AC 2011-541: A METAL CASTING LABORATORY EXERCISE: COLLABORATION BETWEEN THE ENGINEERING AND ART DEPARTMENTS AT TEXAS A&M UNIVERSITY - CORPUS CHRISTI

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A Metal Casting Laboratory Exercise: Collaboration between the Engineering and Art Departments at Texas A&M University-Corpus Christi

Abstract

A metal casting laboratory experiment part of a Manufacturing Processes engineering class is described. Students working in teams design and fabricate expendable patterns according to specifications, perform evaporative full-mold casting of aluminum, and analyze the quality and strength of the castings obtained. This hands-on experience is offered jointly with the Art Department at Texas A&M University-Corpus Christi, which operates a small foundry for their own use. Graduate students majoring in sculpture, who routinely perform metal casting of their work, provided the support and shared their experience with the engineering students in a collaborative environment. Student opinions of the lab experience as determined through anonymous surveys are presented, and ways to improve the lab based on this feedback are discussed.

Introduction

Although there is a steady trend in recent years to outsource manufacturing jobs to countries with lower labor costs, it remains important for American engineering programs to adequately train students in the areas of Materials and Manufacturing. Even if produced elsewhere, the cost, quality and speed to market are not guaranteed unless products are designed for both functionality and manufacturability by engineers trained to work in a team environment[1,2].

This paper describes one of the laboratory experiments developed for the Manufacturing Processes class in the Mechanical Engineering Program at Texas A&M University-Corpus Christi. This four-credit-hour junior-level course is offered along with the following four laboratory experiments:

1) Aluminum casting of multiple parts shaped as tensile testing specimens: Students evaluate the quality of these parts through visual inspection and destructive testing. This is the most involved experiment of all four and the main subject of this paper, performed over a period of five laboratory meetings.

2) Machining of two aluminum parts that must be press-fit together: This exercise requires students to fabricate one square plate having a large central hole in the middle and four assembly holes at the corners. A second part, turned on a lathe, has a section that assembles with the plate. As they fabricate the parts, students must ensure that certain calculated tolerances are attained so that the assembly fits properly on the test rig, and is capable of holding a given applied torque (Figure 1). Students work on this assignment over a period of four lab meetings.

3) Designing and turning of a part on a numerically controlled lathe: In this assignment students design a part that requires revolution, and then turn the part on a miniature CNC lathe (Figure 2). This lab experiment is performed by students in parallel with laboratory assignment number 2.

4) Designing and building a small size sheet-metal box: Following the example of an industrial grade metal circuit box, students design and fabricate one of their own using aluminum sheet metal. This is a three-hour assignment, and it is performed only if time permits.

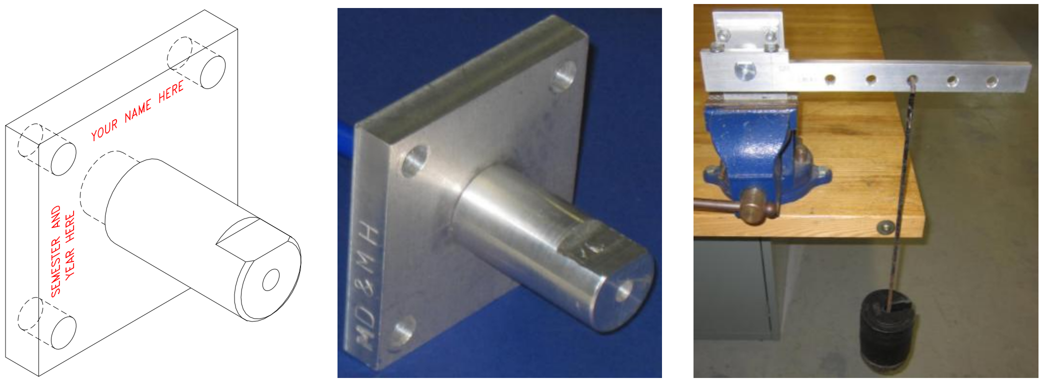


Figure 1: Laboratory assignment requiring milling, turning and tight tolerance control for the press-fit assembly to sustain a given applied torque.

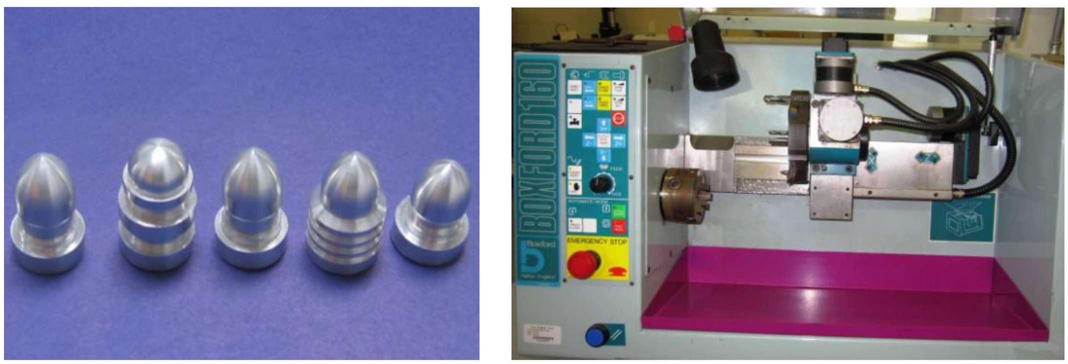


Figure 2: Various parts designed and machined by students on a Boxford miniature CNC lathe [3].

For each of these assignments students work in teams of two-to-three members, and document their laboratory experience and their observations upon the results obtained in formal technical reports. The grades students receive are based on (a) the technical content of their reports, (b) the overall quality of the parts they fabricate, and (c) their individual contribution to the team assignment, assessed through anonymous peer reviews as described in reference [4].

The Evaporative-Pattern Process

Annually over 11 million tons of metal are cast worldwide, mainly for the automotive, aerospace and household appliance markets[5]. Of these, over 8% are cast by the evaporative-pattern process[5] (Figure 3). Specific to this casting method is the use of a pattern glued with pre-made pouring basins, runners, and risers all made from a material (usually polystyrene) that evaporates when the molten metal is poured in. Two such major casting processes are known, namely, the *lost-foam casting* and the *full-mold casting* process[1,6]. In the lost-foam process, the pattern is placed into a flask and then is backed up with dry, unbonded sand. In the full-mold casting process, bonded sand (also known as green sand) is used instead. To prevent sand wash, improve the surface finish of the castings and control the mold permeability, in industry the foam pattern is coated with a thin layer of ceramic investment (Figure 3-b), a step currently not implemented in the lab experiment described in this paper.

(a) (b) (c)

Figure 3: Assembly of a three part foam pattern (a), pattern being coated with ceramic investment (b) and finished part (c) [6].

The evaporative-pattern process is particularly advantageous for complex castings that would otherwise require cores. This process is dimensionally accurate, maintains an excellent surface finish, requires no draft, and has no parting lines, so no flash is formed. It is less expensive than *investment casting* because it is a simpler process, and the cost of foam is less than that of wax. Risers are not usually required because the first metal flowing into the mold that gives away the heat to vaporize the foam cools more quickly than the rest, thus resulting in natural directional solidification. Because foam is easy to manipulate, carve and glue, components that would otherwise require assembling from multiple parts can be consolidated into one integral piece. The main disadvantages of the lost foam processes are that the patterns are expensive to make unless formed in a die, which, in turn, come in with a large initial cost. In addition, while being packed in sand, the foam can easily be damaged or distorted due to its low strength[2,6].

Description of the Evaporative Full-Mold Casting Experiment

The purpose of this lab experiment is to provide students with a hands-on exercise on evaporative pattern mold design, molten aluminum gravitational pour, and quality and strength evaluation of the parts cast. In the process students observe the safety rules associated with a foundry environment, watch trained personnel operate foundry equipment and perform basic foundry operations. According to the lab proceedings handed out at the beginning of their first meeting (see Appendix), specimens with the dimensions in Figure 4 are to be cast in aluminum clustered at least three parts together, using the full-mold casting process. Students working in groups of two or three begin by cutting the patterns, sprues, runners and gates that will be assembled together from Styrofoam material using a band saw and utility knives. For convenience they use commercially available foam coffee cups as pouring basins. All these components are glued together as shown in Figure 5-a.

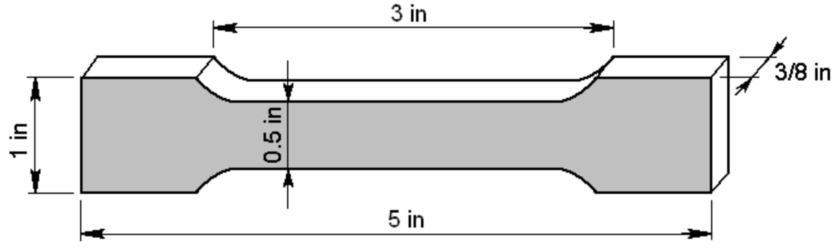
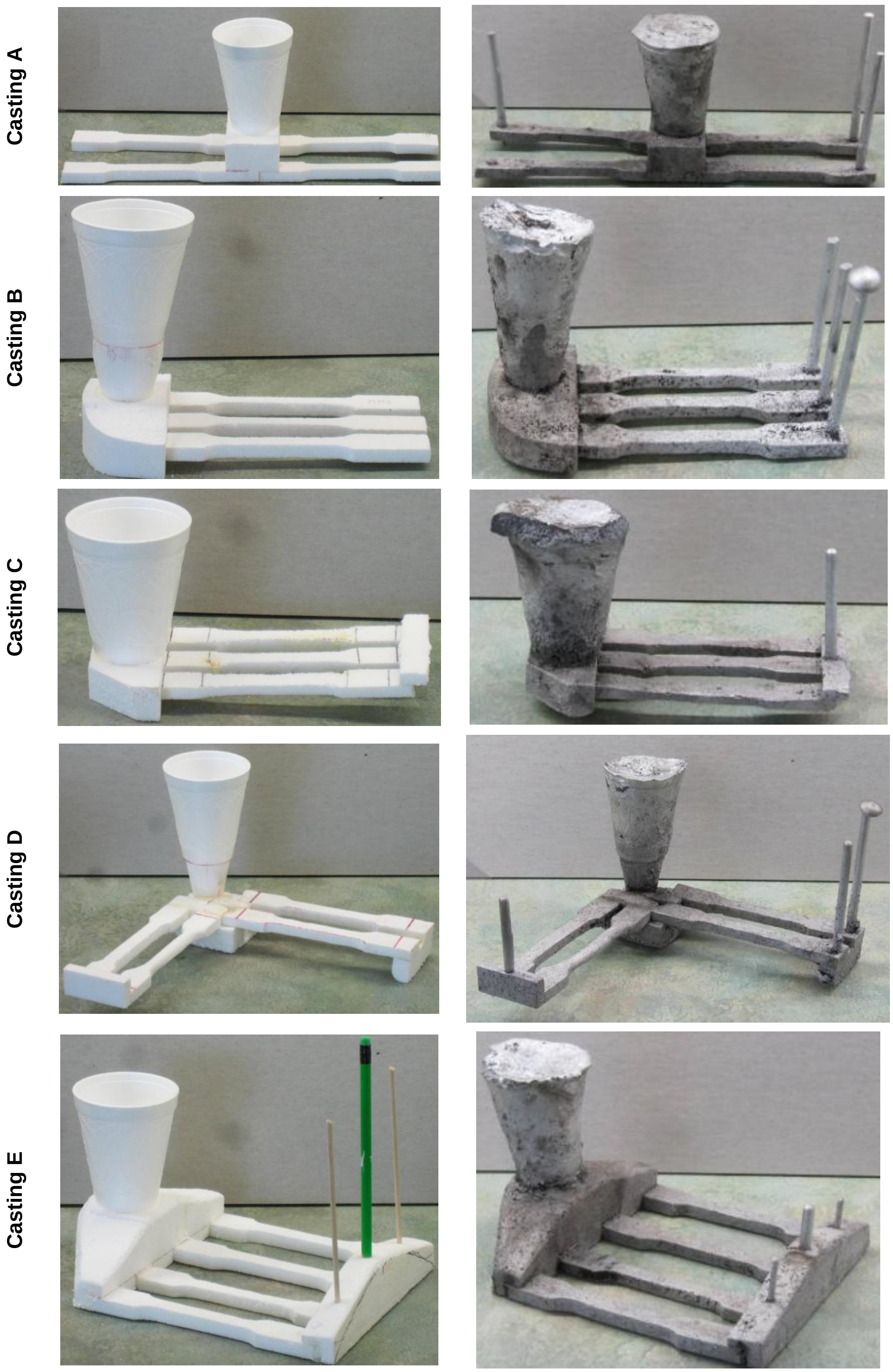


Figure 4: Tensile-testing specimen shaped part to be cast in aluminum.



(a) (b)

Figure 5: Styrofoam patterns (a) and the resulting castings (b). The pencils and wood sticks that were removed to create vents are visible only on one of the patterns.

To allow gasses to escape the mold cavity, pencils or wood sticks are inserted at various locations in the foam pattern; which are removed once sand is compacted around them and result in the desired vents.

During a second lab class, engineering students meet at the foundry operated by the Arts Department at Texas A&M University-Corpus Christi. After a safety briefing, the students begin preparing the green sand using a mixer (Figure 6-a), and then use this sand to support the Styrofoam patterns inside steel flasks (Figure 6-b,c).

(a) (b) (c)

Figure 6: Mixing green sand (a), and compacting it around the patterns inside metal flasks (b) and (c).

Meanwhile, aluminum scrap is melted in a ceramic crucible placed inside of a McEnglevan gas furnace[7]. When the compaction of the sand around the foam patterns is completed, trained students majoring in sculpture remove the crucible from the furnace and pour the molten aluminum inside the mold cavities. As Figure 7-a illustrates, the dross and scum that forms on top of the molten aluminum is prevented from entering the mold.

(a) (b)

Figure 7: Molten metal pouring by the Arts Department students (a), and demolding of the solidified castings (b).

Engineering students observe the process from a safe distance, while noting the order in which their patterns are filled with molten metal. As it will be explained later, this piece of information is relevant to their interpretation of the defect occurrence and strength variability in their parts.

One hour after pouring has been completed, students return to the foundry to retrieve their casting (see Figure 7-b), recycle the green sand and clean the work space.

During two more successive lab sessions, students cut off the useful portions of their castings using a band saw, and if needed, file flat the ends of the parts that will come in contact with the jaws of the tensile testing machine.

The analysis section of the lab consists of evaluating the minimum cross-section of each part, inspecting them for visible defects, and calculating the yield per casting, i.e., the weight ratio of the entire casting over the total weight of the useful parts. Students identify and mark two areas of probable failure on each part (see Figure 8), and, based on the measured cross-sectional area and the occurrence of surface defects, they rank the parts according to their anticipated strength.

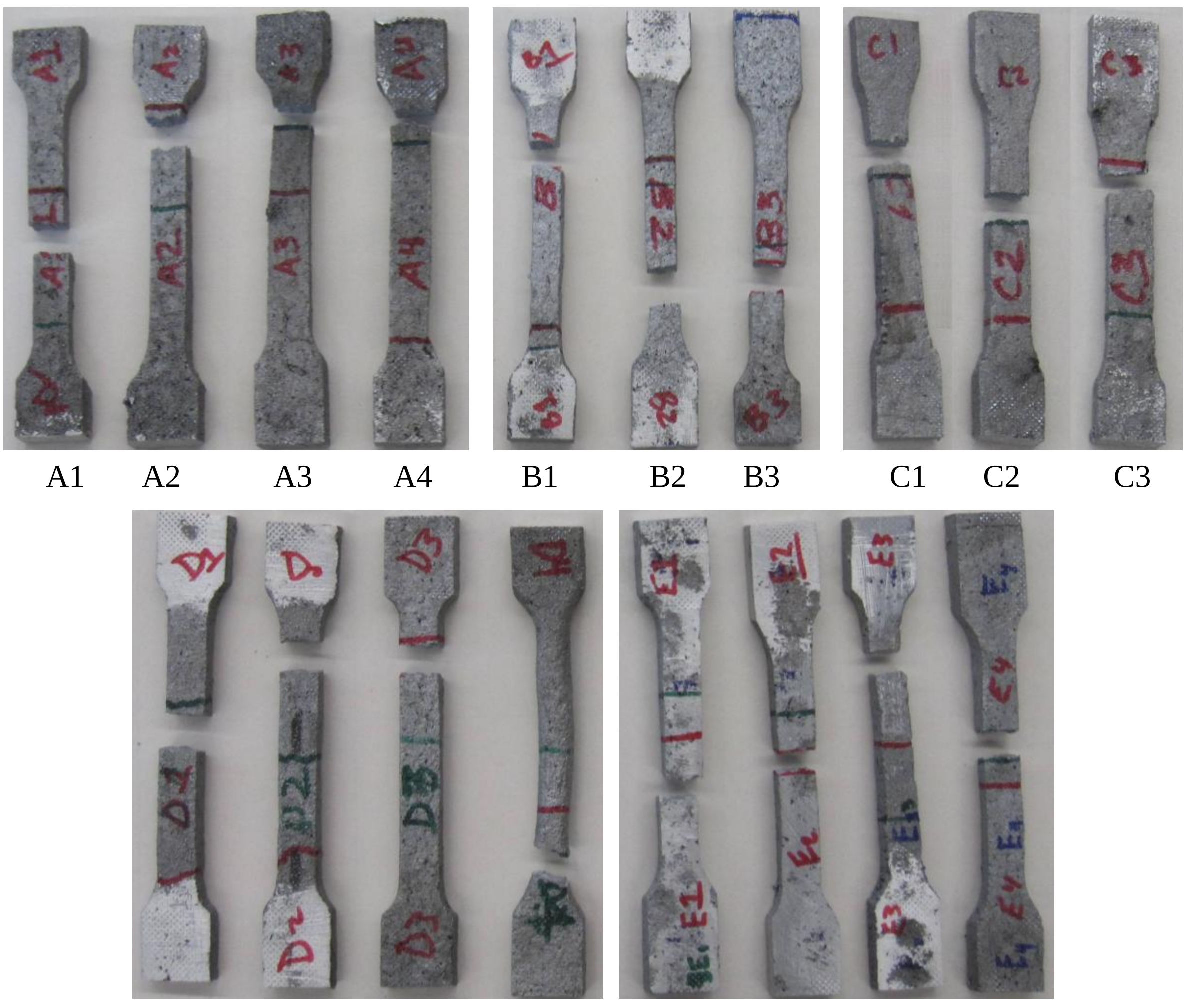


Figure 8: Broken specimens with the potential critical cross sections marked by students. Their predictions were confirmed for specimens A3, B3, C2, D3, E2, E4. Specimen D4 failed prematurely because of a dross inclusion.

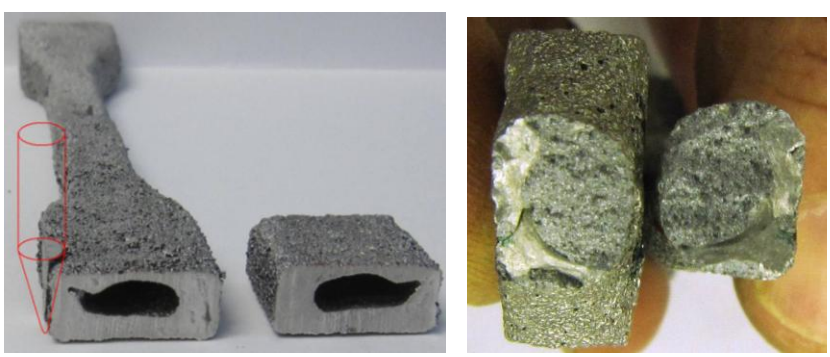
Finally, using an MTI 30K testing machine[8] each of the cast parts is loaded in tension up to the fracture. The specimens are ranked a second time according to their strength determined objectively through testing. Using the cross-sectional area determined earlier and the measured tensile strength, the ultimate tensile strength (UTS) in psi of each part is calculated (see Table 1).

Table 1. Summary of results obtained for the castings in figure 5-b

Part Number	Pouring Order	Min. Area [in²]	Max. Strength [lbs]	UTS [psi]	Avg. UTS [psi]	Guessed Rank	Actual Rank
E4	1	0.20708	3701	17872	**16088**	9	2
E2	1	0.20218	3383	16733		11	5
E1	1	0.19488	3250	16677		13	6
E3	1	0.17114	2237	13071		17	13
A4	2	0.16360	3813	23307	**17424**	14	1
A2	2	0.22442	3833	17080		5	4
A3	2	0.24324	3979	16358		2	7
A1	2	0.22686	2938	12951		4	15
B3	3	0.22201	3594	16188	**14141**	6	8
B1	3	0.17699	2744	15504		16	10
B2	3	0.18200	1953	10731		15	18
C1	4	0.19530	3357	17189	**14760**	12	3
C2	4	0.21545	3034	14082		7	12
C3	4	0.20925	2722	13008		8	14
D1	5	0.22677	3600	15875	**13418**	3	9
D3	5	0.20460	2904	14194		10	11
D2	5	0.22994	2886	12551		1	16
D4	5	0.13175	1456	11051		18	17

In their written report students comment on the differences observed between the empirical and the measured rankings, by factoring in internal defects observed after fracture, and the order in which metal was poured into each mold. For example, the temperature and fluidity of the molten metal is less for the last parts cast, which can translate into increased occurrence of surface defects and rougher surface finishes, as well as incomplete castings and cold shuts. The chances of entraining dross and other lightweight impurities with the molten metal are increased at the beginning and also at the end of pouring from the crucible.

In their reports engineering students also comment on the surface finish quality of their castings and on the factors that influence it, as well as on what caused incorrect dimensions or distorted shape of the useful parts.



(a) (b)

Figure 9: Casting defects observed: Gas inclusion caused by an improperly placed vent (a) and dross inclusion that occurred inside part D4 in Figure 8 (b).

Interpretation of Results

It was noticed that students used primarily the minimum cross-sectional area for ranking their parts, with minimum consideration given to other factors. Still, anticipating the strength of the parts remains a good exercise, because it emphasizes the importance of more accurate evaluation of the castings, either by destructive or nondestructive means. It also helps students to identify the weakest transverse areas along each specimen, which proved to be correct for one third of the cases in Figure 4.

The pouring order also proved to have an effect upon the average strength of the parts, with the parts cast first being stronger than the last ones (Table 1).

It was fortuitous that other casting defects occurred for the students to experience and comment upon their cause. During the first semester this laboratory was performed, a gas inclusion caused by an improperly placed vent occurred (Figure 9-a), while the following semester a dross inclusion occurred in one of the parts with minimum cross-section that was poured last (Figure 9-b).

Table 2. Student Survey Results

		strongly disagree	disagree	slightly disagree	slightly agree	agree	strongly agree	weighted average
1	The experiment did a good job of familiarizing me with the sand mold forming process.	0	0	0	0	2	12	**5.86**
2	The experiment did a good job of familiarizing me with the lost-foam casting process.	0	0	0	0	2	12	**5.86**
3	The laboratory did a good job of familiarizing me with foundry equipment.	0	0	0	2	4	8	**5.43**
4	The laboratory did a good job of familiarizing me with molten metal handling and pouring practices.	0	0	1	2	7	4	**5**
5	The laboratory did a good job of familiarizing me with visual inspection and destructive testing of cast specimens.	0	0	0	2	3	9	**5.5**
6	As an educational experience, the lab exercise complemented the lecture material well.	0	0	0	0	5	9	**5.64**
7	I my opinion the experiment has good industrial practical relevance.	0	0	0	0	5	9	**5.64**
8	Overall this was a good experiment	0	0	0	0	5	9	**5.64**

Student Assessment

After the students turned in their laboratory reports (two weeks after performing the experiments), a short survey was given in order to assess how this laboratory exercise was received. On a six point Likert scale students indicated if they strongly disagree, disagree, slightly disagree, slightly agree, agree, or strongly agree with seven statements. A number from 1 (for strongly disagree) to 6 (for strongly agree) was assigned to each selection. A total of 14 students responded to the survey and the results are summarized in Table 2.

Some of the comments from the first open-ended question about the strengths of the experiment are listed below.

1. *Very interesting lab with hands on learning and good teamwork*.
2. *At first was difficult to understand the process after the experiment I was truly aware and intrigued. I actually grew a lot of interest in the process. I thought it was really neat and helped me out a lot*.
3. *Overall, I enjoyed this experiment*.
4. *We should have more labs like this. They make the course more interesting*.

Examples of comments about how the lab could be improved include the following.

1. *We didn't get to pour the molten metal*.
2. *It was only after burring my foam pattern in sand that I know how is best to shape it*.
3. *If you are not precise with cutting the foam it is visible on the cast part*.

Following these comments from students the decision was made to purchase a hot wire foam cutter for this lab. Also, in the future, some of the less favorable designs that students experimented with will be presented in class before the lab is actually performed so that they will know to avoid them. For example, patterns like **Casting D** in Figure 5 are not easy to compact sand around because the base is not flat. It was also noticed that it is advantageous for the pouring cup edge to be located above the vent openings, so that the molten metal coming out the vent is an indication to the molten metal handlers to stop pouring.

Conclusions

The lab experiment described in this paper can easily be implement in any engineering curriculum where metal melting capabilities exist. As shown earlier, over 90% of the students at least partially agreed that the laboratory was a positive experience based on the post experiment survey. The laboratory can be also integrated with more advanced classes, like rapid manufacturing process as discussed by Creese[9] or computer aided optimization of castings, the latter being however better suited to graduate engineering education[10].

It is fortunate that Texas A&M University Corpus Christi has a metal casting facility that engineering students can have access to once a semester and perform one of their laboratory exercises. Plans are in the making for students to use this facility for casting parts for their projects, including capstone projects, and continue this fruitful collaboration with the colleagues in the Department of Arts.

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