Implementation of 3d printer in the hands-on material processing course: An Educational Paper

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Abstract

Manufacturing equipment and technology will continue to be an integral part of engineering education. Using advanced and modern equipment and technology not only emphasizes hands-on activity-based teaching and learning, but it also makes the educator and the program competitive. There are many advantages to implementing 3-d printers in engineering education; however, there are also some challenges. In this paper, a two-year implementation of 3-d printers in a traditional material processing undergraduate engineering course has been presented and discussed.

Introduction

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Additive manufacturing a.k.a. 3d printing is a buzz word in the manufacturing workplace. There are many advantages of the 3d printer; however, the most significant advantage is the ability to fabricate a more complex part that has never been realized via another manufacturing process. Thus, it brings design flexibility to engineers and students who may not need new knowledge of the manufacturing processes that are usually required to design a complex part. With the evolution of materials and application-specific 3d printers, it has created a paradigm shift for educators and engineers as the term 'design for manufacturing' is being replaced by 'manufacturing by design.'

Manufacturing technology and equipment has been introduced in many engineering labs' curriculum to improve education and provide opportunities for hands-on learning. Modern engineering technologies are an essential tool to add in engineering education to make the program and the educators competitive. Implementing 3d printing in engineering education is highly beneficial to the students as well as the teacher (can also use instructor instead of teacher). It has been used as a rapid prototyping tool in the past. Stereolithography based printers were widely available in universities in the early 21st century; however, it was not feasible to implement towards the educational activities, particularly in teaching labs. With the invention of fused deposition modeling (FDM) based 3-d printers and reduction in the cost of 3-d printers, it is now affordable to implement 3-d printers in educational activities, mainly in teaching labs. There are many pre-engineering and engineering curricula for 3d printing skills that have been developed to teach in high schools and universities [2, 3, 7]. A detail information on where and how the 3-d printers and additive manufacture are implemented in schools and universities are well documented in [8]. Although the core implementation is still in rapid prototyping of a new design and outreach activities, it has also been supplemented in several engineering courses in our university, such as:

- engineering graphics course to improve the student's spatial skills
- machine design to compute gear-ratios [5]
- mechanism design to visualize a mechanism
- components of a senior design project

Sand casting is one of the most used and essential casting processes in the world. A cavity enclosed inside the sand mold determines the shape of the part. The cavity is formed by packing the sand around a pattern. The pattern is a replica of the object to be cast and is generally made out of plastic, metal or wood. The casting metal is heated slightly above its melting temperature. The liquid metal is then poured into the cavity in an open mold casting. The metal is poured through the down sprue and via the gating system (runner) in a closed mold casting as depicted in Figure 1.The quality of casting depends upon many attributes: the thickness of the pattern, pouring temperature, pouring rate, gating system, riser, etc. The pattern is usually a replica made out of wood, metal, or plastic, while the riser compensates the shrinkage that generally occurs during the casting process [1]. Foundrymen (people who work in a foundry) design these patterns based on experience and practice. 3-d printing technology has been implemented in the hands-on material processing course at Georgia Southern University. The 3-d printed parts are used as patterns in the casting industry for the casting of metal parts. The 3-d printed wax pattern has the potential to replace the expensive and time-consuming current wax pattern used in the casting process. Advances in technology have allowed the 3-d printing of sand molds [4] which would not even require a pattern. Ford has used the 3-d printed sand molds for casting prototype engines, cylinder heads, etc. [6]. The implementation of the 3-d printer for pattern making process in the undergraduate level course will bring creativity in design, improve the students' critical thinking ability and teaches the fundamentals of metal casting.

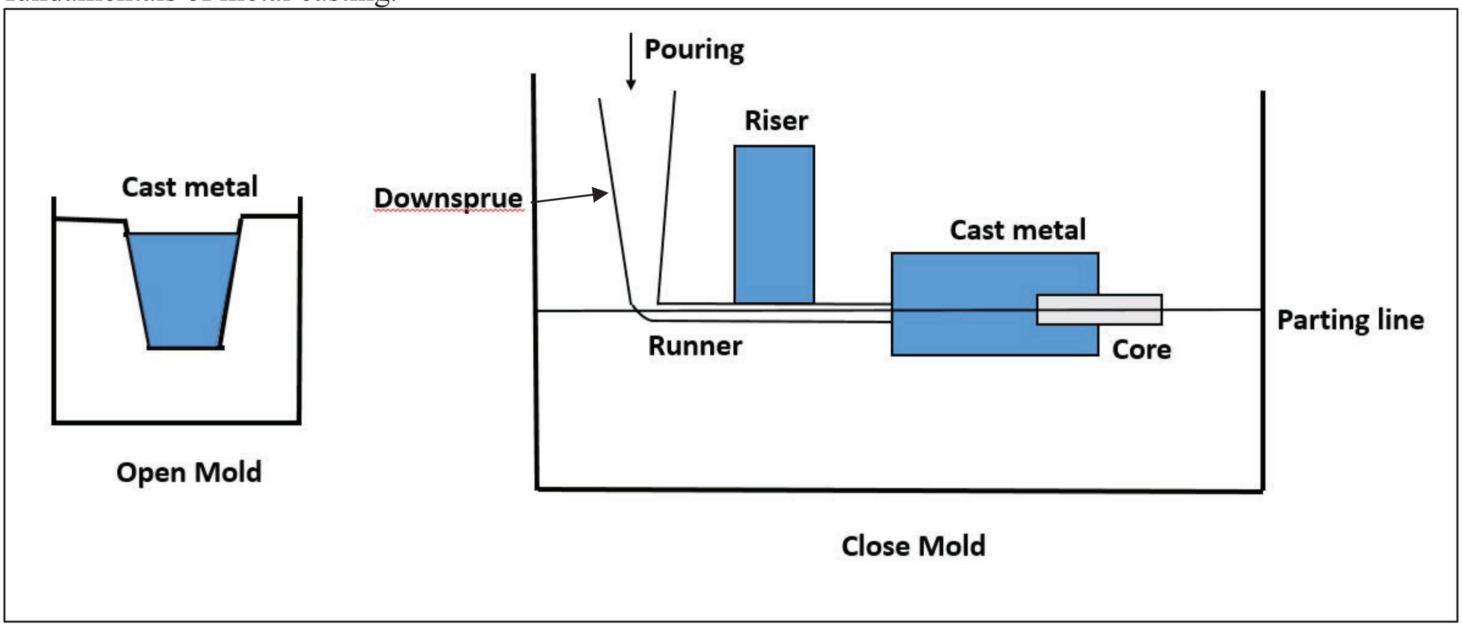

Figure 1: An open mold and close mold sand casting process

Course description

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MENG 3333 (course name and number) is a junior level 'material processing' 15 weeks semester-long course for mechanical engineering students. The course is 2-2-3 level course, which means 2 hours lecture and 2 hours lab are assigned in a week, and students earn three credits. The junior level 'material processing' course teaches the students traditional and modern material processing techniques. The main objective of the lab is to teach the students hands-on-work on key manufacturing processes.

The course objectives are:

1. Demonstrate workplace safety and material and tools handling safety
2. Teach how to create a bill of materials, plan of procedures, working drawings for machine shop production 3. Teach the major applications of a variety of material processing techniques, and how these processes are used in manufacturing
4. Recognize the fundamentals of major manufacturing processes and the process physics

5. Teach how to estimate the cost of manufacturing processes
6. Demonstrate the process and use examples and videos to reinforce the key principles in material processing7. Demonstrate an understanding of the contents and use of machining reference and handbooks and other appropriate material resources

The student course outcomes are:

1. Identify, define, and categorize equipment, tooling, and operations used in the processing of engineering materials.
2. Compare and contrast materials processing techniques and delineate the limitations of each as they relate to manufacturing.
3. Describe the effects of processing on the properties of materials.
4. Explain the influence of materials and processing parameters on manufacturing processes and operations. 5. Conduct analysis of forces, pressures, friction, wear necessary for the processing of a variety of materials.

Communicate information pertaining to design considerations, product quality, and cost factors for each type or group of manufacturing processes.

6. Discuss the four types of engineering materials: metals, ceramics, polymers, and composites and the processing techniques and processing equipment used to manufacture goods from these materials

Lab project

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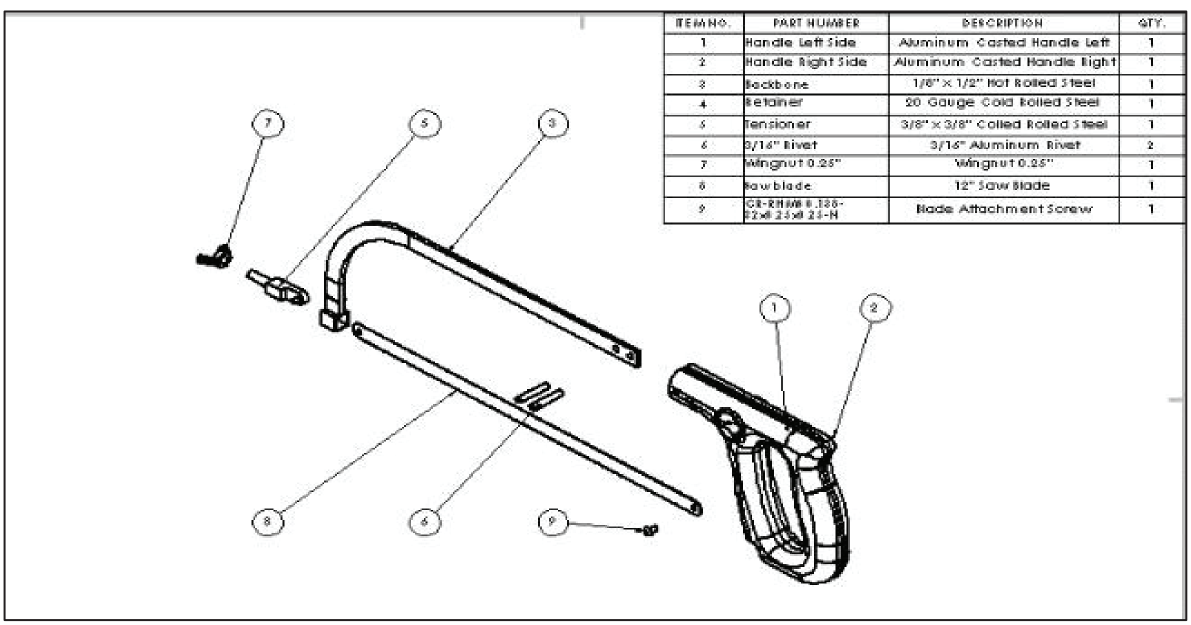
MENG 3333, a lecture and lab integrated project-based course, covers the applications and use of different discipline areas of manufacturing processes, such as metal-casting processes and equipment, forming and shaping processes and equipment, joining methods and equipment, molding, extrusion and fabrication of polymers, and composite processing techniques. The objective of the lab is to

- Fabricate a hacksaw through manufacturing processes learned in MENG 1310 (freshman level course) and casting processes learned in MENG 3333 lecture
- Design a hacksaw assembly using Solidworks software focusing on the draft angle, tolerances, and limitations of the 3-D printers.
- Find an alternative process and compare the two processes in terms of cost, safety and environmental



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Handle Left Side	Aluminum Casted Handle Left	1
2	Handle Right Side	Aluminum Casted Handle Right	1
3	Backbone	1/8" x 1/2" Hot Rolled Steel	1
4	Retainer	20 Gauge Cold Rolled Steel	1
5	Tensioner	3/8" x 3/8" Colled Rolled Steel	1
6	3/16" Rivet	3/16" Aluminum Rivet	2
7	Wingnut 0.25"	Wingnut 0.25"	1
8	Sawblade	12" Saw Blade	1
9	CR-RHMM 0.138-32x0.25x0.25-N	Blade Attachment Screw	1

Figure 2: A typical hacksawn and its components

factors.

The lab requires students to work on a semester long project – design and fabrication of a ‘Hacksaw’ (Figure 2). The hacksaw has the following list of components: Handle (#1 and 2), frame (3), blade (8), fasteners (6, 7, 9), tensioner (5), and a retainer (4). The blade and fasteners are acquired through a vendor. The frame and retainer are made using sheet metal bending. The tensioner is made using CNC and manual machining. The students will learn sand casting, manual and CNC machining, sheet metal bending, resistive welding, grinding, etc in the lab and lecture settings. From the lesson learned, students are required to design and fabricate a hacksaw handle during the semester. The knowledge gained from the previous Solid modeling course (mold design) enables them to design the solid pattern in CAD format. The students then 3d print their design. The main criteria are to leverage the advantage of the 3d printer to group-specific handle design and reduce the volume without compromising the processing and structural integrity. Also, design flexibility can be leveraged out of the 3d printer. A detailed lab schedule is presented in Table 1.

Table 1: A semester-long schedule of the material processing lab

Week 1	**Introduction to lab safety, equipment, and tools**
Week 2	Demonstration of the Sand casting process
Week 3	Design of Hacksaw handle
Week 4	Design of Hacksaw handle/3-d printing
Week 5	Assembly and engineering drawing
Week 6	CNC – G Code Introduction
Week 7	CNC machining/Lathe machining
Week 8	Casting
Week 9	Casting
Week 10	Casting
Week 11	Casting
Week 12	Shaping, Bending, Welding, etc.
Week 13	Shaping, Bending, Welding, etc.
Week 14	Post processing
Week 15	Presentation and Project submission

Every semester, 100-120 students enroll in the junior level material processing course. Each lab covers 16-20 students. There has been a significant investment made by the college to acquire different brands and different scale of 3d printers for research and teaching purposes. Figure 3 presents the varieties of 3d printers at the college additive manufacturing lab.

One of the Accreditation Board for Engineering and Technology (ABET) new student outcomes is that the engineering program must demonstrate that the students can attain: ‘an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.’ The student's project in MENG 3333 is ideal for assessing such an outcome. The students design the hacksaw using the principles of ergonomics, low weight, defect-free higher strength handle. An alternative process Silicone mold casting (cold casting or resin casting) is also used to compare with the sand casting process assessing the environmental and economic factors. Silicone mold casting is a resin casting process where silicone is poured over the additively manufactured pattern to create a silicon mold. A resin is then poured inside the mold to create the desired part.

The students are divided into four groups, with each group containing four students to foster the teamwork. Each group conduct the market survey and design a computer-aided design (CAD) model of the hacksaw handle in Solidworks. A complete sand mold making process using an old pattern (not 3d printed) will be demonstrated before the design process. The instructor fully laid out the requirements to have quality casting. The main reason for this is to integrate metacognition and critical thinking skills in the design process. As the pattern design is dependent upon the mold making and casting process, the demonstration will allow the student to think beyond the box and come up with a better design.

Figure 3: The 3d printer lab, Uprint models on the left, Fortus 450 printer in the middle, Color resin printer on the right and small scale rep-rap 3d printers in the middle

Design for casting

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Draft angle, liquid, and solid shrinkage, etc. have to be considered while designing the handle. The pattern will have two halves. The students are required to understand the sand-mold making process entirely to design the two halves of the pattern considering the draft angle, and shrinkages, Shrinkage: The actual size of the cavity is slightly oversized to allow for the shrinkage. Due to the thermal expansion coefficient, most metal and alloys shrink during cooling.

Riser: The riser (Figure 1) acts as a reservoir and solidifies after the main casting, thus negating the shrinkage in the casting. To compensate the liquid shrinkage in the sand casting process and if the casting is very thick, a riser is design and implemented.

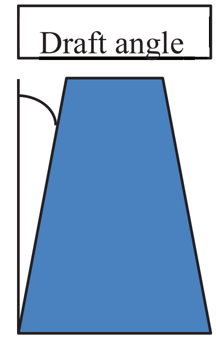

Figure 4: The draft angle

Draft: A draft angle (1°) is required in the pattern (shown in Figure 4) to eject the pattern from the sand effortlessly. A draft angle assists or aids in the removal of the pattern from the sand. A thin film exists between the sand mold and the pattern which creates a vacuum, thus damaging the sand mold while removing the pattern from the sand. A negative mold also tears the mold apart during the pattern removal process.

Split Pattern: Two-piece pattern is the most widely used pattern for sand casting. One half of the pattern is molded in drag and the other half in cope.

Sizing: The 3d printer is capable of printing anything less than 8" x 8".

Creativity in Design and Design Freedom

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Some of the students' pattern designs are presented in Figure 6. A clearance fit between the two split-patterns is required in the design to fit two-patterns together during the mold making process. The top-right pattern (Figure 6) is a simple design of a split pattern where a male end meets with the female end. Critical thinking plays an important role in design, however no critical thinking was not observed in this design; first the weight is not controlled, second no draft-angle has been introduced, and it breaks the sand when pulling out from the sand mold. If the sand gets pulled from the mold, it generates undesirable defects on the casting handle.

The top-left design (Figure 6) is very similar; however, some weight has been removed to reduce material consumption and time in printing. The bottom-left split pattern (Figure 6) is more creative as both the pattern contains the boss, however, the boss is so thin that it broke just after printing. The design of a boss is essential in sand casting as it won't break any sand during the mold removal process as depicted in Figure 5. The pattern also has excess material removed, thus it prints quicker than the other patterns. The bottom right pattern (Figure 6) resembles the grip for holding the handle, design based on the principle of ergonomics.

Figure 7 shows a pattern with a core in place for the sand casting. As seen in the Figure, it is thicker than the other pattern presented in Figure 6 and generates defects in the casting and requires multiple risers to cast the handle without defects. Ideally, it is easier to cast with silicone mold resin casting than sand casting. There is a trade-off between sand casting and silicone casting process. First, the silicone casting process is less expensive than sand casting. Second, the silicone casting process requires minimum effort. Third, the silicone resin casting process doesn't require heating and melting; thus, it may have some environmental benefits. The sand casting, on the other hand, brings aesthetic appeal to the parts being aluminum and has higher strength. The sand casting is the most used process so the fundamental knowledge of heating, cooling, solidification, etc. is ideal for introducing in a junior level course.

Figure 5: Representation of the boss in the pattern to easily removed the pattern from the sand mold

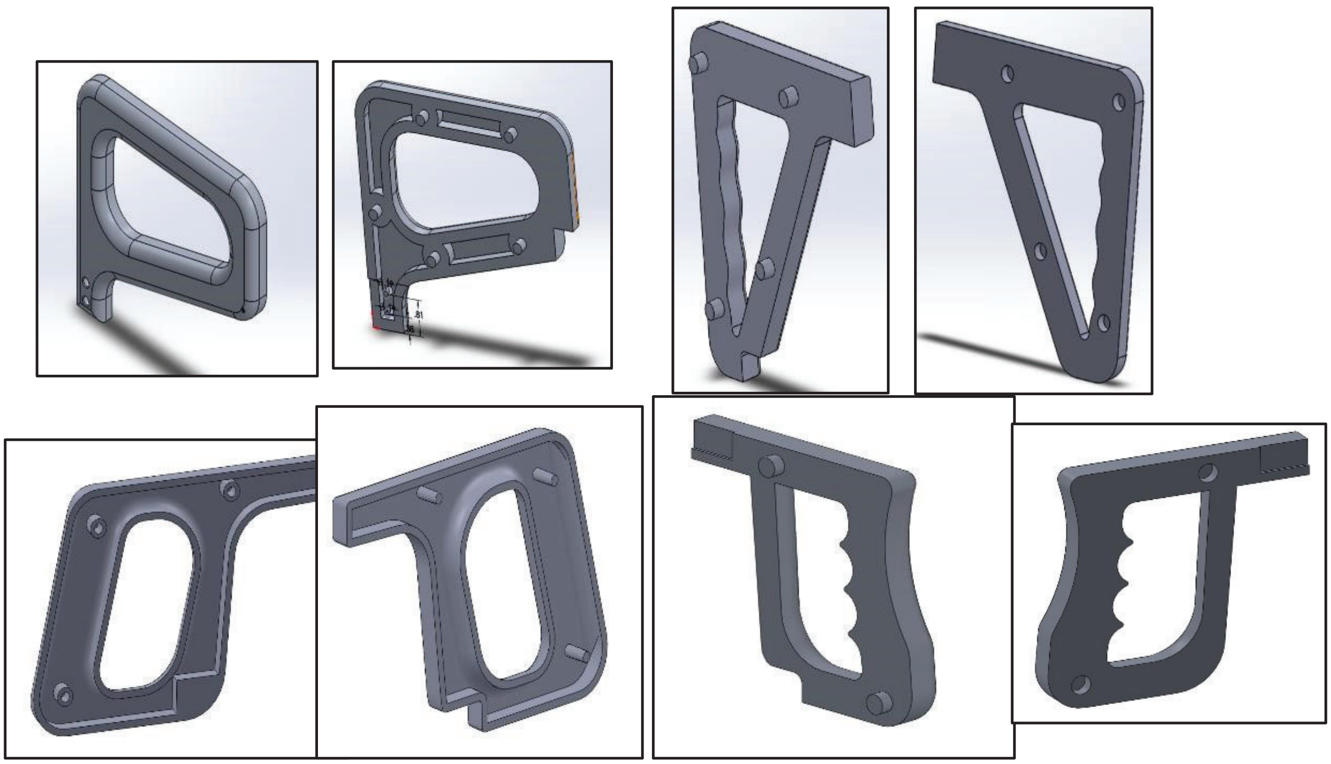

Figure 6: Several split patterns designed by students

Figure 7: A design that requires a core for sand casting and multiple risers, however easier to resin cast without any problem

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Procedure/Investment/Cost

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A price sheet form was designed and placed to implement the 3d printer across the different departments inside the college. The students fill out the form with specific information about the volume and weight of the pattern. The form along with the STL file is emailed to the 3d printer lab where a student worker will perform the printing operation. Once the printing is executed, the student worker will also perform the post-processing and schedule time to pick up the printed parts. Within 8 x 8 x 6 build envelope, the maximum volume for each sandcasting pattern is approximately 115 cm^3. The standard material price is \$2.45 per in^3 (per 16.38 cm^3) and \$4.76 for the support material. These are calculated using the material and depreciation cost of the 3-d printer. Considering 10-20 % of the part volume is used as support material, the total cost of printing the split pattern is approximately \$75.

Challenges in implementing 3d printer in educational settings

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Figure 8: The surface topography comparison between 3-d printer and cast parts

Some of the new factors that were never introduced before the implementation of the 3d printer were the draft angle and solidification shrinkage. An old pattern made out of aluminum was used in every lab. Other processing techniques, such as machining and injection modeling, were quite complex and time-consuming to fabricate a pattern. It was a very cost-effective solution at that time.

The 3-d printed parts are not within the specified tolerance range. The printer has ±0.001" tolerance; however, a tolerance of 0.002 will not provide enough clearance between the hole and peg of the split pattern. The support material surface finish is not smooth enough for casting. Figure 8 provides a comparison between the 3-d printed pattern and sand cast hacksaw handle. As seen in Figure 8 the surface topography is retained in sand casting. One of the essential factors to implement 3-d printing in engineering education is time and reliability. If the students are involved in project-based learning with a fixed timeframe, the reliability of the 3d printers is an important issue. The general requirement is to have minimum maintenance with the 3d printers, however not all 3d printers are consistent with this remark. We have more success with U-print 3d printers without much need for maintenance within the warranty period. Now the warranty period has phased out, they are starting to show their age, and we're starting to have more significant problems. The periodic maintenance and service of parts such as: belts, hot ends, and material drive bay etc. is required. The parent company wants $2800 per year, per machine for the warranty service. Considering total of six printers the cost is relatively high. Most of the educational facility (particularly the university) has budgeted for equipment acquisition; however, there is not sufficient operational budget for the maintenance of out-of-service high-cost 3d printers. Figure 9 shows the out-of-service printer. It is obsolete, and we can't buy parts for it.

Figure 9: A out of service 3d printer ready to recycled

An alternative to sand casting, cold casting or resin casting is a process where a silicone mold is used to make castings from the resin. The surface finish of such casting is far better than the print out of FDM based 3d printer. Figure 10 shows the silicone mold and resin cast hacksaw handle. This process has also been used to compare with the sand casting process in terms of environmental, economic, and safety factors. The students compare the sand casting with the silicon mold casting process in terms of cost, safety, environment factor etc. and make a presentation on their findings.

Figure 10: A silicone mold to use for resin casting process

Students Response

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A survey was designed to collect the students' response (n = 29) on 3d printer use. Based on the results, nearly 50% of the students haven't used a 3d printer or 3d printer related service before this course (Figure 10). 6.9% owned a 3d printer before taking this course. 68.97 % rated the quality of the 3d printed product reasonable. 75.86 % appreciated the 3d printing integration in this course, while the rest presumed that it is common to have 3d printer activities in engineering course. In terms of 3d printing services, 20.69 % find it challenging to access 3d printing services. 100 % responded that they would like to be involved in 3d printing activities postgraduation given an opportunity (Figure 10).

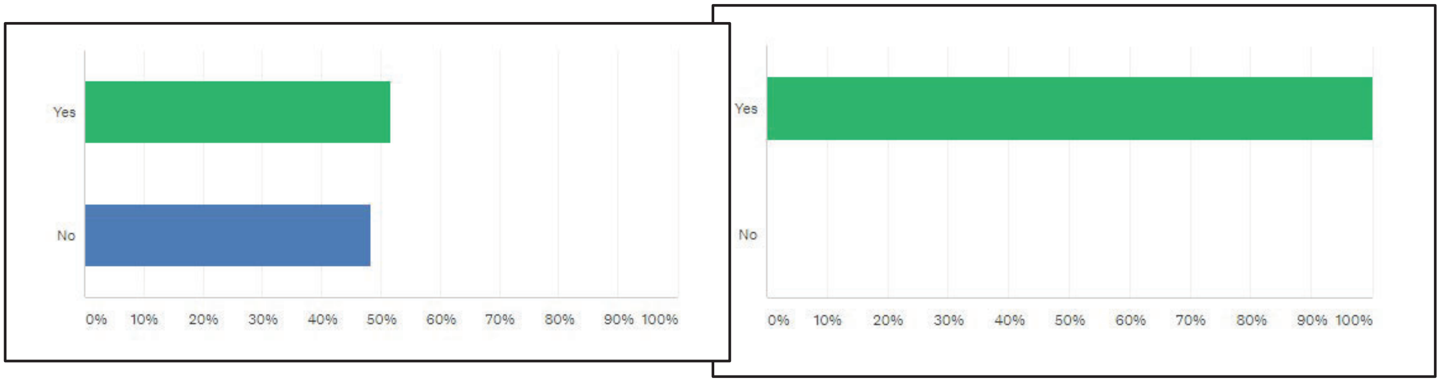

Figure 11: Students response on "Have you used 3-d printer or services prior to this course?" on left and "Will you involve in 3-d printing activities post-graduation given an opportunity?" on right

Concluding Remarks:

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In this paper, the implementation of 3d printers in a material processing course has been presented. The use of 3d printers has helped us to teach both traditional and modern manufacturing processes. Some of the factors that were never introduced before the implementation of the 3d printer were introduced in pattern design. With the implementation, the students have a better practical knowledge of pattern design for sand casting and this paper proves that the engineering design is influenced by manufacturing technique. The students' response suggests they are enthusiastic about the use of 3d printers and its integration in the curriculum. High cost 3d printers need a high operational budget in an educational facility to self-sustain after the warranty period. It is of best interest to acquire intermediate-cost, low maintenance 3d printers rather than high-cost high end 3d printers for teaching purposes.

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