generative modules, students were trained in the class to work on the GE Engine Bracket and Alcoa Bracket. Both of the training and practice modules were adopted from the Fusion 360 learning community and can be accessed in [10].

Table 1: Breakdown of 14 week AM course

Week Number	Lecture modules	Design Modules	Project
Week 1	Introduction to AM	Intro to Fusion 360 – (Student Version), Tour to the Fusion 360	AM Lab Tour
Week 2	Application of AM	Create new project and design, Create 2D sketch and 3D modeling	Team formation and introduction of project
Week 3	Design and Processing Chain in AM	Assemble Components and Joints, File development for 3D printing	Project Requirements
Week 4	Material Extrusion AM	Generative Design with Engine Bracket and Alcoa Bracket	Design of the project
Week 5	VAT Photopolymerization	Static and Thermal Simulation on Generative Design	Design of the project
Week 6	Materials Jetting Exam - 1	File preparation and slicing using Fusion 360	Generative Design
Week 7	Powder Bed Fusion	Training in material extrusion 3D printing machines	Simulation for loadings and analysis
Week 8	Direct Energy Deposition	Training in material extrusion 3D printing machines	Simulation in Fusion 360
Week 9	Sheet Lamination	Presentation - design and analysis of project	
Week 10	Binder Jetting AM	Design for AM using Fusion 360	
Week 11	Design for AM	Manufacturing of the final parts	
Week 12	Industrial Applications - Invited Lectures	Manufacturing of the final parts	Test fixture development
Week 13	Research and Progress Exam – 2	Test Campaign	
Week 14	Final Project Presentation		

After successfully learning the generative design, the project for the AM course was introduced. All teams were tasked to identify mechanical load-bearing components that are traditionally made in machining operations or metal casting operations. In addition, they were tasked to develop the benchmark table for the loading condition for the real-life application. After developing loading conditions, each team was tasked to develop the optimized design part using generative design modules. From the middle of the semester, students were transitioned to the AM lab to train on the materials extrusion 3D printing machines to print parts.

4. Project work and discussion

The overall goal of this course was to embed student engagement part within the learning outcome by introducing hands-on activities via hands-on projects. As shown in Figure 3, examples of representative work of the hands-on projects on the load-bearing brackets are demonstrated. In a sequential process of the project, all teams designed two different parts: (a) the legacy part and (b) the optimized generative design part. Then, all teams processed their legacy part and generative design parts using the respective slicing software (Fusion 360, IdeaMaker, and Cura) in the material extrusion 3D printing machines available in the AM lab. Using the slicing software, various processing parameters were chosen to determine the impact of the processing parameters. As an example, a team has chosen three different raster orientations (0-degree, 90-degree, and $\pm$ 45-degree) to print the generative design parts. Another team has chosen to print the generative design part in three different printing orientations such as (XYZ, ZXY, and YZX). To measure the statistical significance of the mechanical properties, all designs were printed in at least three parts.

To study the weight savings, load-bearing capabilities, and impact of the processing parameters on the final optimized geometry, all the parts were tested in various custom-made fixtures mounted on a Universal Tensile Testing machine. Test results such as ultimate tensile stress, strain at break, force, and displacement-related information were captured from the tests. In the final presentation and final report, all team provided their findings detailing the design, manufacturing, testing, and analysis as shown in Figure 4. After the successful completion of the semester, student evaluations were analyzed to reevaluate the learning outcomes.

Figure 3: Representative images of the project work in AM course: (a) 3D printed jet engine mount bracket of legacy part and generative design parts with different raster orientations, (b) structural load bearing bracket legacy part and generative design parts with different printing orientations, and (c) industrial conveyor belt shaft bracket legacy part and generative design parts were 3D printed with different infill densities.

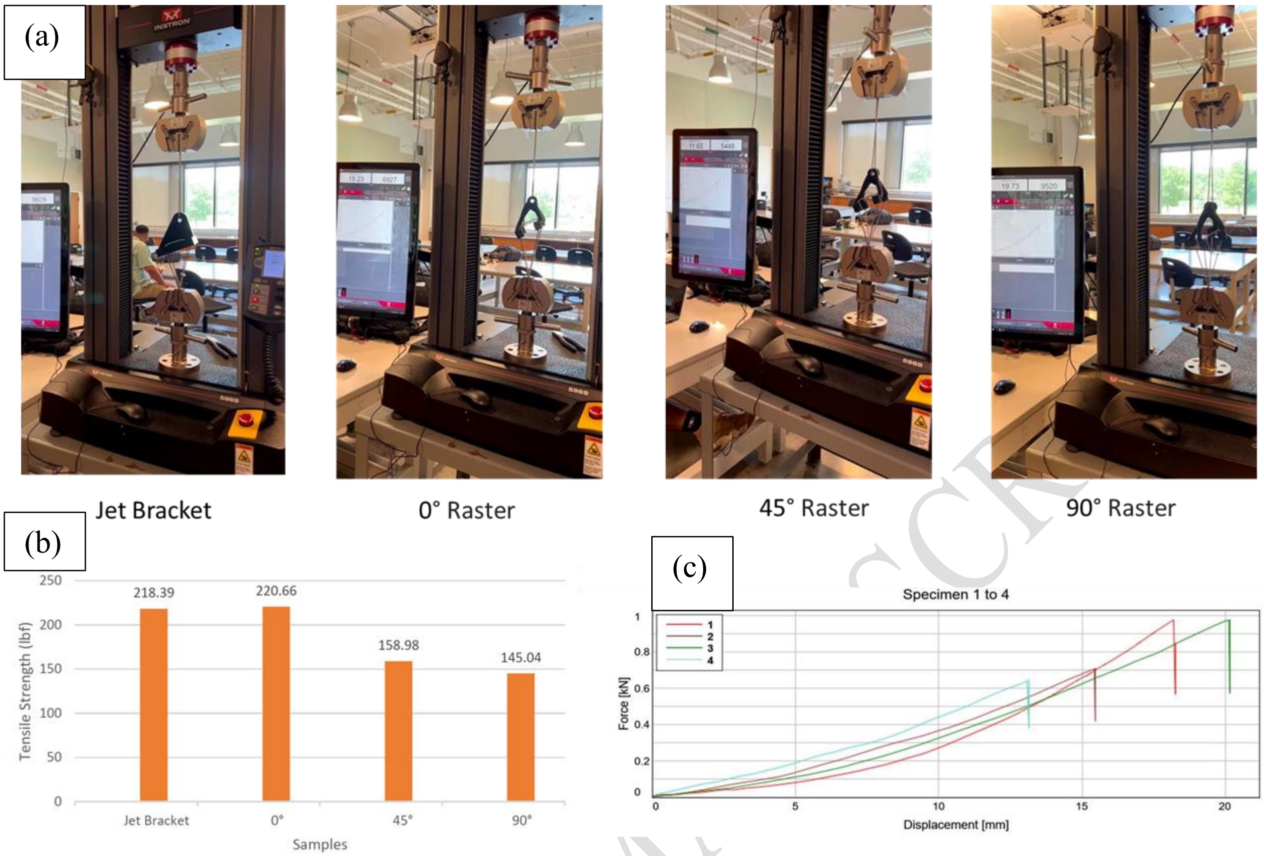

Figure 4: Representative image of the testing of the brackets and results: (a) testing of jet engine bracket at the University Tensile Testing Machine using custom-made test fixtures, (b) comparative study of the tensile strength properties (ultimate tensile stress) of the various design of jet bracket, and (c) load versus displacement graphs for the tensile testing of jet brackets.

As a first-time offering this course, the student engagement throughout the semester was commendable. A couple of examples of student feedback from the student evaluation are provided here:

"*This class would be great to have permanently as an elective because it teaches a very important growing industry, I used this class to determine what type of print I would be using on my senior design and it helped me determine what I needed to do to improve my use of a vat photopolymer printer that I have*".

"*I learned Fusion 360, so easily after figuring out how it worked thanks to instructor---He made additive manufacturing one of the most enjoyable classes I have taken at UHCL. This class allowed me to relearn and draw my attention more into 3D printing and all it has to offer*".

Finally, the learning outcome of this course was measured by a summative approach which is listed in Table 2. Please note that the learning outcome numbers cited in table 2, are listed at the end of the introduction section. The learning outcomes were measured by evaluating the final report, in-class quiz, exams, presentation, and survey.

Learning Outcome Number	Method of measurement
[i]	Conducted in-class quizzes after teaching each module of seven different AM process categories. Midterm exam and Final exam were given to assess the understanding of these process categories.
[ii]	Taught Fusion 360 CAD software for Generative Design Module and 3D printing part file preparation. Assignments were given to study the various printing parameters and design requirements for each AM process category.
[iii]	Trained students in three different commercial yet free-of-cost slicing software (IdeaMaker and Cura,) for the 3D printing applications.
[iv]	Each team fabricated their project parts using several different material extrusions AM machine. Details of the printing process and material were captured in the final report.
[v]	This outcome was measured in the final report. Students were tasked to compare the manufacturing of bracket parts in 3D printing versus traditional manufacturing such as injection molding, compression molding, and machining operations.
[vi]	Guest lecturers from AM industries were invited to discuss various AM processes, State-of-the-art, and research opportunities. Post survey was conducted after the presentation to evaluate the understanding of the presentation content to the students.

5. Conclusion

As a first-time offering this course at UHCL, AM lab played an important role in student engagement for a hands-on-based curriculum. One of the major focuses of this course design was to integrate the design and manufacturing of parts for 3D printing applications. Throughout the semester, students had the opportunity to learn the full spectrum of the typical material extrusion AM process by learning design in Fusion 360 software, relevant 3D printing slicing software, and manufacturing using desktop scale 3D printers that are available at AM lab. A summative approach was employed to measure the learning outcomes. At the end of the semester, the measurement results showed that the learning outcomes were accomplished by design assignments, in-class quizzes, exams, final projects, and surveys. In the future, this course offering will plan for projects with industry partners where students will have the opportunity to work on metal-based 3D printing systems.

Acknowledgment

Part of this material is based upon work supported by the National Science Foundation under Grant No: 2301925. The author is also grateful to the UHCL Mechanical Engineering program for allowing access to the research and teaching facilities and testing equipment used throughout this endeavor.

References

[1]. F42 Committee. ISO/ASTM52900 Additive Manufacturing – General Principles – Terminology [Internet]. West Conshohocken, PA: ASTM International; 2015. Available from: https://www.astm.org/Standards/ISOASTM52900.htm

[2]. Gao, Wei, et al. "The status, challenges, and future of additive manufacturing in engineering." Computer-Aided Design, vol. 69, 17 Apr., pp. 65–89, 2015.

[3]. Carter, W. T., D. J. Emo, D. H. Abbott, C. E. Bruck, G. H. Wilson, J. B. Wolfe, D. M. Finkhousen, A. Tepper, and R. G. Stevens. "The GE aircraft engine bracket challenge: an experiment in crowdsourcing for mechanical design concepts." In 2014 International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2014.

[4]. Agarwala, R., & Chin, R. A. (2015, June), Facilitating Additive Manufacturing Engagement and Outreach. Paper presented at 2015 ASEE Annual Conference and Exposition, Seattle, Washington. 10.18260/p.24086

[5]. LeBlanc, Christopher David, and Donald J. Plante. "An Engineering Technology Course in Additive Manufacturing." In 2018 ASEE Annual Conference & Exposition. 2018.

[6]. Fidan, Ismail, George Chitiyo, Thomas Singer, and Jamshid Moradmand. "Additive manufacturing studios: A new way of teaching ABET student outcomes and continuous improvement." In ASEE Annual Conference proceedings, no. 2018. 2018.

[7]. Maloney, Patricia A., Weilong Cong, Meng Zhang, and Bingbing Li. "Assessing the Results of an Additive Manufacturing Course at Three Large Universities on Undergraduates and High School Students." In 2019 ASEE Annual Conference & Exposition. 2019.

[8]. Prabhu, Rohan, Scarlett R. Miller, Timothy W. Simpson, and Nicholas A. Meisel. "Exploring the effects of additive manufacturing education on students' engineering design process and its outcomes." Journal of Mechanical Design 142, no. 4 (2020): 042001.

[9]. Williams, Christopher B., and Carolyn Conner Seepersad. "Design for additive manufacturing curriculum: A problem-and project-based approach." 2012 International Solid Freeform Fabrication Symposium, Austin, Texas, (2012).

[10]. "Tutorial: GE bracket quick start", Autodesk.com. https://help.autodesk.com/view/fusion360/ENU/?guid=GD-TUT-GE-BRACKET-QS (accessed April, 01, 2024)