Teaching Mechanics of Materials with Lost 3D Print Casting

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Teaching Mechanics of Materials with Lost 3D Print Casting (RapidCast)

Abstract

Many students find that a hands-on experience enhances the learning process, especially when teaching engineering concepts. One of the challenges for integrating a hands-on component in an engineering class is the cost associated with the specialized equipment and processes associated with producing custom components. The advent of 3D solid modeling and 3D printing has reduced the cost of incorporating hands-on education to mechanical engineering classes for plastic components but has little application to metals commonly used in engineering design. This paper presents the use of a RapidCast process for a Mechanics of Materials class project to enable the design and testing of custom metal parts. The RapidCast process' adaptation of traditional casting techniques which replaces wax or foam with a plastic 3D printed model allows complex shapes to be designed, produced, and tested in a matter of days as a demonstration technique. This class project concept has been refined over several semesters to the current process where students are tasked to design, 3D print, and cast a lifting hook. Using failure theory and solid modeling simulation, students calculated the maximum force that would result in their hook's failure and the location of failure which is then verified by testing to failure. A survey of students who have completed this project reveal that adding this project reinforced the learning experience for the students in a junior level Mechanics of Materials class.

1. Introduction

Hands-on learning experiences are active learning approaches that are essential for college students to apply the materials learned in the classroom and to stimulate their understanding[1]. Several educational set-ups are easily obtainable for such courses and they supplement the concepts taught in the classroom. Additive manufacturing has enable the addition of creative design for plastic parts to this list of easy to implement projects. However, the complexity of the manufacturing techniques for engineering metals limit the ability to design and test metal parts.

The cost of equipment is one of the problems of providing a hands-on experience to engineering students[2]. For a typical Computer Aided Design and Manufacturing class, students are typically given a design problem which they work on and solve in the software realm only. Software like SolidWorks[3] and Autodesk Inventor[4] are very effective tools in the conceptual design process, part modeling, parts assembly and analysis, and failure analysis. Some schools are able to extend the learning experience to actually manufacturing the designed part but often to a limited number of students because of a low equipment to student ratio. In addition, the complexity of operating a Computer Numerical Control (CNC) machine and the time needed to develop the skills to operate the machine is prohibitive in a single semester course. However, the advent of additive manufacturing systems such as 3D printers have changed the landscape of Computer Aided Design and Manufacturing.

3D printing is a revolutionary emerging technology that has profound geopolitical, economic, social, demographic, environmental, and security implications[5]. 3D printing, or fusion deposition modeling (FDM), can be considered as disruptive technology. As opposed to subtractive manufacturing, where material is cut out from a block of material, 3D printing is an additive manufacturing approach that adds material one cross-sectional layer at a time. An advantage of 3D printing is the capability of producing a wide range of products without retooling which leads to additional costs and a very short learning curve. RapidCasting is a process that utilizes FDM to create molds that are then used to create a replica in metal using a lost mold technique.

In this paper, we describe the RapidCast casting techniques to produce metal castings as a classroom tool to enhance the concepts of solid mechanics and material failures as a low cost and effort alternative to traditional manufacturing techniques. RapidCasting is very similar to other lost mold techniques. The traditional lost foam casting[6] process utilizes a polymeric foam pattern to produce metal components. The patterns are created and then coated with a refractory material, dried, and embedded in unbounded sand. Molten metal is poured directly on the pattern causing thermal degradation of the foam which is then replaced by the molten metal. Instead of using a polymeric foam pattern, we use a 3D printed plastic pattern in a bound sand mold and burned the plastic form out of the mold.

The main objectives of this paper are:

1. To describe the design project using RapidCasting for a junior level Mechanics of Materials class.
2. To assess the students' experience of this project and determine the value added to the class by it.

2. Methodology

2.1 Mechanics of Materials Final Project

Mechanics of Materials is a junior level class offered with a prerequisite of Statics. The students have completed a course in chemistry for engineers that includes additional material science and a course in graphics and design that familiarizes them with both CAD and 3D printing. The course covers the basics of solid mechanics including the evaluation of stresses and strains as well as the application of standard failure theories. The lifting hook design project was the class's final semester project, and provided an opportunity to utilize these skills in the design and evaluation of a representative mechanical design project. The project, assigned to each two-person student team, was described as follows:

> Lifting hooks are used to pick up large loads and come in many shapes and sizes. The purpose of this project is to design a lifting hook to pick up the maximum load possible using the least amount of material. The lifting hook will have the following features:
>
> 1. The lifting hook must have a round hole to connect to a lifting shackle. The hole must have an inner diameter of 1 inch and the hook can be no more than ½ inch thick normal to the hole.
> 2. The lifting hook must be capable of quickly connecting to the load with an

opening of at least 1 inch. The load must not slip out when slowly put under stress.
3. The lifting hook will be made of A356 or 6061 aluminum and fabricated using any approved technique. Casting is recommended.
4. The maximum weight of the lifting hook will be ½ lb.

This is a competition based on efficiency. The weight of the hook will be measured then the hook will be put under load until it breaks. The weight of the breaking load will then be divided by the weight of the hook to calculate efficiency. The team with the largest efficiency wins. Include a prediction of the weight your hook will fail under in your report.

Although traditional machining and CNC equipment were available to the students, every team chose to cast their hook with the RapidCast technique. This process added both limitations and freedoms for student designs. The hooks were now constrained to fit within the 5x5 inch printing tray of the Stratasys Mojo 3D printer selected as the machine available for this student project. Though there are other 3D printers with larger print volumes the professor chooses to limit the class to the Mojo printer. The limited 3D print size, however, was offset by allowing for more complex hook geometries without adding manufacturing time which would have resulted if a team decided to machine their hook. Students were free to design hooks that would have been difficult, or impossible to machine, but were easily 3D printed and subsequently cast.

Aluminum was chosen as the metal of choice for its low ductility, low melting point, and complexity of the heat treating processes. The low ductility for an engineering metal required the students to guess at which failure theory would most appropriately fit. The low melting point allows for inexpensive refractories in the casting process. The complex heat treatment mechanisms encouraged the students to independently research the topic of precipitation hardening as a learning tool.

2.2 Design and Casting of Lifting Hooks

Once the students decided on groups and were given the requirements, they were free to work through the engineering design process outside of the classroom. Every engineering student was provided a copy of SolidWorks which they used to model their hook designs. Using the tools provided within the SolidWorks suite, students could ensure the weight of their hook would fall within requirements, and could compare stress concentrations and simulated yield force between various hook designs. Prior to casting, the teams could check the interface requirements by installing the plastic in the testing apparatus.

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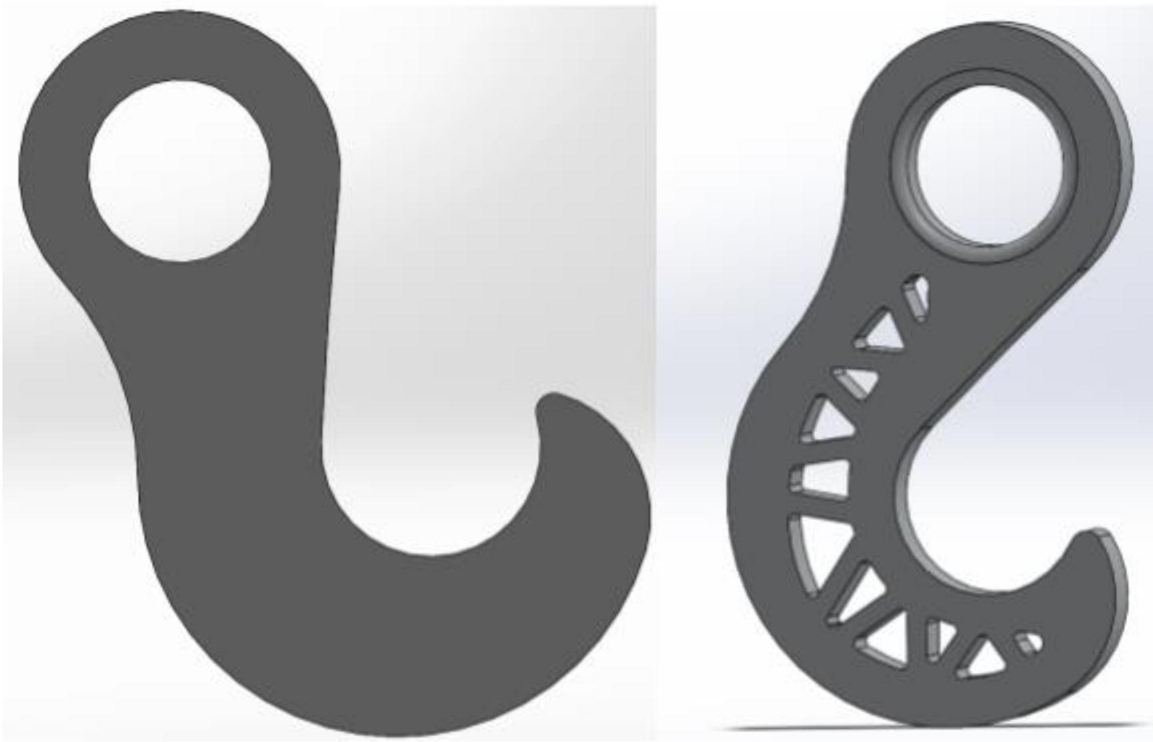

Figure 1. Example of Lifting Hooks Designed Using SolidWorks

The students were then guided in design of a simple gating system to allow for the outflow of the vaporized plastic and inflow of liquid metal. Traditional sprues were created using foam rods about ½ in^2 hot glued to the hook. Special care was taken to minimize possible air pockets in the casting mold. The hook and foam sprues become the void of the mold, so the foam must connect to the hook at the highest points as shown by Figure 2.

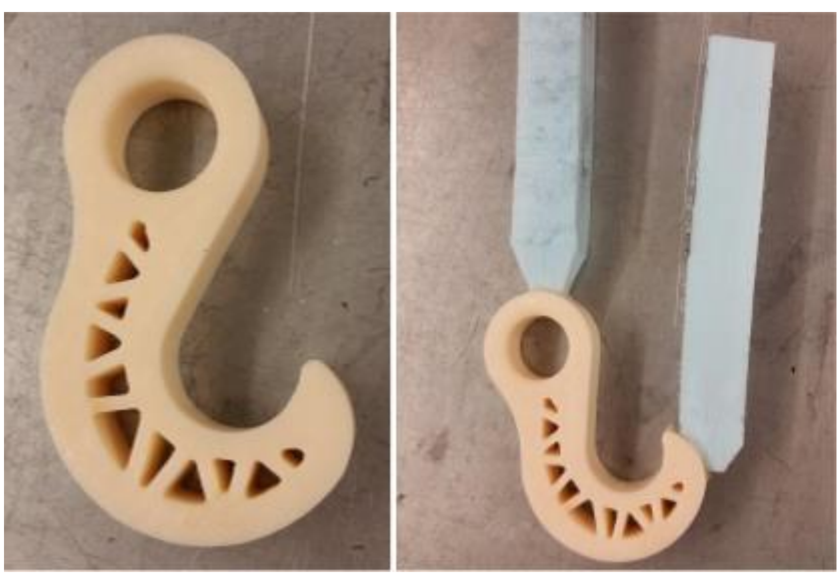

Figure 2. 3D Printed Lifting Hook and Hook with Sprues

The hook, with sprues attached, could now be placed in a mold. A wooden box, with a plastic liner, is used to form the mold. The plastic mold is extremely buoyant in the liquid refractory mixture and needs to be held in place while curing. The hook is secured in the box by pushing sharpened wooden dowels through the foam sprues horizontally at rim height and weighing down the dowel-hook setup. They are centered in the box with at least an inch of space on all sides which ensures the mold will be strong enough to withstand the rest of the process. Once centered and secured a slurry comprised of equal parts water, sand, and plaster-of-paris is poured into the mold after thorough mixing. Enough slurry is added to cover the hook to a depth of at least an inch again ensuring the strength of the mold.

Once the slurry is poured around the hook and it hardens, the mold is ready to be fired in a natural gas kiln used by the ceramics classes in the art department Though students prepared, mixed, and poured their own molds, the ABS burn-out process was done for them. The kiln was manually adjusted to hold a temperature of 1000° F-1500° F for at least 5 hours. This successfully vaporizes the plastic hook and foam sprues. Too high of a firing temperature or too long of an exposure can begin to degrade the integrity of the plaster-of-paris mold, causing cracks and fragility.

Casting can begin after the molds cool or while still hot if care is taken to handle the hot molds safely. If the aluminum into poured into a mold well above its melting temperature, cooling can take so long that hydrogen can leak into the alloy and compromise the strength. At the same time, too cold of a mold can cause the aluminum to flash freeze and increase air pockets. The ambient temperature of our kiln, about 120°F, seemed to provide an ideal cooling speed. An UltraFlex Power Technologies UltraMelt ⅘ Induction furnace was used to melt the aluminum alloy students selected as part of their design process. One crucible of either 6061 or A356 aluminum contains enough molten metal to fill two to three hook molds so that the final cast hook was a single non-joined casted part. Students were given the opportunity to pour aluminum into their hook mold provided they were properly attired in safety gear (gloves, sleeves, apron, and a face shield). The mold is then allowed to air cool and the students could then break the mold, remove and clean their hooks. The spruces were cut off and the final hook ground and polished to produce a finished product using traditional shop equipment. The final hook could then be heat treated if desired to produce a higher strength. Students were informed that heat treating aluminum is required for maximum strength, but the specific heat treating methods for the alloy they chose for their hook was left for the students to research. Figure 3 provides a view of a mold prior to kiln firing and a final, sprues removed, polished hook.

Figure 3. Pre-burn-out Mold and Lost 3D Print Casted Hook

Hook evaluations were done as a class. Students delivered a report explaining their design process and choices, along with their SolidWorks testing results and any hand calculations performed along with the hook for testing. A focus was placed on the student explaining which failure theory or theories they applied to predict failure load and location. One at a time, a hook is connected to the testing apparatus. The testing chamber is an eight-foot-long C beam on its side, with a 2-ton come-along and a crane scale attached to either end of the hook with shackles (see Figure 4). The C beam is deep enough to completely encase the hook and shackle so that a plexiglass protective cover could be added over the open top. The students were asked to declare what force they predicted their hook would fail, and where they predicted rupture would occur. The come-along is used to slowly pull the hook until failure. Observers note the force at failure, which is used to calculate the hook efficiency and is compared to the predicted ultimate force included in the student's report.

Figure 4. Hook Strength Evaluation Set-up

2.3 Student Assessment

Students were asked to take a survey regarding the lifting hook project. They were given the following questionnaire:

Criteria: "This project..."	Scale (1-5)
1. Analytical Skills- ...requires logic in solving and analysing problems. Translates academic theory into practical applications	
2. Creative problem Solving- ...allows for many potential solutions to problems. Suggest new approaches to problem solving	
3. Computer Skills- ...uses computer based resources to design and conduct experiments and validate theories.	
4. Systems Thinking- ...guides understanding on how systems interrelate and demonstrates ability to take new information and integrate it with past knowledge.	
5. Teamwork- ...promotes collaboration, the sharing of information, and helps reconcile difference of ideas when they occur.	
6. ...was interesting.	
7. ...helped me understand Mechanics of Materials better.	
Other Comments (Required):	

Note: The scale is as follows: 1 indicates "not at all," 2 indicates "to a limited extent," 3 indicates "to a moderate extent," 4 indicates "to a great extent," and 5 indicates "to a very great extent"

Figure 5. Student Survey Form

3. Results and Discussion

The hooks designed and cast by the students varied in shape, mass, and effectiveness, but two specific hooks are being described in this paper. The first hook shown in Figure 6 takes advantage of the lost 3D casting method ability to create complex shapes easily. SolidWorks could be used to see that the strut cut outs reduced the mass of the hook from .4lb to .35lb, decreasing the maximum force by only a couple hundred pounds thus increasing total efficiency. The second, also shown in Figure 6 is a non-standard lifting hook that meets the requirements while producing a large hook efficiency.

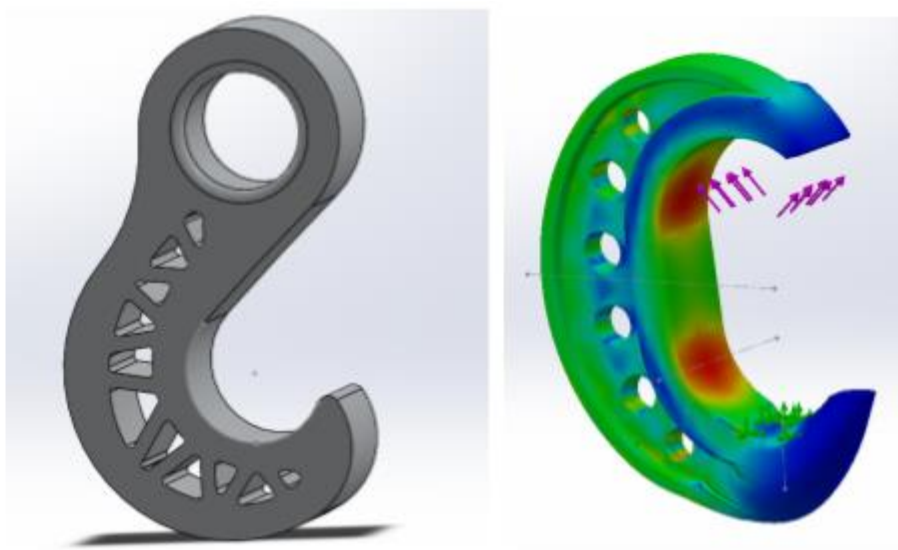

Figure 6. Failure Analysis of Lifting Hook Using SolidWorks

Every group chose to use both hand calculations based on curved beam analysis as well as the SolidWorks simulation suite. Students confirmed that failure happens where stress is maximum. The low ductility of the aluminum alloys chosen made it difficult to identify the best failure theory to apply. This project provided a hands-on experience of the design and evaluation process and reinforced failure theory concepts to ensure conservative design estimates. For example, the hook shown in Figure 7 failed exactly where the FEA simulation predicted.

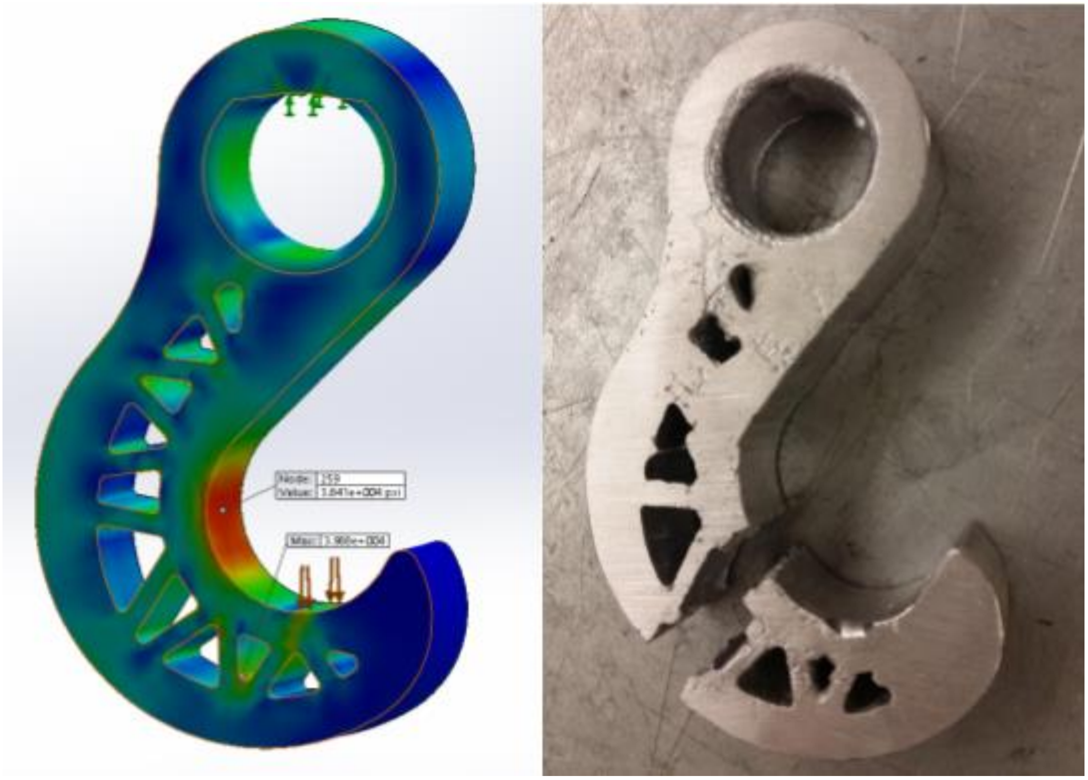

Figure 7. Simulated Failure and Actual Failure of Lifting Hooks

Students were also able to compare the ultimate force calculated by hand and calculated with SolidWorks. In the case of the hook shown above, SolidWorks predicted failure at 2200lb and it actually ruptured at 2400lb. The complex cross section caused inaccurate calculations when the concepts of the course were applied. Consequently, hand calculations inaccurately predicted failure at 8000lb. Students with more traditional hook designs found their calculations to be much more accurate.

The results of the students' survey show that nearly every question was answered with "to a great extent" or "to a very great extent". Table 1 shows the results of the survey. Question 2 and 5 had the largest Variances, due to a student or two that did not agree with the consensus. Both creative problem solving and teamwork are both highly dependent of student effort. For question 7, the students that answered lower tended to be students that tested the best in the class, implying this project was especially helpful for students with a less firm grasp on the subject going into the project. Overall, students agree that the project effectively summed up the class and helped knit together all the concepts a mechanics of materials class focuses on.

Table 1. Result of Student Survey

Question	Average	Variance
1. Analytical Skills- ...requires logic in solving and analysing problems. Translates academic theory into practical applications	4.5	0.4
2. Creative problem Solving- ...allows for many potential solutions to problems. Suggest new approaches to problem solving	4.4	1.9
3. Computer Skills- ...uses computer based resources to design and conduct experiments and validate theories.	4.4	0.9
4. Systems Thinking- ...guides understanding on how systems interrelate and demonstrates ability to take new information and integrate it with past knowledge.	4.1	0.7
5. Teamwork- ...promotes collaboration, the sharing of information, and helps reconcile difference of ideas when they occur.	4.4	1.2
6. ...was interesting.	4.7	0.2
7. ...helped me understand Mechanics of Materials better.	4.3	0.5

One student in particular may have caught the spirit of the project best, commenting, "left as open as it was, the hooks could be almost anything. The theory from class was not as prevalent as in past design projects, but it did not take away from the learning experience." Especially for very complex hook designs, the concepts taught in the course are less useful for finding exact rupture forces, and more for guiding the students to tweak their hook to extract the most strength from their aluminum. The lifting hook project helps give the students a taste of how the knowledge they gained is applied when application results do not line up neatly with the theory. On the whole, not a single student claimed the project did not help their learning and, even if a student felt part of the project could have been different, all felt it was worth their time and helped support the learning in the class.

4. Conclusion

An integrated hands-on experience was developed for a Mechanics of Materials course. The hands-on experience involved the design, manufacture, and test an aluminum lifting hook. The 3D model was designed using CAD and the final product was produced using a lost 3D print casting method called RapidCasting. The students conducted a theoretical analysis of the failure of the lifting hooks and then they loaded their lifting hooks until failure. The students compared the actual load during failure and the estimated failure load. This hands-on activity proved to be a positive learning experience for students.

5. Acknowledgement

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