

Additive Manufacturing in Manufacturing Education: A New Course Development and Implementation

Dr. R. Radharamanan, Mercer University

Dr. R. Radharamanan is currently working as Professor of Industrial Engineering and Director of Mercer Center for Innovation and Entrepreneurship (MCIE) at Mercer University in Macon, Georgia. He has forty three years of teaching, research, and consulting experiences. His previous administrative experiences include: President of International Society for Productivity Enhancement (ISPE), Acting Director of Industrial Engineering as well as Director of Advanced Manufacturing Center at Marquette University, and Research Director of CAM and Robotics Center at San Diego State University. His primary research and teaching interests are in the areas of manufacturing systems, additive manufacturing, rapid prototyping, robotics and automation, innovation and entrepreneurship, quality engineering, and product and process development. He has organized and chaired five international conferences, co-chaired two, and organized and chaired three regional conferences. He has received two teaching awards, several research and service awards in the United States and in Brazil. His present and past professional affiliations include ASEE, IIE, ASQ, SME, ASME, and ISPE.

Additive Manufacturing in Manufacturing Education: A New Course Development and Implementation

Abstract

In this paper, the importance of incorporating Additive Manufacturing (AM) as part of manufacturing curriculum in engineering education is emphasized. A new senior level elective course on Additive Manufacturing has been developed and offered as part of the manufacturing sequence to students of all engineering discipline at Mercer University School of Engineering. To provide hands-on experience to students taking this course, a low-cost rapid prototyping (RP) lab has also been developed consisting of CAD software, 3D scanners, 3D printers, CNC mill, and digital measuring devices.

The course curriculum includes the following: basic principles of AM, difference between traditional manufacturing processes (subtractive manufacturing, SM) and AM, recent advances in the AM technologies that specialize in rapid prototyping of three-dimensional objects such as photopolymerization, powder bed fusion, extrusion, beam deposition, sheet lamination, direct write technologies, and direct digital manufacturing; design for AM, process selection, post-processing, software issues, rapid tooling, applications of AM, business opportunities, and future of AM. Web resources are extensively used in the theory classes including the use of YouTube videos of AM processes and applications.

The open-ended hands-on lab work includes the following: design and make simple to complex parts using both CNC mill and 3D scanning/3D printing machines and compare SM and AM process parameters that include material, speed, complexity, accuracy, geometry, and programming; 3D scanning of objects, editing with proper CAD software, and printing the objects using 3D printers (reverse engineering); casting of 3D objects using basic casting principles; and rapid prototyping challenge among student teams that includes designing, making, marketing, and selling the products that we all use. The difficulties encountered in developing the low-cost RP lab to provide hands-on experience to students taking this course, some of the lab projects completed by the student teams using AM technologies, student learning outcomes and assessment, challenges and lessons learned, and recommendations for improving the course contents(both theory and lab) are also presented and discussed.

Introduction

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. The term “3D printing” is increasingly used as a synonym for AM. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal. Instead of milling a workpiece from solid block, for example, AM builds up

components layer by layer using materials which are available in fine powder form. A range of different metals, plastics, and composite materials may be used. AM is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. The synonyms for AM are: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication¹⁻³. Additive Manufacturing (AM) is any of various processes for making three dimensional object of almost any shape from a 3D model or any other electronic data source primarily through additive processes in which successive layers of material are laid down under computer control⁴.

In this paper, the importance of incorporating AM as part of manufacturing curriculum in engineering education is emphasized. The difference between traditional manufacturing processes (subtractive manufacturing, SM) and AM are highlighted. Recent advances in the AM technologies that specialize in rapid prototyping of three-dimensional objects such as photopolymerization, powder bed fusion, extrusion, beam deposition, and 3D printing processes are discussed in the theory classes. Some of the AM student projects completed in the rapid prototyping lab using 3D Scanners and 3D Printers are presented and discussed.

Background

Additive manufacturing (AM), the process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, is distinctly a different form and has many advantages over traditional manufacturing processes. Commonly known as “3D printing”, AM provides a cost-effective and time-efficient way to produce low-volume, customized products with complicated geometries and advanced material properties and functionality⁵. The generic AM process include the following steps: Conceptualization and CAD, conversion to STL, transfer to AM machine and STL file manipulation, machine setup, build, removal, post-processing, and application¹⁻².

There is consensus among both the research and industrial communities, and even the general public, that additive manufacturing (AM) processes capable of processing metallic materials are a set of game changing technologies that offer unique capabilities with tremendous application potential that cannot be matched by traditional manufacturing technologies. Unfortunately, with all what AM has to offer, the quality and repeatability of metal parts still hamper significantly their widespread as viable manufacturing processes. This is particularly true in industrial sectors with stringent requirements on part quality such as the aerospace and healthcare sectors. One approach to overcome this challenge that has recently been receiving increasing attention is process monitoring and real-time process control to enhance part quality and repeatability. This has been addressed by numerous research efforts in the past decade and continues to be identified as a high priority research goal⁴.

3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. 3D printing is also considered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting

or drilling (subtractive processes). A 3D printer is a limited type of industrial robot that is capable of carrying out an additive process under computer control⁶⁻¹⁰.

While 3D printing technology has been around since the 1980s, it was not until the early 2010s that the printers became widely available commercially. The first working 3D printer was created in 1984 by Chuck Hull of 3D Systems Corp¹¹. Since the start of the 21st century there has been a large growth in the sales of these machines, and their price has dropped substantially. According to Wohlers Associates, a consultancy, the market for 3D printers and services was worth \$2.2 billion worldwide in 2012, up 29% from 2011.

The 3D printing technology is used for both prototyping and distributed manufacturing with applications in architecture, construction (AEC), industrial design, automotive, aerospace, military, engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic information systems, food, and many other fields. One study has found that open source 3D printing could become a mass market item because domestic 3D printers can offset their capital costs by enabling consumers to avoid costs associated with purchasing common household objects⁵.

Additive Manufacturing Course (3-0-3)

A new course on 3D Modeling and Rapid Prototyping has been developed and offered as a senior level elective course to all engineering students. The catalog description of the course includes the following: Product design, CAD and related software; basic principles, development, process chain of additive manufacturing; photopolymerization processes; powder based fusion processes; extrusion-based systems; printing processes; sheet lamination processes; beam deposition processes; direct write technologies; design for additive manufacturing; guidelines for process selection; software issues and direct digital manufacturing; medical applications; post processing; use of multiple materials, business opportunities and future directions; integrated 3D scanning and 3D printing lab experiments.

Textbook: Ian Gibson, David, W. Rosen, and Brent Stucker: Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing, Second Edition, Springer, 2015¹.

Reference Book: C. K. Chua, K. F. Leong, and C. S. Lim, "Rapid Prototyping: Principles and Applications", Third Edition, World Scientific, 2010².

The contents of this course include recent advances in the Additive Manufacturing (AM) technologies that specializes in rapid prototyping of three-dimensional objects: Photopolymerization processes (Stereolithography (SL) Technology); Powder bed fusion processes (Selective Laser Sintering – SLS, Electron Beam Melting); Extrusion-based systems (Fused Deposition Modeling – Stratasys; Reprap and Fab@home); Printing processes (hot melt deposition, solution- and dispersion-based deposition); Sheet lamination processes: Gluing and Adhesive Bonding – Bond-then-Form & Form-then-Bond processes; thermal bonding, ultrasonic consolidation; Beam deposition processes (powder feeding and wire feeding); Direct Write (DW) Technologies (ink-based, laser transfer, thermal spray, beam deposition, beam tracing –

additive/subtractive); 3D scanning and 3D printing (Extrusion Based) processes; Design for AM (STL File Format, Binary/ASCII); Direct Digital Manufacturing (custom soccer shoes, parts for military aircraft, space shuttle, satellites etc.); Medical Applications of AM: Surgical and diagnostic aids, prosthetic development, medically related products, tissue engineering etc; Integrated 3D scanning and 3D printing lab experiments¹⁻¹⁷.

The overall objectives of the course include but not limited to:

1. Review of product design, CAD, basic principles and development of additive manufacturing.
2. Explain the various processes of additive manufacturing.
3. Design for additive manufacturing.
4. Process selection and software issues.
5. Direct digital manufacturing and medical application
6. Explain post-processing and use of multiple materials.
7. Explain business opportunities and future directions.
8. Integrated 3D scanning and 3D printing lab experiments.

This course also provides hands-on training to students in addition to theoretical lessons on AM. The lab activities include:

1. Provide training to the student teams in CAD: use of 123D Design and MeshMixer to design parts; and 3D Printing and Rapid Prototyping: use of 3D printers (MakerBot Replicator 2X and Flashforge Creator Pro) to print the designed parts;
2. Review of literature and watching online tutorials related to AM and 3D Printing;
3. Print simple and complex parts using 3D printers: MakerBot Replicator 2X using ABS material; Flashforge Creator Pro using PLA material;
4. Measure the parts made of ABS and PLA for dimensional accuracy and compare the results;
5. Write the lab reports with the team members and submit for evaluation.

The lab activities are designed to fully/partially satisfy some of the ABET's student learning outcomes that include:

- b. An ability to design and conduct experiments, as well as to analyze and interpret data;
- c. An ability to design a system, component, or process to meet desired needs within realistic constraints such as safety, manufacturability, and sustainability;
- d. An ability to function on multidisciplinary teams;
- g. An ability to communicate effectively (orally and written);
- k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

The topics covered in the theory and the lab classes as well as the course evaluations are summarized in Table 1.

Rapid Prototyping Lab

A low-cost rapid prototyping lab has been developed and it has the following machines and equipment: 1 Roland CNC mill, 1 UP Printer, 1 MakerBot Replicator 2X 3D Printer, 1 FlashForge Creator Pro 3D Printer, 1 Next Engine 3D Scanner, and 1 Hand-held 3D Scanner (Figure 1).

Table 1: Contents of theory and lab classes and course evaluation

Theory Classes:

Week	Topics Covered
1	Review of product design and CAD
2	Basic principles and development of additive manufacturing (AM)
3	Generalized AM process chain
4	Vat photopolymerization processes
5	Powder based fusion processes
6	Extrusion-based systems; Test #1
7	Material jetting; Binder jetting
8	Sheet lamination processes
9	Directed energy deposition processes
10	Direct wire technologies; The impact of low-cost AM systems
11	Guidelines for process selection; Test # 2
12	Post-processing; Software issues for additive manufacturing;
13	Direct digital manufacturing
14	Design for additive manufacturing; Rapid tooling
15	Applications for additive manufacturing; Business opportunities and future directions
16	Final Exam

Lab Classes:

Weeks	Lab Work by Student Teams
1-2	Revision on CAD, Solid Modeling: Use of CAD 123, Solid Works etc.
3-4	Training: 3D Scanning and 3D printing: Use of MakerBot Replicator, Flash Forge 3D Printer
5-6	3D Milling (Roland CNC); Reverse Engineering
7-8	Lab Project 1: SM and AM
9-10	Lab Project 2: 3D Scanning & Reverse Engineering
11-12	Lab Project 3: Casting
13-14	Lab Project 4: RP Challenge
15-16	RP Challenge and Lab Exam

Course Evaluation:

Theory:	
Homework/Class Work	10%
Quizzes	10%
2 Tests	30%
Final Exam	20%
Lab Work:	
4 Open-ended Lab Projects	30%
Total	100%

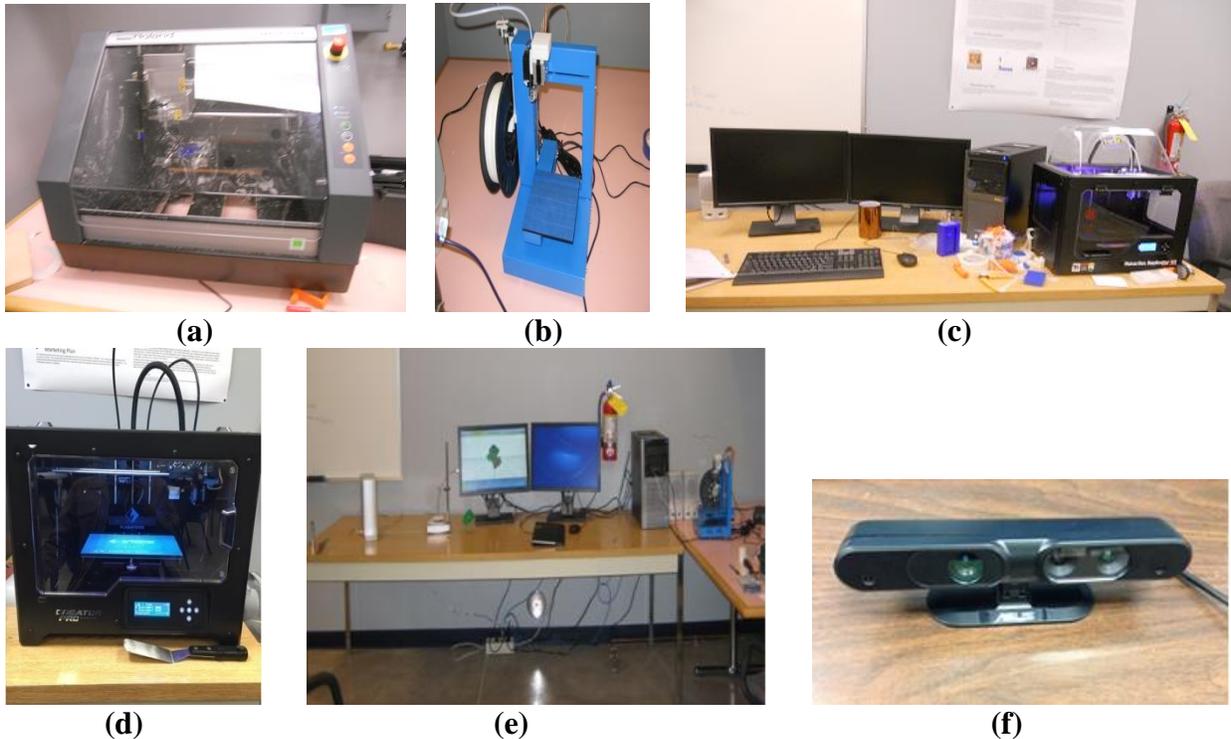


Figure 1: a) Roland CNC mill; b) UP printer; c) MakerBot Replicator; d) Flashforge Creator Pro; e) Next Engine 3D scanner; and f) Hand-held 3D scanner

Open-ended Hands-on Lab Projects

The following open-ended lab projects have been designed for the AM course:

1. Comparative study on AM and SM: Design and make a part of same size and dimensional tolerances using the following machines/equipment:
 - a) MakerBot/Flash Forge 3D Printer
 - b) Roland 3D CNC Milling Machine

Choose appropriate printing and machining parameters. Compare the two processes of making the part with respect to the design and manufacturing parameters related to each one of the processes.

2. Reverse engineering:
 - a) Scan a part using the 3D Next Engine scanner using the appropriate software. Use multiple scans to capture the image of the part. Edit the part using proper software tools (Netfabb, Meshmixer, or other appropriate software tool). Print the part using the MakerBot/FlashForge 3D Printer.
 - b) Using the Hand-held 3D scanner scan a large object. Print the part (scaled down to fit in the printing platform) using the MakerBot/Flash Forge 3D Printer.

Compare the 2 processes of scanning and printing the objects with reference to the scanning and printing parameters.

3. Casting 3D Objects: Make a 3D object using casting principles and procedures. Write the lab report.
4. Rapid Prototyping Challenge (RPC): Designing, Making, Marketing, and Selling of Products We All Use (PWAU).

Sample lab projects from students are presented and discussed.

Lab 1. Comparative Study between SM and AM

The purpose of the project was to create or select a 3D model to be 3D printed and milled using the CNC machine so that the students can observe the difference in the two types of manufacturing SM and AM. By using the Flashforge Creator Pro 3D printer and the Roland 3D CNC Mill they compared the two processes of making the part with respect to the design and manufacturing parameters related to each one of the processes. This lab project allows the students to gain a better understanding of what is required to print a 3D part, as well as allow them to see the advantages of using a CNC versus a 3D printer and also gain an understanding of the importance of 3D modeling and rapid prototyping in a real world environment.

A typical lab project done by a student team is summarized below. The team selected a Captain's wheel (Figure 2) from Thingiverse.com¹⁴ to be printed. The part could have been printed as a 10-piece assembly with the outer ring, the inner ring, and the eight spokes; however, the merged object was the one that the team selected and printed. This part was selected for its simplicity in design but also for the details on each of the spokes. The team wanted a part that could be easily processed and developed on either machine, so that they could compare the 3D printed versus the CNC milled parts. Simplicity was the key factor that was assessed when selecting this part because they wanted to compare the accuracy, process, and speed of the two machines.

Some modifications were made in order to print the part. The team had to scale up the part to 1.5 times the original size, so that the part would be 4.0656 inches from tip to tip. The measurements from the original CAD drawing (before scaling it by 1.5 times the original size) is shown in Figure 2 (a).

When printing on the Flashforge Creator Pro 3D printer^{13, 17}, 21.84 grams, or 7.183 m, of PLA filament was used. The part was printed at a speed of 40 mm/s and a layer thickness of 0.30 mm, thus taking 1 hour and 3 minutes to print the part. In order for the part to form correctly given the material used (PLA), the extruder head was at a temperature of 230°C, and the platform was at a temperature of 55°C.

When milling the part using the Roland 3D CNC mill, the type of material used was a 6-in x 6-in x ½-in acrylic block. The part was printed at a speed of 40 mm/s and depth of cut of 0.40 mm. The print was projected to take 6 hours and 8 minutes per side (12 hours and 16 minutes total). The final dimensions of the CNC wheel and the 3D print wheel were measured with calipers from the lab. The Captain's wheel with proper dimensions is shown in Figure 2(a). The 3D printed part is shown in Figure 2(b). The CNC milled part is presented in Figure 2(c).

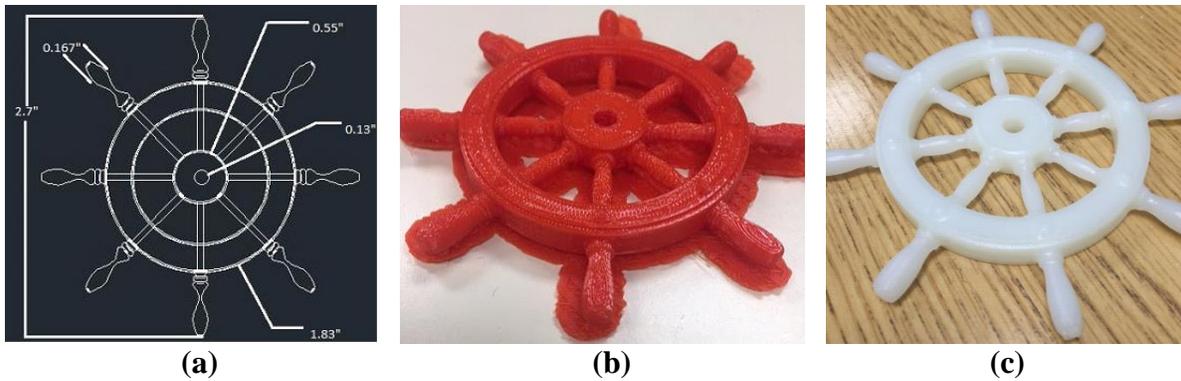


Figure 2: Captain’s wheel: a) Dimensional part; b) The 3D printed part; c) CNC milled part

The detail and the surface finish of the CNC print were much smoother than the 3D printed part. Also, the resolution of the 3D print was much lower than that of the CNC machine. As the 3D printer builds upon its layers with melted PLA plastic, the CNC would cut away layers from the acrylic piece. This allowed for the better quality on the CNC while the 3D print is much lighter. The 3D print seemed to be more accurate in dimensions than the CNC machine. The time to print the part on the 3D printer compared to the CNC machine was significantly less. The 3D print took a little over an hour and the CNC machine took more than 12 hours.

Lab 2.Reverse Engineering

The purpose of this project is to create a physical rendering of the Camshaft using engineering software applications and CNC machining. For this project the software applications used were 3D Next Engine, Pro E, Solid Works, Meshmixer, and Netfabb¹⁰. The MakerBot Replicator 2X¹² was utilized to print the 3D model out as a 3D object. The 3D Next Engine was used to precisely scan the object to capture the complex, organic shape of the part. Multiple scans with this program were necessary to ensure the scanner accurately captures the image. Netfabb and Meshmixer¹⁶ were utilized after the 3D Next Engine scan is complete to help edit the Camshaft mesh file, as needed, to insure the part is not too big to fit in Makerbot platform for printing.

The MakerBot Replicator 2X^{12, 17} makes solid, 3D objects out of melted PLA filament. This process involves heating the PLA filament and squeezing the melted filament out through a nozzle to build the model layer by layer. The MakerBot is connected to a PC and its OS can import .stl formatted file types. A mesh rendering of the object is converted into StereoLithography (.stl) file format from the specific CAD design software file format that was used to create the 3D model (AutoCAD, SolidWorks, Pro-E, etc.). The .stl file format describes the mesh rendering to the 3D printer by using a 3D Cartesian coordinate system and assigning vectors to the vertices of the thousands of triangles comprising the surface of the mesh. The MakerBot Replicator was used to 3D print the physical rendering of the Camshaft.

Figure 3(a) shows all four pieces printed and the actual Camshaft. Once the pieces have cooled, some pieces needed some filing to remove any unnecessary plastic. The next step is super glue the parts together and set to dry as shown Figure 3(b). Figure 3(c) shows the display of the

printed and the original Camshafts. Measurements were made on the 3D printed Camshaft and found to be well within the dimensional tolerances of the original Camshaft.

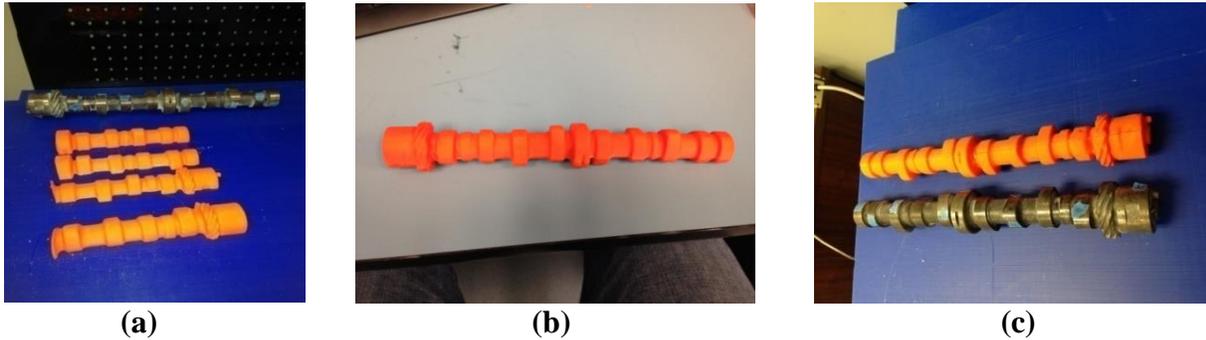


Figure 3: a) Cam shaft and 4 pices of printed parts; b) Printed and glued cam shaft; c) Display of printed and original cam shafts

Lab 3.Casting

The purpose of this lab was to make a 3D object using casting principles and procedures. Three things are need to cast: an item to cast, the mold, and some liquid material to pour into the mold, such as resin. There are two types of casting. One-piece casting, which was performed in this lab, requires the casted item to have a flat back which creates a level hole in the mold into which the resin is poured. The other option is a glove mold where the resin is poured into a mold formed in a hollow container. This creates more fully formed parts that do not need to have a flat back. A step mandrel, seen in Figure 4(a), was selected to cast since it was small enough to fit in a plastic cup used for the mother mold and has a flat back.

The following materials were used to complete this lab: item to cast, plastic cup, Smooth-On Mold Star 16 FAST platinum silicone rubber, and Smooth-On Smooth-Cast 300 liquid plastic. The characteristics of the Mold Star silicone is as follows: the pot or kick time is about 6 minutes, the cure time is about 30 minutes, and the parts A to B mix ratio is 1:1. The Smooth-Cast 300 Series of liquid plastics are ultra-low viscosity casting resins that yield castings that are bright white and virtually bubble free. The characteristics of the liquid plastic is as follows: the pot or kick time is about 3 minutes, the cure time is about 10 minutes, and the parts A to B mix ratio is 1:1. All of these times are not exact because it depends on the size and shape of the item to cast. Both the silicone and plastic use exothermic reactions to solidify. This means that when the silicone or plastic are confined to a smaller area, more heat is generated which results in a shorter cure time. Likewise, if the part is long and wide, the silicone or plastic must be spread out into a thin layer which reduces the overall heat and increases the cure time.

To begin the process, cardboard was used to protect the work surface from spillage of silicone or plastic. A plastic cup was used as a mother mold for this part due to its size and weight. Mother molds for smaller parts would be created by cutting the top of the plastic cup taller than the piece to be cast and then using hot glue to attach the top of the cup to an acrylic sheet. If needed, the part can also be hot glued to the sheet inside the cup to hold it in place. Parts A and B of the silicone were shaken to mix and then let sit to eliminate bubbles. The bubbles could cause a distortion in the casting part. This part took about 50 minutes to be cast: 5minutes to mix the

silicone, 30 minutes to create the mold, 5 minutes to mix the plastic, and 10 minutes to cast. Figure 4(b) shows the silicon mold, cast part, and the step mandrel (from left to right). Measurements were made on the cast part and found to be well within the dimensional tolerances of the original step mandrel.



Figure 4: a) Step mandrel; b) Silicone mold, cast part, step mandrel (from left to right)

Lab 4. RP Challenge: Product We All Use (PWAU)

A student team wanted the item to be practical and to have multiple uses while still being portable. The solution is a combination of a bottle opener and a phone stand which fits on a keychain. The team decided to print all of the PWAU items in orange PLA plastic to accentuate the school spirit that is demonstrated by the engineers. To further promote Mercer University school of engineering, the bear logo was also included to remind customers where the item came from. Finally to promote the school in the marketing campaign, every time the student team speak to a potential client about the product, they mentioned the rapid prototyping lab and how it was produced.

Fabrication and Assembly

All production of the ten combo bottle opener and phone stand took place on the FlashForge Creator Pro 3D Printer¹³ in the RP lab. In order to create the file for printing, a model in SolidWorks was created and exported it as an STL file. This was loaded into the MakerBot printing software. An SD card was used to transport the file to the printer from the computer. Printing a single unit took 40 minutes and used 8.57 grams of material. This was completed using the following machine parameters:

- Bed Temperature: 55°C
- Extruder Temperature: 230°C
- Layer Height: 0.2mm
- Infill: 25%
- Supports: On
- Rafts: Off

In final production, the student team was able to place 5 units on the print bed at once. This made the print time 3 hours 7 minutes and contributed to a usage of 42.64 grams of material. The student team chose to do five units per print so that not to risk a print failure with all ten required units on the print bed. The only post-processing that is required in this product is to remove the support material in the penny slot. Assembly is also fairly simple. All that is required is to insert the penny into the designated slot and ensure that it is secure. After just these two short steps, the part is ready to be sold. The cost breakdown based on 1,000 parts as sales volume is shown in Table 2.

Table 2: Cost breakdown

Sales	
Price per unit	\$2.00
Sales Volume	1000
Total Sales	\$2,000.00
Costs (per unit)	
Labor (\$7.25/hour)	\$0.36
Materials	\$0.27
Machine Operation	\$0.67
Total Cost	\$1.30
Cost for 1,000 units	
All Costs	\$1,299.17
Total Profits for 1,000 units	
\$700.83	

Final Pricing and Justification

The price of the final item was set at \$2.00. This was done so that the item could be easily be purchased face-to-face with no coins involved. The student team also wanted to keep the price low to make it more accessible to customers, while still making a profit. To estimate the cost of labor, the team took minimum wage of \$7.25/hr and estimated it takes 3 minutes to remove support material and input a penny. The team took a 1kg spool of material costing \$30.00 and split it between the cost of material, and added \$0.01 for the penny. The machine operation cost was estimated \$5.00/hr and used a print time of 40 minutes for 5 parts. The following equations were used to calculate the cost values:

$$Labor = \frac{3 \text{ min}}{\text{part}} * \frac{1 \text{ hr}}{60 \text{ min}} * \frac{\$7.25}{\text{hr}} = \frac{\$0.36}{\text{part}}$$

$$\text{Materials} = \frac{\$30.00}{\text{kg}} * \frac{1000\text{g}}{\text{kg}} * \frac{8.57\text{g}}{\text{part}} + \frac{\$0.01}{\text{part}} = \frac{\$0.27}{\text{part}}$$

$$\text{Machine Operation} = \frac{\$1.00}{\text{hr}} * \frac{\text{hr}}{60 \text{ min}} * \frac{40 \text{ min}}{\text{part}} = \frac{\$0.67}{\text{part}}$$

Delivery and Sale of Items

Items were hand delivered to their final destinations by one or more members of the team. No special packaging was used. This decision was mainly to save cost on the consumer end, since the team did not have to purchase any extra materials for packaging. Therefore, the item was able to maintain a very low cost so that it can be sold at a good price point for the consumer. The items made and sold are shown in Figure 5.

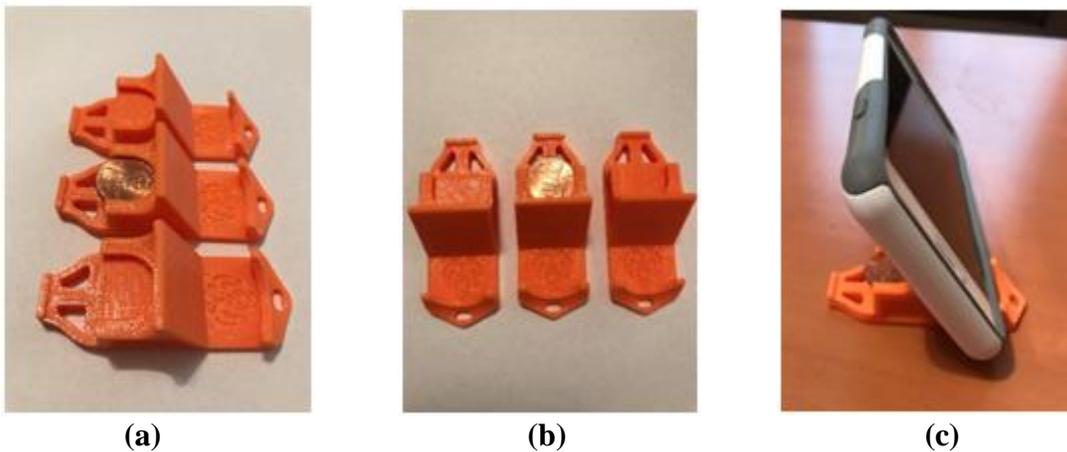


Figure 5: a) The left-hand side of the item is the bottle opener portion (one with penny inserted) and the right-hand side is the phone stand portion with the University logo. b) Side views of the items; c) Penny inserted and phone placed on the item.

Conclusions and Recommendations

In addition to learning the AM processes, the students were trained in using design tools such as SolidWorks, Pro E, 123D Design, MeshMixer, and Netfabb and emerging technologies such as 3D printing and rapid prototyping as well as reverse engineering. The students learnt to use 3D printers and printed parts using two different materials (ABS and PLA). They were able to measure the printed parts for dimensional accuracy and compare the results. They were able to print/machine/cast 3D parts and scan/fix/print 3D parts.

Assessment made by student peers and the faculty members on the theory and the lab projects in this course indicated that the student teams on average scored greater than 4 in the 5-level Likert scale in all five ABET's student learning outcomes (b, c, d, g, and k) considered for the lab projects.

Challenges and Lessons Learned

The lab facility has one CNC mill, two 3D scanners, one casting facility, and two 3D printers. There were 22 students enrolled in this class during the Fall semester of 2016. Provide training on CAD and 3D Scanning and 3D Printing to all students was a challenge during the first few weeks of the lab classes. After the training, the students were given access to the lab 24/7 to work on the lab projects. The rapid prototyping lab is also being used by other students: senior design teams, honors student teams, special project teams, graduate students for their MS design projects, and students enrolled in other manufacturing classes. Additional machines and equipment are needed in the rapid prototyping lab to take care of the students' need.

Recommendations

From the outcome of this course evaluations, it is noted that the students need additional training in CAD and 3D scanning. They are encouraged to read related materials (reference manuals, books, articles, internet resources, etc.) and watch online tutorials and YouTube videos on CAD, 3D scanning, AM processes, and related topics.

References

- [1] I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, Springer Verlag, 2010.
- [2] C. K. Chua, K. F. Leong, and C. S. Lim, "Rapid Prototyping: Principles and Applications", World Scientific, Third Edition, 2010.
- [3] A. Gebhardt, "Understanding Additive Manufacturing: Rapid Prototyping, Rapid Tooling, Rapid Manufacturing", Hanser Publishers, 2012.
- [4] G. Tapia and A. Elwany, "A Review of Process Monitoring and Control in Metal-Based Additive Manufacturing", *J. Manuf. Sci. Eng* 136(6), 060801 (Oct 24, 2014 (10 pages)).
- [5] Y. Huang, M. C. Lau, J. Mazumder, and A. Donmez, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations", *J. Manuf. Sci. Eng* 137(1), 014001 (Feb 01, 2015 (10 pages)).
- [6] P. K. Venuvinod and W. Ma: 'Rapid prototyping: laser-based and other technologies', 1st edn, 6; 2001, Norwell, Kluwer Academic Publishers.
- [7] "3D Printing Basics: The Free Beginner's Guide - 3D Printing Industry", May 2014. 3dPrinting Industry.com/3d-printing-basics-free-begineers-guide/, Retrieved July 14, 2016.
- [8] M. Petronzio, "How 3D Printing Actually Works", Mashable, March 28, 2013, meshable.com/2013/03/28/3d-printing explained/, Retrieved July 14, 2016.
- [9] B. Evans, "Practical 3D Printers: The Science and Art of 3D Printing", A Press, 2012.
- [10] D. Bryden, "CAD and Rapid Prototyping for Product Design", Laurence King Publishing, 2014.

- [11] 3D systems (<http://www.3dsystems.com>), Retrieved July 14, 2016.
- [12] "MakerBot Replicator 2X User Manual", www.makerbot.com/Replicator2X, Retrieved July 14, 2016.
- [13] "Flashforge Creator Pro 3D Printer User Manual", www.flashforge-usa.com/creator-pro/, Retrieved July 14, 2016.
- [14] Thingiverse (www.thingiverse.com): Digital Designs for Physical Objects. Retrieved July 14, 2016.
- [15] RepRap Forum (<http://groups.google.org>): Discussion on all RepRaps, development, electronics, and software. Retrieved July 14, 2016.
- [16] MeshLab (<http://meshlab.sourceforge.net>): 3D model processing and editing. Retrieved July 14, 2016.
- [17] XYZ Printers (<http://xyzprinters.com>): Electronics, 3D printer hardware, and kits. Retrieved July 14, 2016.