Board 127: Adding Inexpensive Sand Casting to Mechanical Engineering Capstone – Impacts on Student Inventiveness and Attitude

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Adding Inexpensive Sand-Casting to Mechanical Engineering Capstone – Impacts on Student Inventiveness and Attitude

Introduction

The mechanical engineering capstone course at University of Florida (UF) challenges seniors to combine design and manufacturing skills to produce a working product prototype for a customer external to the course. During the prototyping phase, parts are either purchased off the shelf (OTS) or fabricated using the most appropriate manufacturing methodology available in the Capstone Design Lab (e.g., 3D printing, machining, bending, or water jetting). While desktop additive manufacturing processes can create desired parts in plastic for prototypes, there are many concepts containing complex geometries that need to be made from metal that are best manufactured using more flexible methods, such as metal casting. To avoid high-cost custom manufacturing of complex parts from outside sources, UF's Capstone Design Lab acquired a tabletop casting furnace to be used for manufacturing complex-geometry parts using sand casting. This equipment has cost-saving potential for the capstone projects by reducing machining waste.

This paper's purposes are to 1) provide the necessary background information to fully understand the key elements of metal casting in an engineering Capstone course and 2) document how the availability of in-house sand casting impacts students' design thought process and enjoyment of the course. These goals provide direction for future capstone project curriculum development to exploit the potential of sand casting for prototyping purposes while remaining under safe working conditions in the lab. This process can also lead to a significant cost reduction in the capstone project development and raw material purchase, as metal waste from subtractive manufacturing processes can be recycled to perform casting.

Background & Theory

Sand casting is associated with a limited number of Capstone senior design programs offering bachelor's degrees in Materials Science and Engineering [i]. However, the technique is absent in the mechanical engineering Capstone literature; presumably because it is not used elsewhere to support ME senior design. Some casting examples do exist in ME manufacturing laboratory classes [ii,iii], but predominantly simulation is used in leu of the physical casting process to aid student learning and understanding of underlying phenomena. [iv,v]

To incorporate sand casting applications in an ME Capstone senior design course, we deployed the "Energy Engineering Laboratory Module" (EELM) pedagogy. EELM posits that energy is ubiquitous across all Science, Technology, Engineering, and Mathematics (STEM) curricula, and thus pragmatic energy engineering lab experiences can be spirally inserted into any college or high school STEM course. A growing catalog of EELM examples permeate the literature that demonstrate and share the following characteristics: they are 1) economical, 2) hands-on, and 3) "turnkey". EELM pedagogy has been used to incorporate additive manufacturing into middle school classes [vi]; teach high school biology, chemistry, and physics labs [vii,viii,ix]; demonstrate thermodynamics applications to high schoolers [x,xi]; teach hands-on fluid mechanics classes [xii,xiii,xiv,xv,xvi,xvii]; add gas turbine experiments to thermodynamics classes [xviii,xix,xx,xxi]; and anchor ME Capstone projects in solar concentration [xxii,xxiii], building energy auditing [xxiv,xxv], and waste-to-biogas generation [xxvi].

The EELM connection to sand casting, enabling its spiral insertion into an ME Capstone course, is focus on fluid mechanics and heat transfer. Fluidic characteristics that affect the quality of the final cast part include molten metal fluid viscosity, surface tension, inclusions in the material, and the solidification pattern of the alloy. Another important parameter is time for part solidification so they can be removed from the mold and quenched to obtain the desired microstructure. The solidification time for casting, based in heat transfer fundamentals, is estimated using Chvorinov's rule [xxvii]

$$t_{solidification} = c \cdot \left(\frac{V}{A_s}\right)^n \tag{1}$$

where C is constant depending on the mold material, V is the volume of the cast part, A_s is the surface area of the cast part, and n is the coefficient of cooling which ranges from 1.5 to 2.

Also, while the cast part is undergoing solidification, it experiences shrinking effects caused by the phase change from liquid to solid. Part shrinkage must be accounted for during mold creation to obtain accurate dimensions for the final cast part. Part shrinkage highly depends on the coefficient of expansion and contraction of the material being used in the casting. For instance, Aluminum has a contraction percentage of 7.1%, meaning that the part will shrink about that same percentage during the solidification phase.

Methods - Pedagogy

UF's ME Capstone design course has implemented several innovative pedagogical best practices arising from being a low-resourced, high enrollment two-semester program with both an on-paper design component and a build-realization component.[xxviii] Innovations include 1) a sophisticated Qualtrics-based peer evaluation system [xxix], 2) implementation of an Open Educational Resource (OER) mechanical engineering design textbook [xxx], 3) use of SolidWorks Project Data Management software for CAD administration [xxxi], and use of online presentation environments to accommodate large numbers of panelists at final oral presentations [xxxii]. Addition of sand casting capability to the course to complement the conventional machining already available is another innovation to expand student learning and utility of the course as preparation for professional practice.

The Summer 2022, a new benchtop sand casting capability was introduced to UF's ME Capstone senior design course. The class had an enrollment of 13 students broken into a team of 7 and one of 6. Both student teams worked with the same Customer Needs Statement to build a sun-tracking 1 m^2 reflecting heliostat for sunlight focus and concentration to a 1 m^2 collector target atop a 100-meter-tall tower for power generation. Each team built a single working prototype unit of its unique sun tracking heliostat design with understanding that ~2,000 identical units would be mass produced in the future to meet the solar power plant's needs.

From the outset, students were informed of the availability in lab of a Quickmelt tabletop furnace allowing small parts to be sand cast. The foundry's capabilities were demonstrated in class by the Teaching Team. Student teams were not required to use this capability for their build process. Both Capstone groups initially elected to cast parts. One group was successful in casting viable parts but the second was not successful, and they decided to abandon the technique early on in the course in lieu of more conventional Capstone fabrication methods. This dichotomy set up a natural experiment enabling comparison of the two teams' attitudes toward casting given that they were otherwise subjected to near-identical scholastic expectations, constants, and conditions within the course.

At the end of the semester, students were assigned via the Canvas Learning Management System an extra credit assignment consisting of five open-ended self-reflection questions concerning casting. Of the 13 enrolled students, 9 (69.3%) answered the questions, and they were awarded full extra credit regardless of the content provided. These 9 students include 6 of 7 students from the group that used casting responded along with 3 of 6 students from the group electing not to cast. The questions were as follows:

1. Comment on how sand casting capability in Capstone influenced your design thinking.

2. Describe how using sand casting in Capstone helped connect the course with other ME disciplines (e.g., manufacturing & heat transfer).

3. Explain how ability to cast parts yourself (not watching someone else or a video but doing it yourself) enhanced understanding of the casting process.

4. Did sand casting improve your enjoyment of the Capstone course? Explain your answer.

5. Did sand casting in Capstone improve your efficacy as an engineer? Explain your answer.

Once responses were collected, answers were made anonymous to protect student identity. After the course concluded and grades were conferred, a member of the Capstone Teaching Team (and co-author of this paper) read all the responses, coded them to categorize students' answers, and categorized the results for analysis.

Each sentence written by a student in their response was evaluated individually by the coder to ascertain whether it included a substantive and relevant comment. If a sentence was deemed substantive, the comment was color-coded with similar ideas coded with similar colors to facilitate a qualitative bunching together. After several read-throughs of all the answers, they were categorized into six major categories emerged through a process of subjective classification and consolidation, including tangible benefits, curriculum connection, improved understanding, enhanced enjoyment, effect on product and negative comments. Once this process was complete, a second evaluator reviewed the categorization to verify validity of the sentence coding.

Methods - Casting Procedure

The Capstone Design lab was equipped with a Quickmelt tabletop furnace that allowed metal parts to be sand cast. During the Summer 2022 semester, this equipment was used to cast various objects to teach Capstone students best practices for quality parts to be cast in a safe and controlled environment. In this section, the detailed casting process for educational labs is described.

Safety – General

Casting safety protocols are the most critical aspect of this operation. General lab safety guidelines include wearing long pants and closed-toe shoes. A lab staff member should always be present when this process is performed. The mold generation process involves oily sand particles that end up coating most of the mold frame surroundings; so, safety goggles and gloves are constantly required in the casting lab.

Safety – Furnace Setup & Liquid Metal Pouring

To protect the furnace operator and anyone surrounding the equipment, face shields and leather gloves are always required during equipment setup. The equipment's temperature reaches over 2000 °F, representing enormous danger if safety measures are not followed correctly.

Before turning the furnace on, the operator and anyone within 6 feet of the area needs to be fully protected with high-temperature Personal Protection Equipment (PPE): 1) a leather jacket covering the torso and arms, 2) a leather apron covering the torso and legs at least until the knees, 3) leather gloves placed over the jacket sleeves fully covering the hands, 4) foot protectors enclosing all the front side of the shoe and the lower part of the legs, and 5) a visor protecting the entire face. Figure 1 shows the minimum equipment required to perform casting in the lab.

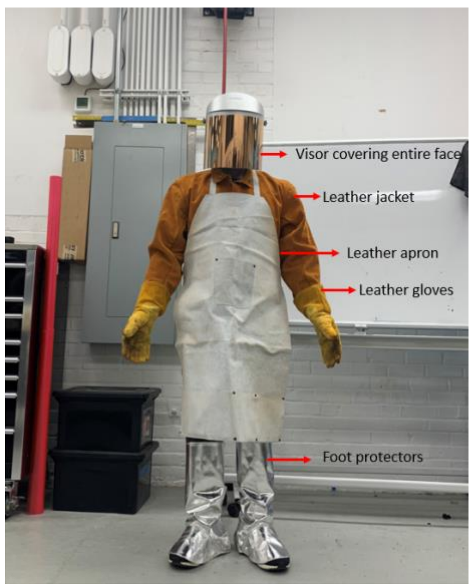


Fig. 1 Minimum high-heat PPE equipment required for in-lab casting.

In addition, tongs are required to handle the hot crucible, and a graphite stirring rod is needed to mix the slurry. Even though the leather gloves provide high-temperature protection, they will get hot when in contact with high-temperature objects, such as the furnace handle. Very short leather glove contact with hot objects represents no harm to the operator, but longer contact transfers heat through the gloves and will burn the skin. Under no circumstances should the crucible or molten metal be in contact with any of the PPE equipment used.

Safety – Cast Part Handling

High-temperature PPE can only be removed after the furnace has cooled down, the sand mold has been opened, and the cast part has been quenched for at least 10 minutes. After the final part is quenched for 10 minutes, it can be handled with minimum PPE. In addition, part features can be sharp. So, post-manufacturing de-burring must be completed before parts can be safely handled.

Sample Part Creation

The initial step is creating a mold that represents the desired final cast part. This part will be referred to as the "pattern". Prusa i3 MK3S+ is used to print the pattern. Although 3D printing allows the creation of complex geometries, it is important to consider the limitation of mold creation when 3D printing the sample part. Too small features are difficult to be transferred to the sand mold, and they are lost during the metal pouring process. After various attempts to create and mold the final casting part, it was found that only features greater than 5 mm in depth are possible. Additionally, most internal part features must be machined using post-manufacturing methods as casting inserts are not available in the lab. The sample part created by the group electing to proceed with casting, shown in Fig. 2, depicts an internal feature (hole) that is machined using post-casting processes in a lathe.

Fig. 2 Sample part modeling and removal feature with pin attachment.

When 3D printing the sample part, print layers are visible in the part surface as shown in Fig. 3, which causes sand particles to adhere to these layers. To minimize this phenomenon, printing settings for the sample part were set at a layer height of 0.1 mm. When working with small and detailed features, surface treating the sample part before creating the mold is recommended; for instance, sanding the surface smooth. Best results were obtained when sanding the PLA sample part with 120J-CTC-Aluminum Oxide sanding paper until no clear visible printing lines were observed.

Fig. 3 Sample part filament printing layer lines.

Mold Creation

Once the pattern is printed and its surface treated to achieve the desired finish, the green sand mold can be created. The equipment needed, shown in Fig. 4, includes 1) the pattern, 2) a cast-iron mold frame, 3) Petrobond sand, 4) parting powder, 5) gloves, 5) a compression tool, and 6) a hard flat surface.

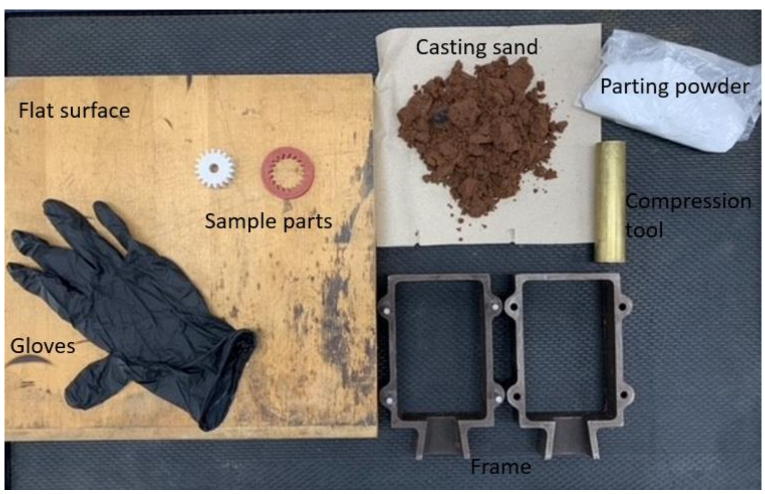


Fig. 4 Parts needed for sand mold generation.

The parting face of the mold frame needs to be placed flat. When the mold is completed, the part cavity (core) should be aligned with the parting line of the mold frame, and the external faces of the mold should be fully covered with sand. The sample part must be coated with parting powder, and powder should be distributed across the flat surface inside the mold frame area to provide a release agent layer, Fig. 5 (Step 1).

Because Petrobond sand is a wet mixture, it forms lumps which can cause excessive air gaps in the mold. These gaps are not visible. However, it may distort the final product geometry. After multiple mold attempts, it was found that using the finest sand around the sample part can reduce the air gaps and generate the strongest bond between the particles. These bonds are essential when removing the sample part to retain desired fine features in the mold. To eliminate lumps, the sand was sifted using a kitchen strainer to create a fine mixture.

Once the sample part is fully covered with fine sand, as shown in Fig. 5 (Step 2), sand compression is performed around the entire sample part and mold frame's interior. This can be done using gloved fingers first, then other tools such as a round stock to apply greater forces to the sand and compress it further. To finalize this process, the mold needs to be fully filled with compressed sand, represented by Fig. 5 (Step 3), and leveled to obtain a flat surface at the opposite end of the sample part, Fig. 5 (Step 4). If this process is performed correctly, the sand mold will hold the sample part in place and its area will be tightly filled with sand, as shown in Fig. 6.

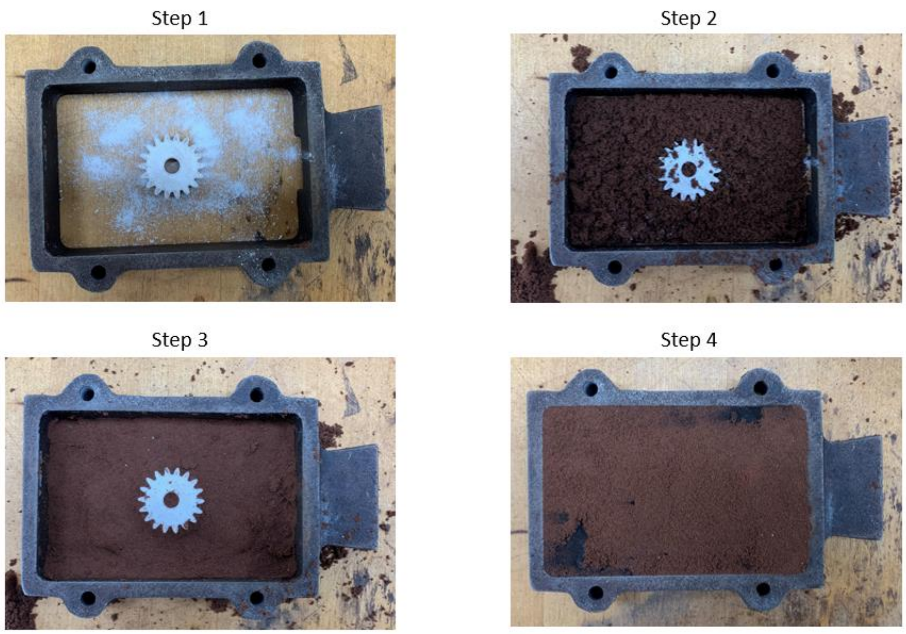


Fig. 5 Sand mold generation process.

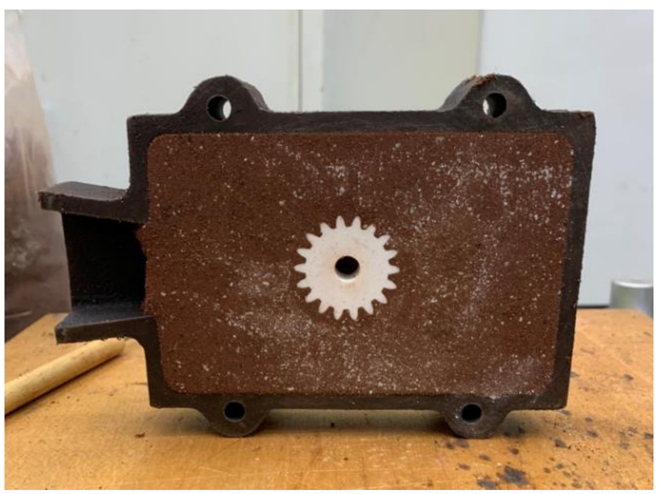


Fig. 6 Completed sand mold with sample part in place.

After one side of mode is created, the other half can be easily done by filling inside area with sand and compressed until solid. For a pattern with different sized cross sections, it is recommended to split the part into uniform cross-sections and place one on each side of the mold. Alignment pins could be used to help aligning them correctly when combining the top and bottom sides of the mold. An example of a variable cross section part that could made using this approach is shown in Fig. 7. The side with the gear teeth should be molded in one end of the mold, preferably the bottom, while the shaft of the gear should be molded on the top frame.

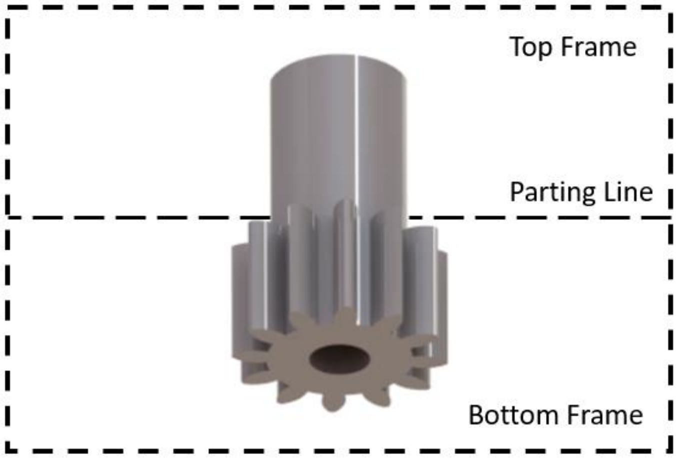
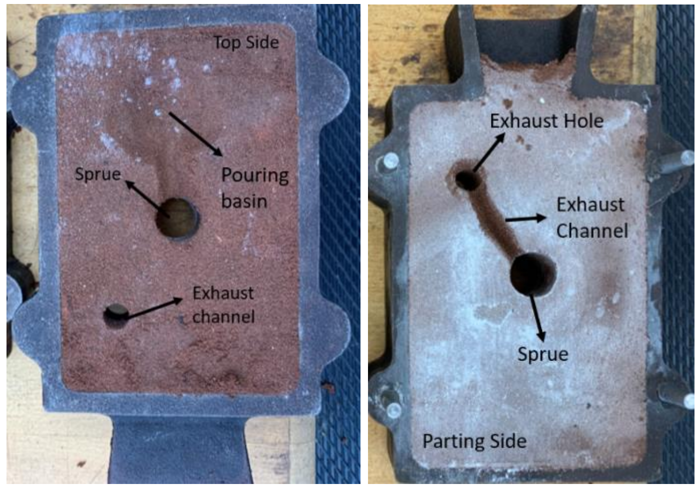


Fig. 7 Sample part to mold using both ends of the mold frame.

It is recommended to create the mold molten metal flow features before removing the pattern to avoid damaging the mold cavity. A sprue is a tapered channel from the top of the mold from which the molten metal flows into the mold parting section. To produce the sprue, the two mold frames are placed together and the specific location where the molten metal will flow through is identified. Using this reference location, a hole through the sand is created on the top frame where the molten metal will be introduced. Additionally, creating the pouring basin on the side of the sprue provides a pouring management system that prevents the molten metal from falling directly into the cavity of the mold where it could damage features preserved in the sand. The sprue channel and the pouring basin feature are represented in Fig. 8a. They are located at the opposite face of the parting line of the top frame mold. Also using the sprue channel created at the parting side of the top frame, an exhaust runner must be carved along with another through hole located outside the sample part area. This vent allows exhaust gasses to leave the mold and avoids air pockets forming inside the cast part. The exhaust vent features can be seen in Fig. 8b.



(a) (b)

Fig. 8 Top mold frame pouring and exhaust features.

Once the top mold frame is finalized and ready for casting, the last mold preparation step is removing the pattern from the sand mold. This generates the cavity for the molten metal to take the shape of the pattern. This step is the most challenging, as it is the primary definer for the quality of the cast. We used the negative side of the pattern as a guide on the surface of the mold to hold the sand features in place while removing the pattern from the mold. A free body diagram (Fig. 9) reveals the physics behind the methodology.

Trial-and-error revealed the shrinkage scaling factor of the negative sample part was 6-7% for aluminum. The scaling factor is essential for the negative part, as casting at the same dimensions introduces interference between the parts that does not allow removal from the mold. This interference is produced by the tolerance of the 3D printers and the contraction of the plastic after being melted on the nozzle of the printer.

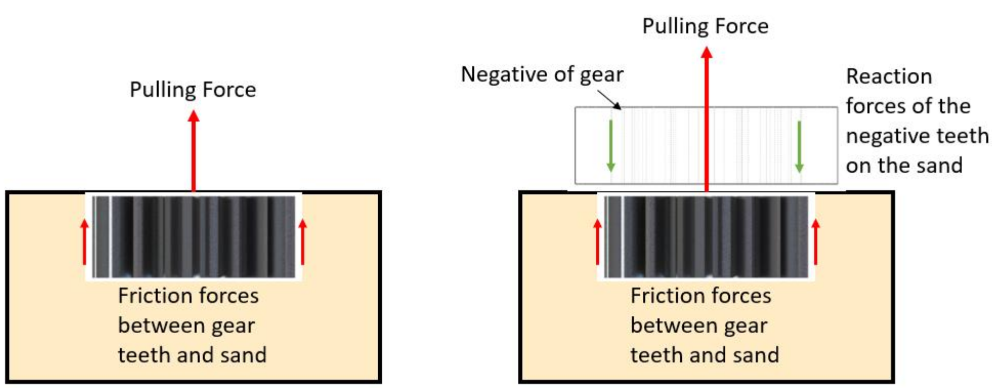


Fig. 9 Free body diagram of both sample part removing methodologies.

Applying the necessary support on the negative of the sample part generated the mold used for the first gear cast in the lab (Fig. 10). Note the mark left by the negative sample part.

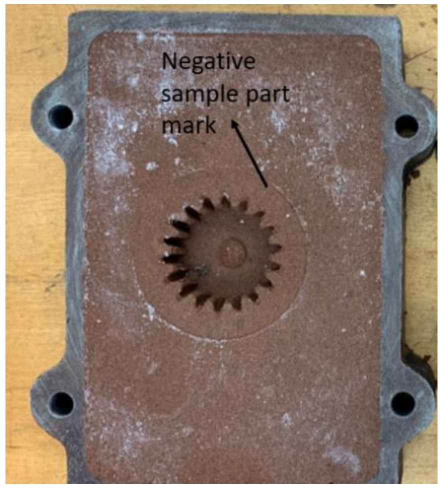
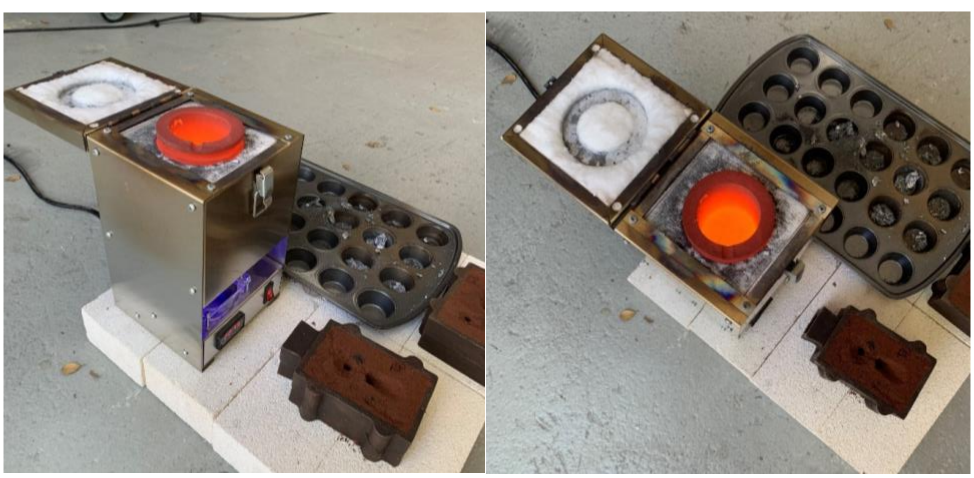


Fig. 10 Gear sand mold generated using the negative sample part for support.

Furnace equipment and guidelines

UF's ME Capstone Design lab is equipped with a Quickmelt Pro 120 furnace available from the Tabletop Furnace Company ($599 at time of publication). This equipment provides 1500 watts of power, rapid heating over 2200 F, and graphite crucible attachments for multiple volumes required [xxxiii]. The material used for the Capstone casting process was Aluminum 6061. After the furnace reaches steady state, the crucible glows bright red and the metal inside is fully liquified (Fig. 11a). If the raw material has impurities, these emerge as slag at the top of the crucible, and they can be removed, fished out, with the graphite stirring rod. If the process is done correctly, the molten metal should look like a bubble of aluminum inside the crucible, which will create a viscous layer at the top (beginning of solidification) if the lid of the furnace remains open for extensive periods, as shown in Fig. 11b.



(a) (b)

Fig. 11 Powered furnace with molten Aluminum inside.

With the casting aluminum fully liquified, the molten metal is quickly poured into the pouring basin created at the sand mold's top face. This area in the mold allows the metal to flow slowly into the sprue, creating a laminar flow into the cavity. Laminar flow is beneficial for mold filling as it does not produce eddies that could disturb the sand in the mold. The mold is filled until molten metal can be seen emerging from the sprue and/or the exhaust channel, meaning that the core was filled with metal.

After pouring is complete, the empty crucible should be placed back in the furnace for the final cool-down or to begin the process of melting metal again. Cool down time should be calculated using Chvorinov's rule, Eq. 1, with a factor of safety. Once the part is solidified, the mold frame is removed. Tongs can be used to separate the mold at the parting line, and the solidified cast part is removed from the sand. Next, the cast part can be submerged in cold water to initiate the quenching process until fully cool it down to room temperature. Parts must reach room temperature inside before any post-manufacturing processes occur.

Results - Final Cast Parts

One of the two Capstone groups in the Summer 2022 senior design class required customized planetary gears with a 4:1 reduction to facilitate axial motion of their heliostat. The outer gear housing was fabricated via waterjet cutting, but the inner gears themselves were not available commercially and could not be fabricated in-house via conventional machining processes. This group were thus highly motivated to sand cast the planetary gears. So, this group followed the above-outlined process to make their gears, and the results can be seen in Fig. 12.

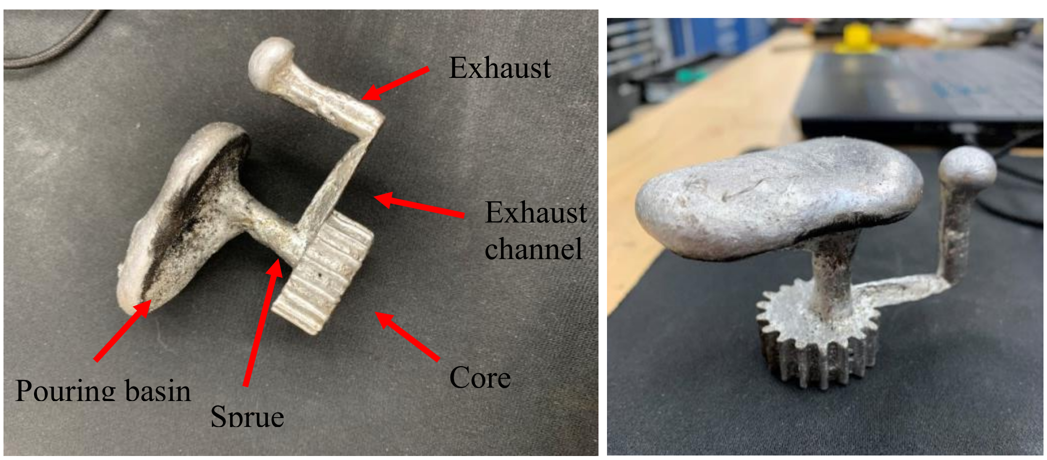


Fig. 12 Final cast part detailing mold features.

Additionally, the multiple cast gears are compared based on the various detail methods used. In Fig. 13 the first cast gear (left) has big deformations due to the low compression of the sand mold around the teeth. This issue was resolved by following the step of adding fine sand to the mold and compressing it with fingers before adding the rest of the sand. The second cast gear (middle) was created using a mold with no pouring basin. The gear developed an air bubble inside its structure that was not visible until post-manufacturing processes were completed. To avoid this issue the mold should contain all the previously mentioned characteristics and the liquid metal should flow under laminar conditions when filling the mold core. Lastly, the third cast gear (right) was created following every step of the procedure described above. It is the most accurate representation of a final product, which validates the procedure described above.

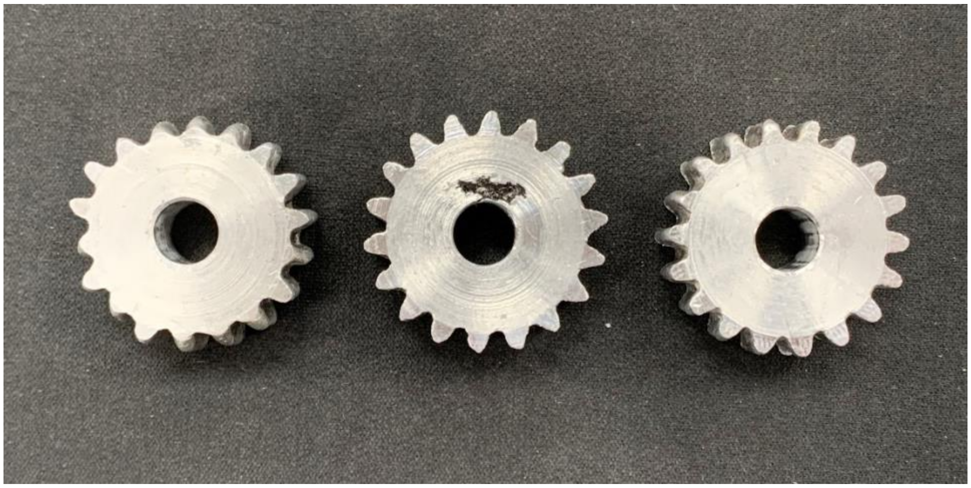


Fig. 13 Final cast gears using multiple methods to define their final characteristics.

Figure 14 shows the final planetary gear assembly with the cast gears in this project in conjunction with a ring gear manufactured using waterjet cutting.

Fig. 14 Cast gears used in a planetary gear set for the capstone project.

Results - Pedological

Collected anonymous student answers to extra credit survey questions described above were coded by a Teaching Team member to categorize students' answers. In general student comments about casting fell into six major categories: 1) Tangible benefits of casting, 2) Connections to other courses in the ME curriculum, 3) Improved understanding of the casting process, 4) Enhanced enjoyment of the class, 5) Casting availability impact on design thinking, and 6) Negative comments. Of the 67 total unique comments made by the 9 students who completed the voluntary survey questions, 55 were positive and 12 were negative. Figure 15 summarizes and quantifies the count of specific answers identified as fitting into each category.

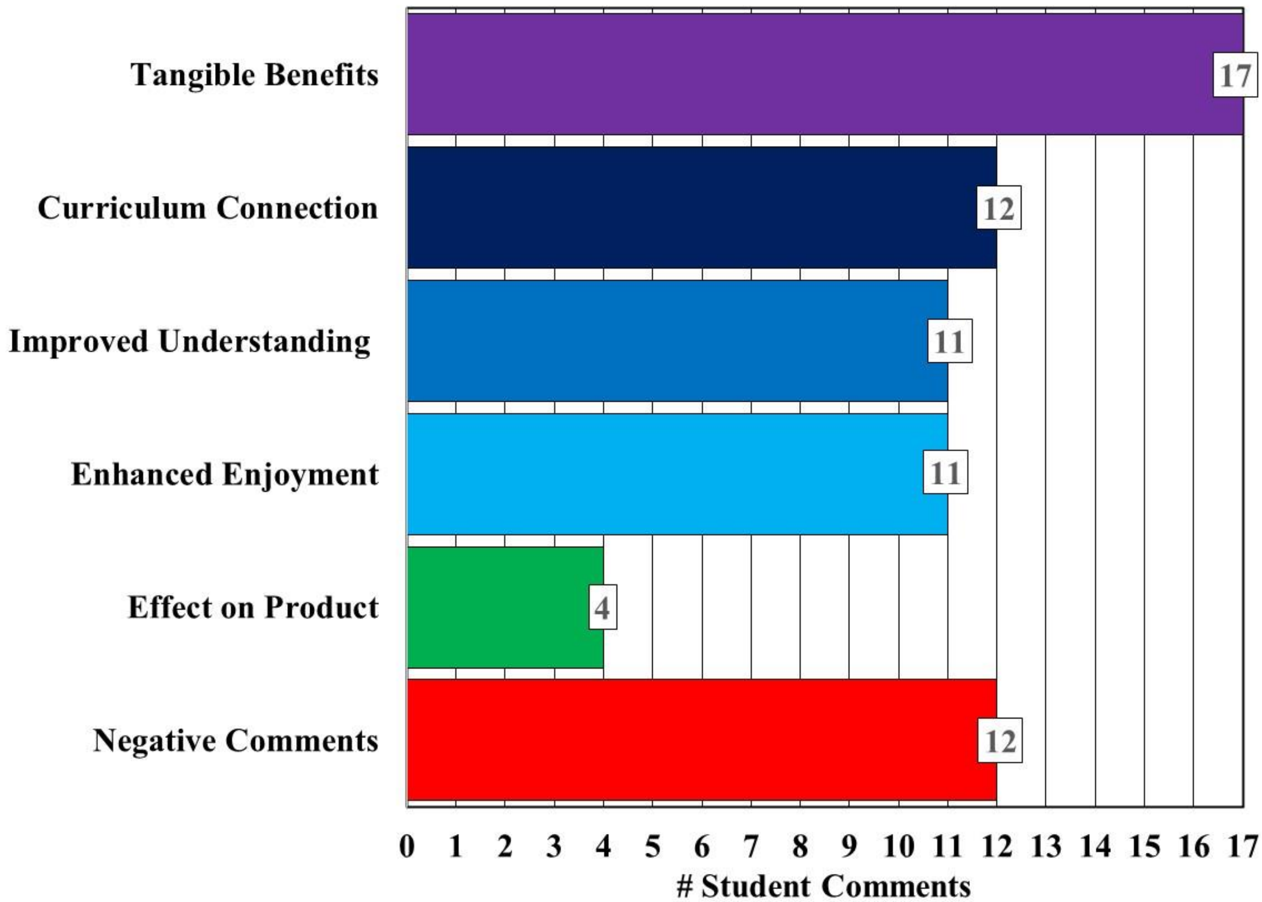


Fig. 15 Student response results reflecting attitudes on sand casting in Capstone.

With respect to the 12 total negative comments there was a distinct disparity between students from the group that successfully cast gears and the group that did not pursue casting. On average the group that succeeded in casting made 0.83 negative comments per student survey response while the group electing not to cast made 2.33 negative comments per student. Negative comments from the successful casting group focused on detail-level issues with the process itself such as poor dimensional accuracy or difficulty releasing the pattern from the sand mold while preserving small features. For example, one student said,

“The casting failed several times because the friction between the sand and the gear was too big.”

By contrast negative comments from the group that did not employ sand casting viewed the process from a larger perfective of being inadequate to form the part geometry they sought. For example, one student said,

“Using sand casting to make worm gears is totally impossible because we can’t make worm gear-shaped sand molds; otherwise, the gears would still be too rough and discontinuous.”

The most numerous type of positive comments were centered on the tangible benefits of sand casting. There were 17 of these comments with the highest clusters surrounding cost savings (5 total comments) and process capability (5 total comments). Other mentioned benefits were possibility to reduce or recycle waste, ability to make metal parts for material variety and temperature endurance, and process speed. On average the group that succeeded in casting made 1.5 benefits-related comments per student while the non-casting group made 2.67 comments per student. It was interesting to note that despite not incorporating casting into their build process, the latter group illuminated more benefits per student than the team that employed casting. A student from the group that did not cast said,

"Sand casting is great for small complex geometry parts that would require significant material removal if those parts were machined."

Similarly, a student from the group that did cast said,

"Casting in the class can help in manufacturing parts that are easier to cast than machine, which opens possibilities to pursue different designs."

There were 12 total unique mentions in the student survey comments of how sand casting in Capstone connected the class to other courses in the ME curriculum. Table 1 gives the names of each class mentioned and the number of mentions in the complete survey data set.

Table 1: Student ME Curriculum Connections

ME Course	# Comments
Manufacturing	6
Material Science	3
Heat Transfer	2
Thermodynamics	1

There were 11 comments in the student survey responses related to how pragmatic application of sand casting in Capstone improved their understanding of this manufacturing technique itself. Most notable among comments of this type was the variety comments illuminating detailed understanding arising from carrying out the process themselves. Understandably 10 out of the 11 comments of this genre came from the group that performed sand casting while only 1 comment arose from those who did not. Comments described new understanding of the following details (with # of mentions in parentheses):

A. Casting limitations and capabilities (3)
B. General process steps/sequence (2)
C. Choice of equipment and materials (1)
D. Safety considerations (1)
E. Mold creation (1)
F. Pattern removal techniques (1)
G. Time required to cast parts (1)
H. Slag removal (1)

Enhanced student enjoyment also was mentioned 11 times, and interestingly this topic was also more intensely represented among the students who did not cast (2.00 mentions per students) than those who did (0.83 mentions per student). The majority of these comments reflected the students' appreciation of learning through pragmatic, hands-on experience and the opportunity to learn and test new skills. For example, a student from the casting group said,

"Putting processes in practice is one of the best ways to learn and master a subject."

Similarly, a student from the non-casting group said,

"Most of our classes are theoretical and we rarely have the opportunity to make parts; sand casting not only expands our creative ideas but also enriches our experience."

Finally, there was a small set of four student survey responses addressing how availability of casting in Capstone impacted the engineering design process. A representative comment of this type from a student who participated in casting was: "Having the ability to sand cast parts in senior design affected my design thinking by allowing me to be more creative when we needed very specific parts. We could allow ourselves more flexibility in the design because we knew that custom parts could be made through casting."

Discussion

Is there pedagogical value in incorporating benchtop sand casting into ME Capstone as a general best practice? Thanks to application of EELM pedagogy, casting capability can be spirally inserted into a Capstone lab for less than $1,000 using the equipment and protocol outlined here, which puts the process cost on-par with adding a hobby-scale 3D printer or an entry-level tabletop manual milling machine to a Capstone shop. For comparison, at time of publication, a Prusa MK4 3D printer costs $1,099 [xxxiv], and a SIEG X2D Mini Mill costs $999 [xxxv].

This study included a very small sample size (9 survey responses) and lacked direct results (e.g., course assessments) to corroborate student self-reported indirect evidence collected through surveys. So, discussion and conclusion drawn can only be categorized as preliminary. Nonetheless, this student produced a preponderance of positive student comments (67) about casting in Capstone that far outweighs negative comments (12). Plus, there was a general tendency for students from the group that did not perform casting to describe the technique and opportunity to learn about it as favorably or even more favorably than the group that performed casting.

This evidence, through circumstantial and anecdotal suggests that adding casting to Capstone is at least equally beneficial to student learning and enjoyment as adding a conventional subtractive fabrication capability like machining or an additive capability like 3D printing. It is also instructive to examine in more detail juxtaposition of topical areas students described in answering the survey questions with anecdotal observations about their design process.

Tangible Casting Benefits vs. Effect on Product/Process

Students recognized the cost benefit to their project and to the class in general (via machining tailings recycling) of including a casting capability in Capstone. There were 17 such comments, the most of any category. By contrast, however, students were nearly silent on how access to casting impacted their creativity, design process, and the end product with only 4 comments of this type. This outcome was surprising to the authors as we believed the trend would be reversed; that availability of casting would encourage much more design creativity in Capstone where different thinking is valued highly. A student from the group that did not cast even stated "our initial problem was manufacturing a torque transmission mechanism… and sand casting would have enabled us making those parts." Yet as seem in the comments above, this group became fixated on a worm drive gear torque multiplier that ultimately was not viable to cast.

Even the group that did perform casting made an unusual decision to cast a set of gears when a variety of OTS gears are available. In examining their design process, this group settled on a planetary gear torque converter and let design considerations other than manufacturing drive the dimensions of its components. When they finally focused on internal gear design and dimensions, it was determined no OTS gear was available with the correct diameter and pitch to satisfy all other constraints. So, (in the words of a student) they "could allow ourselves more flexibility in the design because we knew that custom parts could be made through casting." However, this thinking aligns with the classic design fallacy of Maslow's Hammer [[xxxvi]]: "it is tempting if the only tool you have is a hammer to treat everything as if it were a nail." In other words, the most constrained and difficult to fabricate part of this subsystem design was the internal planetary gears and this group over-constrained everything else about this subsystem then vested faith in ability to sand cast this difficult gear to rescue themselves from a poor design process. A better approach would have been to find a viable OTS gear and design the rest of the planetary torque converter around that OTS part. This fallacy was pointed out to the group by the Teaching Team early enough in their process to give them time to change course. However, they fell prey to an additional thought distorting phenomena, the Sunken Cost Fallacy. Having invested so much time in learning about casting gears, designing and 3D printing viable patterns, and figuring out how to release gears from sand cast molds the group felt it impossible to change direction. Ultimately casting should have been applied to make custom parts that were neither available OTS nor easy to machine. So, in this respect, introducing casting to Capstone proved detrimental to the student's design process by making them more susceptible to common pitfalls in the design process.

Improved Understanding vs. Enhanced Enjoyment

Another surprising juxtaposition illuminated by this study and anecdotal observation was the prevalence of comments concerning the impact of hands-on experience as a learning modality versus the impact of pragmatic experiences on student learning. At UF, the Manufacturing course is effectively a prerequisite to the Capstone build course as it is a co-requisite to the Capstone preregister. Therefore, students should have taken Manufacturing prior to Capstone and should be familiar with the steps, capabilities and limitations of the casting process as a result. According to their survey responses, they do not possess this knowledge since they are learning it in Capstone! Perhaps the reason they do not come to Capstone with this knowledge is UF's ME manufacturing course is theoretical survey of fabrication techniques, and it does not have a lab component. Repeating a student comment from above, "most of our classes are theoretical and we rarely have the opportunity to make parts." Thus, by adding casting, Capstone becomes the de facto manufacturing laboratory course that should exist in the ME curriculum but does not. We observe a similar phenomenon with mechatronics knowledge; since there is no UF ME mechanics course, Capstone includes an entire module in DC motor, stepper motor, and servo motor control. This module provides students the hands-on skill set needed to create functional mechanical engineering prototypes that move as they do not learn it elsewhere in the curriculum.

Interestingly, students report enhanced course enjoyment fostered by the opportunity to learn new skills. So, it is positive that they do learn these skills somewhere in the curriculum and through hands-on application in Capstone rather than a pure theory-based exposure. It is, however, worrisome that they are having these experiences for the first time in Capstone rather than learning in a prerequisite course, bringing those skills into Capstone, and using the pragmatic experience of designing a new product to continue practicing and mastering those skills. So, as with the Maslow's Hammer fallacy illuminated above, having casting capability in Capstone is generally positive, but it does exacerbate a systemic problem in a curriculum that does not teach or emphasize casting prior to Capstone by providing a first exposure to this manufacturing technique when students should come to class already knowing it and developing the experience of using it in a more complex, rich, and integrated way than simply casting gears.

Conclusion

Casting is a manufacturing process that allows creation of part geometries in metal that could be costly, complicated, or impossible to machine otherwise. Adding a benchtop casting capability to mechanical engineering Capstone senior design can be accomplished safely in a conventional teaching laboratory environment for less than $1,000 – about the cost of a high-end hobby-scale 3D printer. The capability to create sand casted parts greatly expands students' design thinking in ME Capstone, allowing them to imagine designs that contain metallic parts that could only previously be made in-house through an additive 3D-printing process in plastic. In the case of UF's summer 2022 Capstone course, availability of casting enabled one Capstone group to fabricate a metal planetary gear system for a heliostat. In this case, plastic gears were not strong enough to bear imposed loads, and a hobbing rig (the conventional metal gear manufacture process) was unavailable.

After various casting attempts, a detailed procedure for in-lab benchtop casting was develop and is provided in this paper. This procedure covers safety consideration, creating a sample part using 3D printing, sand mold creation, furnace equipment setup, and the metal pouring process. Representations of the resulting cast gears created with the lab equipment was shown along with discovered failure modes and explanations and recommendations to mitigate them. With this information, mechanical engineering Capstone instructors beyond UF can successfully cast parts for use in their institution's Capstone courses.

An interesting benefit discovered during the process of developing this casting protocol for Capstone using waste material from complimentary machine shop manufacturing methods as feedstock to produce final cast products. Waste material can be melted in the furnace and used to produce more cast parts. If implemented, this recycling process could reduce aluminum chip waste produced in educational machine shops and make drive casting feedstock cost to zero.

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