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Integrating 3-D Printing and CAD into a Materials Science and Engineering Curriculum

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Abstract

Integrating advanced technologies into established engineering curricula is often challenging for a variety of reasons, including cost and availability of equipment and methods, inertia to change and difficulty fitting more content into an already full curriculum. This paper describes how 3D printing (3DP) and computer-aided design (CAD) were integrated into a Materials Science and Engineering (MSE) curriculum and the impact of the integration over the past five years. The integration focused on two senior-level courses that include both a lecture and a lab component as well as a design project. The fall course addresses materials performance and failure, including plastic deformation, fracture, fatigue and creep, and the spring course focuses on materials processing, including traditional routes such as extrusion, injection molding, forging and powder compaction, as well as a variety of 3DP (additive manufacturing) methods. The lab activities and design projects incorporated into these classes are described along with examples, lessons learned, student performance data and the impact on the students and program.

Introduction

3D printing (3DP), also known as additive manufacturing, is an important manufacturing method that has become more accessible for academic lab facilities in the last ~five to seven years [1]-[5]. Traditional manufacturing techniques, such as injection molding and forging, involve fixed molds or dies that are expensive and present limitations to the 3D shapes that can be fabricated. In 3DP, no molds or dies are required. Parts are designed using a computer-aided design (CAD) program and then the digital part file is loaded into a slicer program that prepares the part file for printing on a 3D printer. From idea and concept development to final printed object, 3DP is fast and inexpensive, which opens the door to creativity, individuality and multiple redesigns in student projects. Moreover, CAD programs offer performance simulations that can be included in the design process, and the diversity of materials and methods for 3DP (or additive manufacturing) is inherently fascinating to Materials Science and Engineering (MSE) students and important for them to fully appreciate in the course of their degree program.

The introduction of cost-effective 3D printers has led to new ways to teach engineering and scientific concepts in an academic setting. The scope and goals of these new experiences are often dictated by a particular academic program's needs. Experiences that utilize 3DP have included teaching iterative design using turbine blades [2], demonstrating mechanical properties testing [3], assessing performance variability in mechanical properties [6], and introducing ASTM standardized testing protocols [3], [4]. Furthermore, the introduction of 3DP technologies in academic environments has allowed for educators to demonstrate how 3DP can be one part in a larger manufacturing design process [5] and highlighting the importance of waste, sustainability, and materials recycling [7], [8]. Complementary to this rise in 3DP inclusion in the engineering education space has been the further incorporation of CAD programs to teach iterative design [2], and simulation analysis software (either standalone or coupled with a CAD program) to study how a proposed product performs under a virtual stimuli [9]-[11]. Based on the successful implementation of these technologies and teaching styles, a logical evolution of these trends would involve the holistic integration of 3DP methods, CAD programming and simulation, and iterative design together into an undergraduate engineering program. This blending of concepts would be particularly useful for a MSE program by having students explore the interactions between materials performance, materials properties and selection, and product design.

The MSE program at the University of Minnesota, Twin Cities, a large R1 research university, is a four-year, semester-based program. After the first two years of preparatory work in math, physics, chemistry, mechanics, and liberal arts, the program has a full schedule of materials science and engineering focussed courses in the final two years. The foundational topics of thermodynamics and kinetics, including diffusion, are lecture courses in the junior year as is a course on numerical methods in materials science and engineering. Each of the five classes of engineering materials (metals, ceramics, polymers, electronic materials and composites) is covered in its own lecture class with a focus on structure and properties. Three of these classes are in the junior year (metals, electronic materials, polymers) and two are in the senior year (ceramics, composites). There is a laboratory-based class each semester. In the junior year, there is a lab course on materials structure and another on materials properties. In these courses, students not only learn the fundamentals of methods of structure and property characterization but they also develop their skills in lab notebook upkeep, data analysis and presentation, teamwork, and report writing. In the senior year, students take two lab courses on topics central to engineering – materials performance and materials processing. In addition to lab experiments, there is additional content delivered in lectures and design projects. Finally, the capstone senior design class involves student teams working with industrial mentors on a semester-long design project that includes developing solutions to industrial problems, economic analysis as well as performance predictions. Given the direct connection of 3DP to materials processing and the importance of CAD to engineering and design, the natural place to integrate these topics into the curriculum was the senior year lab courses (*Materials Performance* and *Materials Processing*).

This paper provides details about the integration of 3DP and CAD into the two senior-level lab courses in an MSE curriculum, including lab activities and team design projects. The rationale, strategies and evolution of these changes are detailed along with lessons learned in the development and implementation of these changes, examples, and a discussion of impact.

Course Overview

Materials Performance is a fall semester, senior-level course that focuses on the factors that influence the long term performance of materials, including mechanical, chemical and electrical failure processes. The course focuses on engineering topics and builds on the foundation of laboratory skills and fundamentals of the engineering materials classes developed in the junior year. In the 2013/14 academic year, this course received a major overhaul. While the central theme of the course – the mechanistic understanding and prediction of failure from processes, such as plastic deformation, fracture, fatigue and creep in metals, ceramics and polymers – remained unchanged, the update included the development of new experiments, the addition of a semester-long design project and the inclusion of CAD and 3DP. The objectives (see Figure 1) now include CAD and 3DP with the highlighted text indicating how the integration of these topics impacts several of the course objectives. In particular, the understanding of how conditions, such as mechanical loading and thermal gradients, impact the response of a material and its resistance to failure is greatly improved with simulation tools that involve finite element analysis. One motivation for integrating CAD into the course was to harness the power of simulations in an easy-to-learn and intuitive format. The inclusion of 3DP into the course enabled a semester long design project, providing a means for student teams to create unique physical objects whose performance can both be simulated in CAD and tested in physical form.

For students to:

1. Learn the fundamentals of materials performance across three classes of engineering materials (metals, ceramics and polymers), and in the context of design and materials selection.
2. Learn how to identify, analyze and prevent various modes of failure: mechanical (elastic, plastic, fracture, creep, fatigue), thermal (thermal shock), chemical (corrosion, degradation) and electrical (breakdown).
3. Apply and integrate their knowledge of structure-property relationships with design and performance.
4. Complete experiments that reinforce lecture material, involve data analysis and include design problems.
5. Complete a project using computer aided design (CAD), structural analysis, 3D printing and component testing.
6. Gain experience in teamwork and communication skills.
7. Build an appreciation for the professional responsibilities of an engineer.

For students to:

1. Learn the scientific and engineering principles underlying the processing of metals, ceramics and polymers.
2. Integrate processing – structure relationships with their knowledge of structure – property relationships in order to solve materials selection and design problems.
3. Use processing equipment and related experimental techniques for process monitoring.
4. Conduct experiments, as well as analyze and interpret data.
5. Write a technically correct, readable and visually appealing lab report.

Figure 1 Course objectives for *Materials Performance* (Left) and *Materials Processing* (Right) with the objectives most impacted by 3DP and CAD highlighted.

The spring senior-level lab course, *Materials Processing*, focuses on the processing of metals, ceramics and polymers by a variety of methods and with an emphasis on understanding the fundamentals of the processing steps as well as the commonalities and differences between the engineering materials classes. Processes are categorized by the state of matter most central to the process - melt, solid, powder, dispersion and solution, and vapor [12]. While this course had been taught and developed with this focus for many years, the rise of 3DP as a means of materials processing led to significant changes in the course beginning in the 2013/14 academic year. At that time, 3D printers had become affordable, which opened the door to lab experiments and a creative design project into the course. In addition, this led to the inclusion of additive manufacturing methods comprehensively in the lecture portion of the course. The importance of

3DP to the objectives of *Materials Processing* is understandably far-reaching (see Figure 1). Furthermore, the inclusion of CAD was also important for this course as knowledge in CAD is required in understanding the implications of part design on specific processing routes, both traditional and additive.

Curriculum Development

Integration of CAD and 3DP into the curriculum was a progressive, multiyear process, as detailed in Table 1. Equipment purchases were brought online over several years. Lab experiments evolved and changed content year-to-year, as is typical of all experiments in these courses. The two senior lab courses work in tandem with *Materials Performance*, a fall course, leading the way with an intensive CAD experience, including part design and simulation, and 3DP utilization for creative mechanical design projects. *Materials Processing* follows with a focus on the fundamentals of the 3DP process, how it compares to traditional manufacturing processes, and designing 3D printed objects that account for aesthetics, fit and print parameter selection. While the two courses worked together, understanding how each developed is best approached separately.

Materials Performance

In the development of the *Materials Performance* course, the incorporation of CAD-based activities grew steadily over the five-year period. See Table 1. The first critical decision was the selection of the CAD program. After considering several candidates, SOLIDWORKS (SW) [13] was chosen for several reasons. First, it is a powerful CAD program in terms of features for complex and facile part design with options for creating engineering drawings as well as assemblies. Second, SW also has a simulation package that allows the prediction of the material response to external forces, heat sources, etc. Third, the University of Minnesota has a site license that allows all students access. Last, the program is widely used in industry and therefore is potentially very useful in careers of the students post graduation.

Specific lab activities were developed to help students learn the program. In the first three years of the curriculum development (2013 - 2015), an introductory SW lab utilized tutorials native to SW. Students completed the tutorials in a computer lab with help from the instructors and teaching assistants (TAs), and then they practiced their new skills by creating a part according to the information provided in an ASTM standard. In 2016, a new SW Introductory Lab was developed specially to teach the student the key tools and features that they need for labs and the design project. The students were also instructed to learn on their own with resources such as video tutorials on Lynda.com [14]. A second, specially designed SW Lab that focuses on simulation was added in 2017. In this lab, students learn how to use the simulation environment of SW, a skill that they use in subsequent lab experiments as well as in the semester-long design project, by exploring how complex stress states and boundary conditions influence local stresses and yielding.

Table 1 Integration of SOLIDWORKS (SW) and 3D Printing over time in the two senior labs

Year	Materials Performance (Fall)	Materials Processing (Spring)
2013 /14	● Stratasys Dimension FDM 3D Printer added to the undergraduate lab facility ● Introductory SW Lab added (see text) ● Semester-long design project added – SW design, physical testing and performance calculations	● 3D Printing Lab added – explored fundamentals of FDM, compared FDM with injection molding ● Design of a unique part included in the 3D printing lab.
2014 /15	● MakerBot FDM 3D printers added to the undergraduate lab facility ● Introductory SW Lab continued ● 3D Printing Lab added to introduce students to the process ● Semester-long design project continued – SW design, physical testing and performance calculations or SW simulations	● 3D Printing Lab modified to compare 3D printing performance of different models of FDM printers ● Separate design project focused on process parameter selection, aesthetics and dimensions added ● Lectures on additive manufacturing added
2015 /16	● Introductory SW Lab continued ● Mechanical Properties of 3D Printed Parts Lab added – compared Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA), included SW simulation and design ● SW simulation added to an existing lab on failure of electrical heaters ● Semester-long design project continued	● Form 1 Stereolithography (SLA) printer added to undergraduate lab facility ● 3D Printing Lab modified to compare FDM with SLA ● Mechanical profilometer and low magnification, long working distance microscope added to undergraduate lab facility, used to characterized 3DP part structure ● Design project continued
2016 /17	● Fusion3 F400 FDM 3D printer added to undergraduate lab facility ● Introductory SW Lab redesigned with content tuned to the needs of students ● Mechanical Properties of 3D Printed Parts Lab Experiment improved; SW simulation continued ● SW simulation continued in Electrical Heaters Lab ● Semester-long design project continued	● 3D Printing Lab Experiment continued ● Rheology of PLA and connection to 3D printing added to existing lab experiment ● Design project continued ● Additive manufacturing lectures refined
2017 /18	● Introductory SW Lab similar to previous year ● Second SW Lab added with focus on simulation ● Mechanical Properties of 3D Printed Parts Lab Experiment continued ● SW simulation continued in Electrical Heaters Lab ● Semester-long design project continued	● 3D Printing Lab Experiment modified to include an emphasis on printing speed ● Design project continued ● Additive manufacturing lectures continued

Over the years, SW simulations were added to several lab experiments. In a lab experiment devoted to uncovering the source of failure in a resistive electrical heater, students take temperature data in a fixture (Figure 2, Left) under different input currents to the heater in order to understand the performance and eventual overheating and failure. SW simulation (Figure 2, Right) helps the students see how heat transfer fundamentals are the heart of the performance problem. SW simulation is also used to explore the stress states in a 3D printed dogbone in a Mechanical Properties of 3DP Parts Lab. See Figure 3. This lab experiment helped students understand how the mechanical response of a 3DP part is affected by its internal structure, and it also provided valuable experience with printing and evaluating the mechanical properties of 3D printed parts, which are needed for the design project.

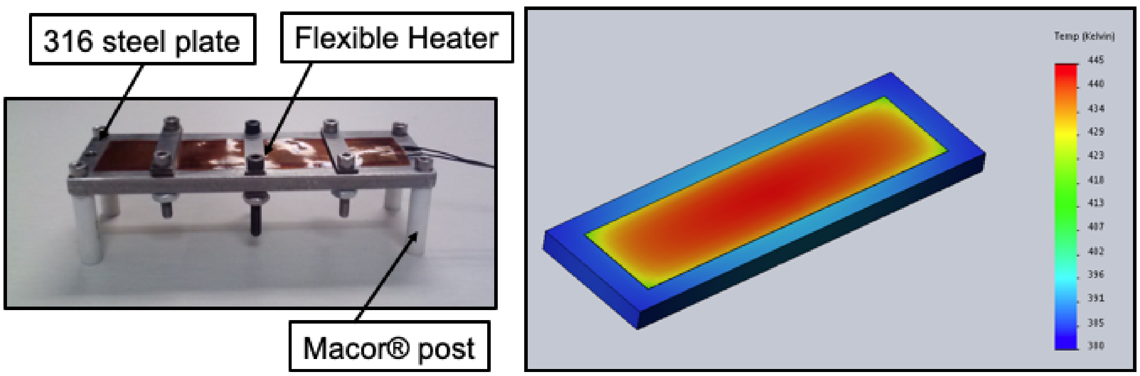

Figure 2 Left: Set up for the electrical heater lab, including a steel fixture with a polyimide flexible heater (variac, electrical and temperature monitoring systems not shown). Right: SW Thermal Simulation package temperature profile output.

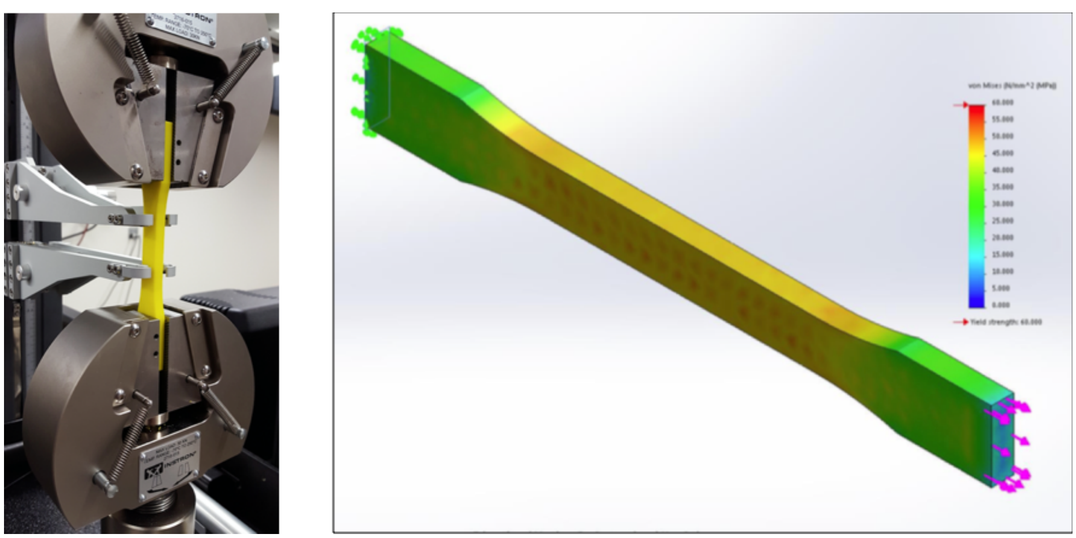

Figure 3 Left: Photo of a 3D printed dogbone undergoing a tensile test. Right: Result from SW simulation, which shows a range of stress levels in color with the faint color variations in the center of the specimen due to the internal structure of the 3DP part.

In *Materials Performance*, 3D printing is first and foremost a means for students to create unique design projects. Prior to the current era of affordable 3D printers in academic laboratories, design was an exercise on paper with predictions of performance for selected materials and geometries with little hope of the satisfaction of making and testing actual parts. Now, 3DP enables student teams to tackle a true iterative design with testing over the course of a single semester. To prepare students for the design project, a hands-on 3D printing experiment was developed in 2014. For all labs and projects in *Materials Performance*, the most common 3DP technique available, Fused Deposition Modeling (FDM), was used. In this method, polymer is extruded through a nozzle in 2D layers. In 2015, the Mechanical Properties for 3D Printed Parts Lab was developed. This lab explores how part orientation relative the build plate, printing direction, infill (i.e., part density), and material choice influence the mechanical properties in tension. As mentioned earlier, this particular lab also includes a SW simulation exercise for students.

The team design projects launched in 2013, as soon as the first 3D printer was donated to our facility, and they have continued to evolve ever since. Table 2 summarizes the design projects over five years, including the project name and the key specifications. Given the emphasis on mechanical failure in the course, each project revolves around a specific mechanical demand and has the goal of functioning without failure, including plastic deformation, excessive elastic deformation, and fracture. Other specifications include the project dimensions and other specifics, such as material choice.

The implementation of the design project follows a classic iterative design format [15], [16], as shown in Figure 4. As mentioned above, each project has a common set of specifications that all student groups work toward. After brainstorming and selection of a prototype idea, the teams design their part(s) in SW and begin 3D printing, and redesign iterations. In 2013 - 2015, students carried simple analytical calculations of the performance, although some ambitious students did SW simulations. Starting in 2016, SW simulations were a required part of the design process.

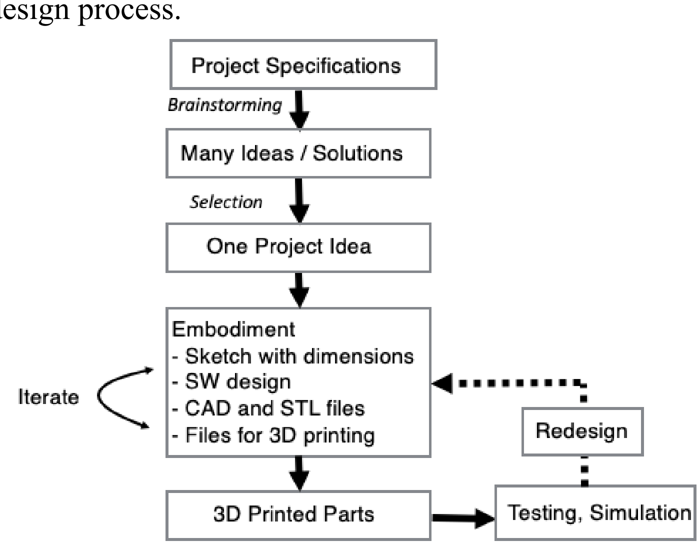

Figure 4 Schematic of semester-long design project in *Materials Performance.*

Table 2 Team design projects titles and specifications

Year	Materials Performance (Fall)	Materials Processing (Spring)
2013/14	Backpack Hook ● Supports a 10 lb weight without failure ● Made of ABS ● Secures to wall with two screws ● Designed in SW	Custom Duplo®-like bricks ● Has a curved or irregular profile ● No taller than standard brick and no more than 1.5x larger in lateral dimension ● Fits onto a standard Duplo block
2014/15	Portable ice scraper ● Removes ice from windshield without failure ● Made of ABS or PLA ● No larger than 3.5" x 2" x 0.25" ● Designed in SW	Class Message in Lego®-like bricks ● Two letter bricks no larger than 5 x 5 cm in the plane of the letter and 2.5 cm deep; ● Attaches to standard board; one brick attaches horizontally and the other vertically ● Designed in SW or other CAD program ● Creative approaches encouraged
2015/16	Prosthetic thumb ● Attaches to hand ● Thumb moves by some actuating mechanism without failure ● Made of PLA ● Designed in SW	Monuments to Materials Science and Minnesota ● Two bricks no larger than 5 x 5 cm containing a 3D object that fits the theme ● Attaches to standard board; one brick attaches horizontally and the other vertically ● Designed in SW or partially created by 3D scanning ● Creative approaches encouraged
2016/17	Compact Multifunctional Tool ● Performs at least three functions and contains at least one moving part ● Functions without failure ● Designed in SW	Picture This – Minnesota ● Brick no larger than no larger than 6 x 4 x 3 cm, depicting a familiar image from [Institution] ● Attaches to standard board ● Designed in SW, "Sketch Picture" option encouraged ● 3D Printed in at least two colors
2017/18	A Hook and a Hinge ● No larger than 5 x 5 x 9 cm ● Includes as working hinge and a hook, each with a function ● Designed in SW ● Secures to the wall with two screws ● Hook must sustain a hanging load of 15 lb without failure	Your Best Block M ● Brick no larger than no larger than 6 x 4 x 3 cm, featuring the [Institution Logo] ● Attaches to standard board ● Designed in SW ● 3D Printed in at least three colors

To track and assess student progress, the design project is broken up into four stages, with each stage concluding in either a written memo or presentation. While details between each stage varied slightly from year-to-year, stage progression overall follows the iterative design format previously shown in Figure 4. The first stage, which is documented in "Memo 1", primarily encompasses the Brainstorming and Selection sections of Figure 4. In this stage, student groups conceptualize various solutions for a given year's design project requirement, come to a consensus on a prototype idea, and create sketches of their proposed part(s) (either hand sketches or SW). The culmination of this stage ends with a short "memo" that describes a group's proposed solution and how it addresses the various design criteria. Course instructors then provide feedback on the overall design and printability of the part(s) and this feedback is utilized in the second stage of design, which is documented in "Memo 2". In this stage, which focuses around the Iterate portion of Figure 4 (primarily the Embodiment step), students create prototype SW drawings and assemblies of their part(s) and begin to iterate the design of their project based on mechanical simulation testing results. This stage also culminates with another memo detailing how their project evolved during the Embodiment stage and the results of their simulation analysis. Upon further review by course instructors, the project moves to the third stage, which is is documented "Memo 3". Here, groups 3D print their prototypes and further refine their projects. Thus, this stage completes the Iterate loop shown in Figure 4. Students ultimately document their 3D printing experience and how their project evolved via this final memo. The last stage of the design project requires groups to print out their now refined part(s) and create a final presentation describing their project to the rest of the class. This "presentation" has evolved from year-to-year depending on the design project, but has included presentations, live demonstrations of the part, or a video that describes their project creatively.

To assess group performance throughout the semester-long design project, Figure 5 tracks group scores as a function of the design stage for each academic year. Since the design project was introduced when the course was reworked and 3DP introduced in 2013, there are no data before this date. It is important to remember that this paper discusses how the incorporation of 3DP and CAD technologies in the two senior-level lab courses have *evolved with time*. Referring back to both Tables 1 and 2, the amount of 3DP and CAD technologies incorporation has increased in both courses since their introduction in 2013, and consequently the complexity of the projects and demands on the groups for the most part have also increased. As a result, one of the important results from Figure 5 is the overall lack of student performance change for each design stage as a function of time. This highlights that even with the increased inclusion of 3DP and CAD technologies, students have been able to learn more without a drop in their overall performance. Furthermore, Figure 5 potentially highlights the importance of iterative design and constructive feedback that instructors provide to groups by noticing an overall increase in group scores from Memo 2 to Memo 3 and finally to the Presentation stages. Interestingly, it was noticed that student group scores either slightly decreased or stayed the same between Memo 1 and Memo 2. One possibility for this observation could be from groups grappling with the realities involved with transcribing their initial sketches to a formal CAD part. However, scores in general do improve as a function of the design stage as students learn from their mistakes and iterate their project.

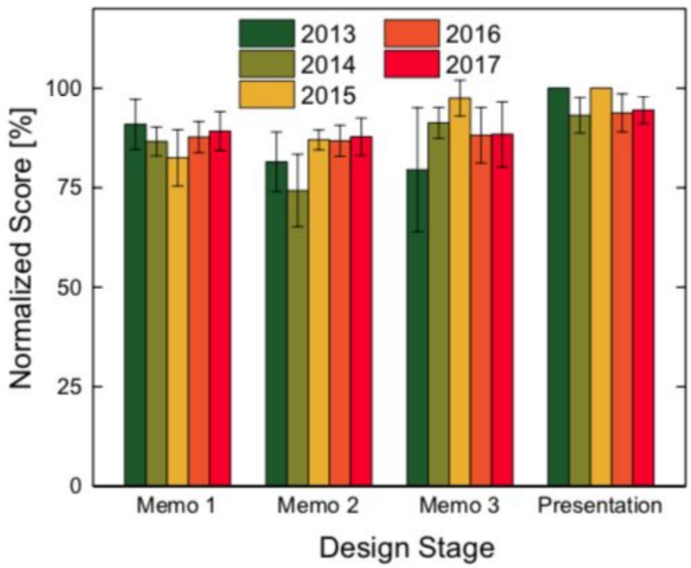

Figure 5 Schematic of semester-long design project in *Materials Performance.* Error bars represent the standard deviation of the average group score.

A demonstration of the success of the curriculum is in the creativity and excellence of the student design projects themselves. In a given year, each team produces a unique project that meets the specifications. As an example, a compilation of the prosthetic thumbs designed in 2015 is shown in Figure 6 (top). This project began with the students 3D printing the e-NABLE [17] prosthetic hand as a learning exercise, and then teams focused on designing a thumb that could be actuated. This particular project was the most challenging to-date. Subsequent projects were more defined, but still allowed creative engineering. For example, Figure 6 (bottom) shows innovative designs for multifunctional tools. A highlight of the semester is the project test and presentation or video.

Materials Processing

In *Materials Processing*, the focus is on the 3D printing process with CAD playing a supporting role. There were three main areas for development as 3DP and CAD were integrated into the curriculum: (i) 3D printing lab experiments, (ii) a half-semester design project and (iii) lectures on 3D printing (additive manufacturing). Table 1 shows the development in these areas over a five year period. Again, it is important to note that students take *Materials Processing* in the spring, after *Materials Performance,* and hence they are already familiar with FDM and proficient in CAD. Therefore, no instruction in CAD is provided in *Materials Processing*.

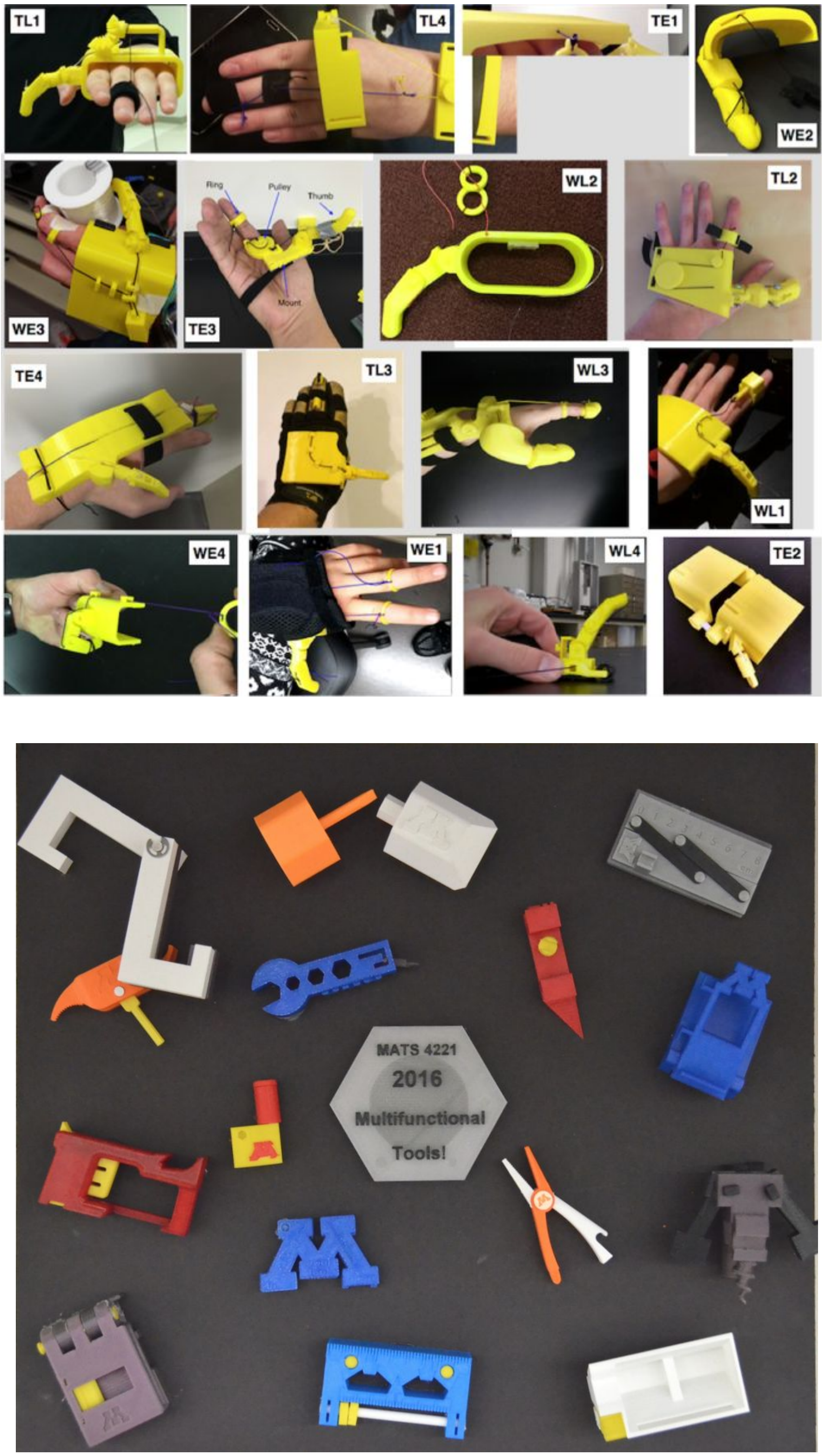

Figure 6 Top: Photo compilation of team projects from *Materials Performance* (2015): Prosthetic Thumbs. Bottom: Photo of the team projects created from *Materials Performance* (2016): Multifunctional Tools. See Table 2 for details.

A processing focused 3D Printing Lab started in 2014 as a combined lab and short design project. At that time, the undergraduate lab facility had one printer, a Stratasys Dimension. The aim of this first experiment was a comparison of 3D printing using this FDM printer with injection molding. The students designed a part and tracked the 3D printing time and material usage. They then carried out a comparative design for injection molding of the same part. Economics were featured in this lab along with a comparison of shape complexity.

As more 3D printers were added (see Table 1), the 3D Printing Lab developed into an exploration of 3D printing process parameters and eventually a comparison of FDM and stereolithography (SLA). The SLA printer was added in 2016. The slicer software used with the newer printers is highly flexible in terms of the user-adjustable settings. The experiment addressed the key trade-off between speed and resolution and also included the use of a long working distance microscope and a stylus profilometer to characterize printed structure. See Figure 7 for an example of data taken in the lab. Economic analysis and comparison continued to be featured in this lab.

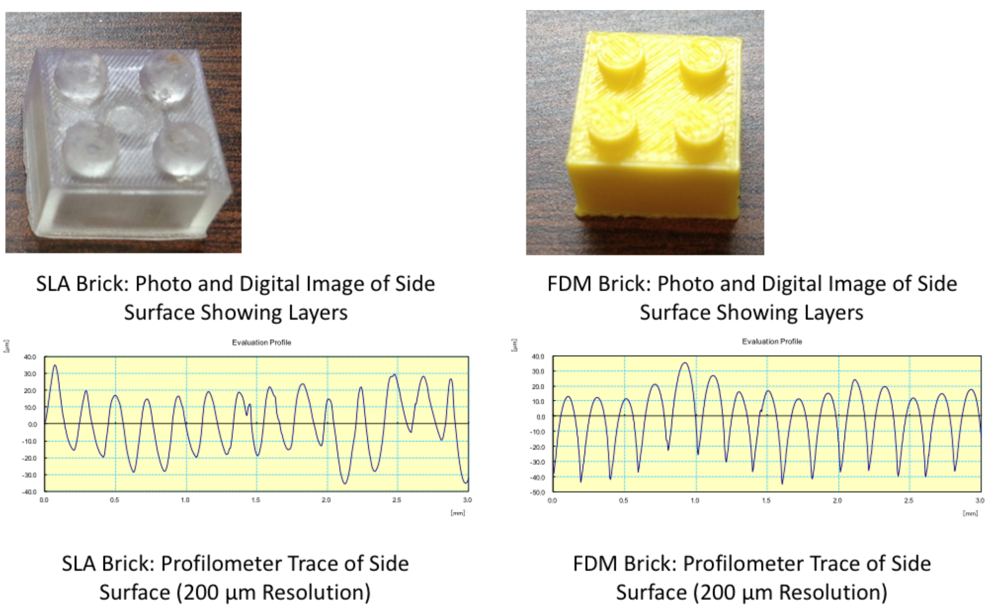

Figure 7 Top: Photos of bricks printed with an SLA printer (right) and an FDM printer (left) along with profilometry traces below each brick.

Materials Processing also has a half-semester long design project aimed at designing a 3D printed part for dimensional accuracy as well as aesthetic appeal. Table 2 lists the design project names and specifications. The project builds on the understanding of the FDM process from the 3D Printing Lab, which uses Lego®-like bricks, and extends it to a specific aesthetic goal together with fit to a Lego® board. The specifications vary from year to year but typically include size, orientation of the brick relative to the board, and expectations for color. The project also follows an iterative process, as shown in Figure 4. In the case of this project, assessment was carried out in two phases. In the first phase, students brainstorm ideas and select one for an embodiment, and they produce a memo that describes the project idea, including preliminary CAD drawings and discusses how the project idea meets the specifications. Instructors provide feedback and then the second phase begins. Here the students continue with the CAD design, prototype printing, redesign and then final 3D printing. An emphasis is placed on selecting printing conditions to develop the dimensions as well as appearance. The students write a report about this phase and the projects are added to board on the last day of class.

Similar to the projects for *Materials Performance*, the creative and exacting projects produced in *Materials Processing* are evidence for the success of the curriculum. Examples projects are given in Figure 8. In 2015, the class (graduating seniors) decided on a message to leave behind based letter-shaped bricks that attach to a Legos® board. One letter was assigned to each of the student teams. Each team designed two versions of their letter in CAD - one vertical and one horizontal - and developed a plan for creating color by changing filament. Additionally they had to ensure that the base of the brick had the correct design and dimensions to fit onto the board. In 2017, student teams created bricks that depicted a scene, image or memory of the University of Minnesota.

The final change to *Materials Processing* that occurred during the integration of CAD and 3DP into the curriculum was the addition of lectures on the major additive manufacturing processes. Powder bed processes such as Selective Laser Melting (SLM) were discussed in the same section of the course as traditional powder processing methods like compaction and sintering, for example. Since the course was well-established before this change, some content needed to be dropped in order to add this new material. Some older techniques, such as metal casting, were not covered in as much detail, and the section on starting materials was eliminated. The result was a class that addressed the needs of the current students, many of whom will work in industries where 3D printing is commonly used.

Impact

The addition of CAD and 3D Printing to our MSE program has had significant impact. One key question was whether these new technologies improved student understanding of performance and design. Examining exit survey data (from graduating seniors) is one way to try to answer this question. Figures 9 shows data both before (2012, 2013) and during the implementation (2014 - 2018) for two questions given on the exit survey. The results show a greater fraction of students agreeing or strongly agreeing with the statements about performance and design after the addition of CAD and 3DP. Of course, the answers to these questions reflect the entire student experience and not just two courses, but none-the-less the results are encouraging.

Figure 8 Top: Photo of the 2015 Materials Processing design projects: Class Message. Bottom: photo of 2017 Materials Processing design project: Picture This - Minnesota! See Table 2 for details.

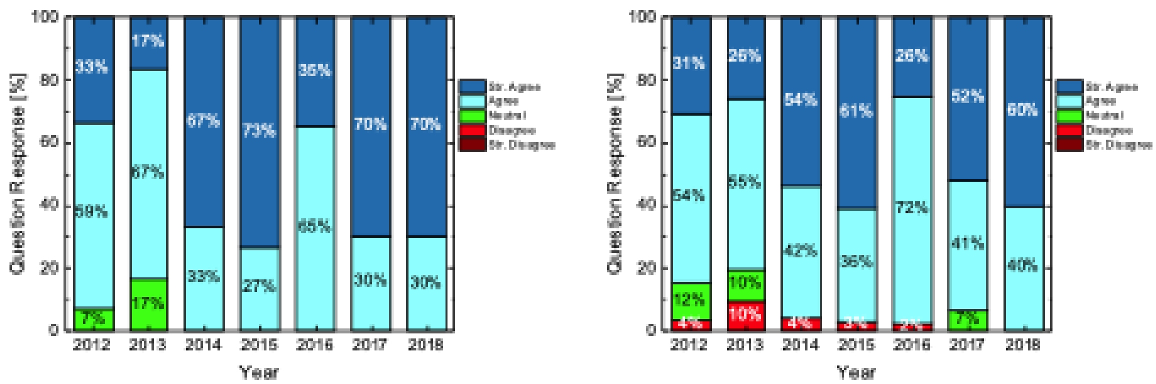

Figure 9 Graduating senior exit survey data for the questions: "*Through my education in the Materials Science and Engineering program (including required courses, technical electives and other educational experiences) I have developed…*" Left: "*...an understanding of the performance of engineering materials*."Right: "*...an ability to integrate these four elements (structure, properties, processing, performance) to solve materials selection and design problems.*"

The developments in CAD and 3D printing have had additional impacts on the students. The Material Advantage (MA) student group has been using 3D printing to make forms for creating ceramic parts. In this case, the 3DP form is used to make a gypsum mold, which is then used to create a ceramic mug. The MA team successfully fabricated a mug and competed with other MA chapters from universities around the country in a mug drop contest, which was held at the Materials Science and Technology Conference in Columbus, OH in October 2015. Recently, our MA group also joined forces with another student organization to provide a ceramic part for a rocket, again using 3DP in the process. In the *Senior Design Project* course, seniors in their last semester complete a 'capstone' engineering design project in collaboration with a mentor from a local industry. While these projects usually do not use 3D printing, instructors of this course have noticed that student teams routinely use SW for CAD model development and simulation. As an example, one student team used SW to design the frequency and placement of the pneumatic vibrators in a paint tank. Lastly, discussions with seniors have provided anecdotal evidence that adding their experience with SW and 3D printing has had a positive effect on their career prospects.

While difficult to quantify, the addition overall has led to a high degree of enthusiasm during the semester and a sense of student pride in their accomplishments. Students are eager to begin the design and print their prototypes. The final classes with the project videos or building of the project boards are always much anticipated and fun. We have a display of the design projects in the MSE undergraduate lab. Before the graduation ceremony, students bring their families to the lab open house to show them the equipment and the design project displays.

Lessons Learned and Conclusion

During the incorporation of 3DP and CAD into our courses over the past five years, numerous important lessons were learned.. We found that slow integration works well, and it is important to iterate and evolve experiments and design projects with time. Adding new technology requires an investment of time (instructor effort) and cost (capital cost, maintenance costs, and upgrades). As a result, it is important that instructors are enthusiastic about the prospect of adding 3DP and CAD to their programs. Equally important is that the instructors gain expertise with both of these technologies. Instructors who incorporate 3DP and CAD technologies into their curriculum may need to increase project complexity with time as they themselves become more used to the technologies. Another important lesson learned was that size restrictions on projects help to keep printing times reasonable, and as a result, encourage iterative design. Design specifications (i.e., restrictions) do not stifle creativity. There are many different solutions to the same problem even with design restrictions. Also, it is important to keep the design project themes fresh from year-to-year. This requires students to innovate rather than replicate last year solutions.

CAD incorporation has been extremely useful in teaching materials performance concepts virtually and enabling iterative design. While pre-made generalized tutorials are useful in the initial stages of incorporating CAD programs into a curriculum, tailor-made lessons that stress the important concepts for a particular class are significantly more useful in enhancing the students' ability to learn the software and perform well in subsequent labs. Furthermore, in order for students to fully embrace the use of CAD software, it is important to incorporate it throughout a course (or courses) schedule. This may require the addition of CAD to other lab experiences or even in homework assignments.

Overall, the incorporation of 3DP and CAD technologies into two senior-level MSE-focused lab courses has significantly enhanced the student experience and career preparation. With these technologies, students have been able to experience iterative design projects and more deeply appreciate the core MSE-themes of materials performance and materials processing.

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