The Development of a Project-Based Introduction to Manufacturing Laboratory Involving a Stirling Engine

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Abstract

Many current introduction to manufacturing courses contain a series of individual labs illustrating different processes: turning, milling, polymer processing, casting, etc. Although students leave these courses with an understanding of manufacturing processes and some limited experience analyzing them, they all too often dislike these laboratories since they discourage self-learning, and often appear contrived. In addition, many of these labs do not give students hands-on experience with a variety of the subtle manufacturing-related issues like tolerances, surface finish, quality, assemblability, and the trade-offs between accuracy and time, since these issues have essentially been designed out of the exercises.

A new project-based laboratory has been developed and tested where students manufacture a working Stirling engine. The engine contains approximately 30 parts that require the use of a wide range of processes. Although complex, the engine can be produced by teams with as few as eight students within a one quarter course. The project is a truly team-driven exercise, requiring both student participation and communication, and has received extremely enthusiastic response. This paper describes experience in developing a project-based manufacturing laboratory, and includes a description of the manufacturing processes employed, associated exercises, and expected outcomes.

Introduction

At the University of Washington, we currently have one undergraduate course devoted to manufacturing processes, ME 304. This course is intended to be taken during the middle of the Junior year, and has minimal prerequisites: knowledge of stress-strain relations in engineering materials, and metallurgy of ferrous and nonferrous metals. The course is 3 quarter-credit hours, and consists of two one-hour lectures and a three hour laboratory each week. Lectures cover a wide range of topics, including: concurrent engineering concepts, machining, bulk deformation, joining processes, polymer processing, and casting. The course is designed to provide engineering students with the necessary knowledge to use materials effectively, and introduce them to processes and equipment that can bring their designs to reality. The course also presents the basic processes and fundamentals of manufacturing, and intends to provide a foundation for the practice of professional engineering.

Previously, the lab portion of the course consisted of eight individual laboratories, including a safety seminar. For each of these labs, a process was demonstrated, and specimens were generated for further analysis. For example, the lab instructor would pour fluidity spirals at different levels of superheat for the casting lab. Students would then measure the length of the fluidity spirals and generate a two page report describing their findings. Laboratories that had been used in the past included:

1. Heat Treating
2. Casting Processes
3. Sheet Metal Forming - Springback

4. Machining Processes-All lathe work
5. Welding Processes

Although these labs illustrated a number of manufacturing processes and also gave students considerable experience generating technical reports, students generally disliked these exercises. A critical evaluation yielded the following observations:

1. These laboratories were primarily demonstrations and students were not always allowed to participate directly. A majority of the students were only allowed to observe.

2. Often times there were aspects of the labs that students would have explored on their own, but were not given the opportunity. Usually, the labs were so structured that students could not spend their own time with the equipment.

3. The labs were not tied together in any way.

4. Even though this was a manufacturing lab, students rarely produced anything other than test specimens.

To address these observations, a quarter-long team project was introduced, where groups of approximately 10 students manufacture a working Stirling engine, as shown in Fig. 1.

Hands-on labs where students produce working mechanical devices are far from new. Since the late 1950's however, many of these labs have been replaced with analytical work and exercises in engineering science [1,2]. Dejong [1] reminds us that it was the Grinter Report [3] that sent engineering education in a much more theoretical and science based direction. Although these changes in engineering curricula led to many improvements, practice-based courses in the areas of design and manufacturing have suffered.

In the past several years, many authors have reported their efforts to reintroduce engineering design and manufacturing to their curricula [2,3,4,5]. Most of these courses include hands-on exercises [2], which promote active learning and emphasize practical experience. Two such exercises in the area of manufacturing education are the gearbox produced at Lafayette College [2], and another Stirling Engine Project at MIT [5]. Although similar to our own project, these institutions present manufacturing processes in slightly different ways. The most notable differences occur due to quarter vs. semester systems. This paper details our experiences at the University of Washington by first discussing the course goals and expected outcomes, and then describing some issues regarding institutionalization of this laboratory project, including plans for future work.

Course Objectives

In addition to the broad goals of the course, the goals of this new set of laboratories were formulated as follows:

1. Give students the experience and satisfaction of manufacturing a <u>working</u> mechanical device.
2. Encourage self-learning.
3. Introduce a truly team-driven project requiring participation by all students.
4. Provide an environment where many manufacturing related issues like tolerances, design for manufacturability, etc. arise and can be discussed.
5. Engage students in a project which requires them to practice engineering design.

6. Give students experience in planning and executing a project in a specified amount of time.

Although mechanical engineering students are typically taught machine design, they are rarely provided with the opportunity to design processes. For this project, students did very little part design and spent considerable time developing processes to produce their parts.

Expected Outcomes

In addition to the above goals, we also wanted to see that students had improved their level of skill in a number of areas. Morell de Ramirez and Beauchamp [7] have categorized engineering skills into three broad groups: (1) Design/problem solving, (2) Communication, (3) Awareness of self, others, and the environment. We intended for every student to gain experience in each of these areas as described below.

(1) Design / Problem Solving

For this project, students must start by looking for information/data on the processes to produce their parts. Most of them have very little experience in a machine shop. They must then evaluate this information and make decisions about what processes they will use. For example, some students decided to use the CNC milling machine to produce their flywheel, where others used the lathe. In this respect, student are given the option design their own processes, and have the opportunity to explore these designs on their own. In addition to self learning, students are also required to manage their projects. These labs span eight weeks, requiring a modest amount of planning. Since there are about 30 parts for the engine, and typically only 10 students per lab, each student is responsible for approximately three parts, depending on complexity. These parts must be completed before assembly begins, and time must be scheduled to use the various pieces of equipment. For example, scheduling was especially important for the milling machine, since our shop only had two.

(2) Communications

Students are required to organize different process ideas and formulate questions so that “experts” can help them. They need to communicate these ideas orally and with simple sketches. Through the development of the final process plans (discussed below), they must communicate, in detail, how their parts were produced. The students must then use the WWW for communication by posting their process plans for future students to see and benefit from.

(3) Awareness of self/others

This laboratory exercise develops a great deal of self-esteem, especially for those students who have little or no prior hands-on experience. We find that most of our students have very little or no shop experience. This lack of experience keeps them away from projects that may require these skills. After completing the labs, all students have the confidence to build simple prototypes of their designs, and are aware of the proper tools and safety issues when accomplishing this task.

This project is also intended to develop a great deal of teamwork skills. Unlike most other projects the students will experience, this project requires interpersonal relationships to develop over several months instead of several weeks. It also requires students to work in very diverse groups; within a single lab section there are some students who have worked as professional machinists, and some who have never stepped into a shop in their lives. There is also a great deal of cultural diversity, with some students who speak English fluently and others who may have only been in the U.S. for two or three years. In addition, every student is a member of a relatively large group, about 10 students, requiring much more effective communication than the students are used to. Some students will naturally fall into a leadership role, while others will simply produce their parts. Regardless, every student understands that their contribution is significant, for without their help, the engine will not run at the end of the quarter.

Lab Schedule

The schedule for the lab is shown in Table 1. During the first week, students are introduced to basic safety issues, and the proper use of hand tools and some machines, including bench grinders, drill presses, bandsaws, etc. In the second week, they are trained to use the lathe. This is accomplished by demonstrating many of the operations that can be performed and then allowing students to produce a very simple part. In the third week, students are trained to use the milling machine in much the same manner. Students are also assigned their parts during the third week, and are given their first process plan assignment (described below). For weeks 4, 5, 6, 7 and 8, the students work on their parts individually, or as part of a sub-team with 2 to 3 members. Week 9 is then left for assembly and rework. Often students realize that some parts must be re-manufactured before the eighth week. Casting, injection molding, and brazing are also demonstrated during the middle of the project as time permits. These processes are usually shown at a time which coincides with their presentation in lecture.

Associated Exercises

We have developed a two part exercise to retain some of the writing content for the laboratory portion of this course. During week three, the students are assigned their part(s), as stated above. At this point they have been introduced to basic shop safety, common equipment, the lathe, and the milling machine. However, their experience using these machines is limited to approximately 4 hours. Most students are very excited about making their parts, and given the opportunity would start cutting immediately. However, after two quarters of letting students do this, we realized that a great number of mistakes could be eliminated, and quality could be improved if everyone was required to plan out the process to produce their parts.

All students are now required to write a process plan for the parts they will produce, before they start machining. These process plans must contain descriptions of the stock material, how the stock will be held, speeds, feeds, tools required, order of operations, etc. Since most of the students do not have enough background to completely describe their processes, they now can formulate questions in a straightforward manner. Students can then get answers to their questions from several sources.

1. Previous quarter's process plans - All students are required to submit a final process plan (discussed below) for their parts. These plans are then made accessible to the students on a series of web pages after they have turned in their preliminary plans.
2. The Instructor
3. The Lab Technician
4. The Teaching Assistant

Once these questions have been answered and the students have a well formulated plan, they can then begin machining their parts.

During the course, student are encouraged to keep notes on the effectiveness of their process plans; they keep track of what worked and what did not. At the end of the quarter, they are required to submit a complete process plan that details all of their experiences. This plan is intended to be used by future students who will produce the same parts. Using these plans will then allow future students to benefit from the successes and failures of all previous students who have produced these parts. The detail of these reports is required to reflect the new knowledge the students have gained throughout the quarter.

All of the final process plans are submitted electronically in HTML format. The plans can then be linked to the main course web page for all future students to view. These web pages must include at least one figure and may also contain links to other files (NC code, AutoCad, etc.). For most students in our curriculum, this is their first experience publishing information on the web.

Institutionalization

Development of the Course

The development was undertaken in Summer 1996 with financial support from ECSEL. During the first quarter, we wanted to see if it was possible for groups of approximately 10 students to manufacture a working engine within a single quarter (8 three hour lab sessions). To do this would mean eliminating all of the previous labs, and devoting all lab times to the production of the engine. Production of the engine would also require a number of new processes to be implemented. Most significantly, student would need to be trained to a level where they could produce all of the engine parts on the lathe and milling machine. Previously, students were only required to produce a plum-bob which involved simple turning, taper turning, and the use of a tap. Therefore, machining was covered in much greater depth.

At the end of the first quarter, two of the four engines actually ran. All of them were complete and assembled, but two were so poorly produced that they could not overcome losses due to leakage and friction. Even though these engines did not run, we believe the students in these groups actually learned more. The students in these groups spent many more hours trying to figure out what went wrong and how they could fix it. All of them gained invaluable first-hand experience with such issues as tolerances and quality, even though these topics are not formally covered as a part of the labs.

After having success with the Stirling lab in the first quarter, we continued with the goal to have all labs produce working engines. In the second quarter, an undergraduate was hired to help the teaching assistant and the instructional technician with general questions from the students. The addition of this third person led to a marked improvement in quality and success for all four lab sections.

At the end of the second quarter we were very comfortable with the Stirling labs, yet many of the processes that we had covered in previous labs were missing. For example, the engine required no sheet metal forming, welding, and no parts were cast. During the next two quarters, we would try to reintroduce new processes, de-emphasize machining, and also bring back some of the report writing content**.**

During the third quarter, several new processes were brought to the engine labs, including injection molding, CNC wire EDM, brazing, and rapid prototyping. Two of those processes were introduced based purely on the interest of the students. One student, who had done some rapid prototyping work previously, wanted to extend her experience by producing a flywheel prototype using a BMP rapid prototyping machine. She manufactured a working flywheel by producing a RTV mold which could then be used to form a polyurethane hub and spokes. The hub and spokes were then mounted within a steel ring.

Another group of students who had seen CNC wire EDM during a class tour early in the quarter approached us and asked if they could use this process to machine the spokes of their flywheel. These two examples from a single quarter illustrate how a project based manufacturing lab encourages students to seek information on their own and do things beyond the instructor’s expectations. During the 3rd quarter, we also introduced the concept of process plan writing.

In the fourth rendering of this project, two new elements were added to the lab - CNC milling and sand casting. We found that a bottleneck occurred in the lab since we only had two traditional milling machines available. To reduce the total time required to produce the engine and eliminate some mistakes, students were trained to use the CNC mill and associated software (EZ Feature Mill). We felt that giving the students this skill would benefit them greatly in future design courses and as practicing engineers. Once the students have experience with generating CNC code and using the mill, they can produce many of their own simple designs within several hours. This gives them the ability to rapidly produce accurate prototypes for future projects.

After being absent for three quarters, sand casting was also reintroduced. Students were shown how a sand casting mold is produced, and then they produced several flywheel molds from a match plate pattern. These wheels were then poured and cleaned up with minimal additional machining.

We have now successfully produced 14 Stirling engines in the past four quarters using student teams with as few as 8 members. Although a project of this type requires slightly more resources than the previous labs, student enthusiasm has improved markedly. The unforeseen motivating aspects of this project are truly some of its greatest assets.

Resource requirements

In a typical quarter at the University of Washington, there are approximately 4 lab sections, which are composed of approximately 10 students. For each of these labs, we have found that two trained individuals (teaching assistant or lab technician) are needed to help the students with questions. In lab sections where only one TA was available, quality dropped significantly, and many students found themselves waiting long periods of time for answers to simple questions. Typically one assistant would help with "traditional" machining questions, and the other would help student debug CNC code and help them operate the CNC milling machine. Each engine's raw material costs are approximately $150, including scrap and parts thrown away due to error.

Faculty Criticism

As can be expected, the Stirling engine lab has generated a fair amount of criticism from analytically oriented faculty. Two comments are common: 1) the Stirling engine project does not cover all of the processes that were previously covered, and 2) a large portion of the science content of the labs has been removed. Although these comments are generally true, we believe that this project benefits students far more than the previous labs.

It is true that the Stirling engine project does not cover the same processes that were previously covered. However, the students now gain first hand experience with far more processes, including injection molding, and milling to name two. Other processes added to the project are shown in Table 2. In addition, the students are free to explore related processes and issues on their own, as was described above, and as shown in Table 3. When considering the other benefits this lab brings to the course and the entire curriculum, we believe they far outweigh any negative effects from any science content that may have been lost.

Future Developments

After improving the labs for four quarters, we feel that some topics that were covered in the original labs are still missing. These include a welding demonstration, and a sheet metal forming lab. Although these processes could be integrated into the Stirling engine project, they would probably be best covered separately. To show these processes would require shortening of the Stirling engine project. In subsequent quarters, we will try to have two sections, approximately 20 students, build a single engine, expecting that they can produce all of their parts within 3 weeks. Communication between these students will become an issue however, since they are never in the shop at the same time. We plan to facilitate communication using a Stirling engine project web page and extensive use of e-mail.

We continue to develop this project in related areas such as materials selection, and plan to incorporate materials related issues in the future. We also have begun to develop ideas where this engine could be used to illustrate principles in other courses.

Summary and Conclusions

A new experiential manufacturing laboratory has been developed at the University of Washington, where groups of approximately 10 students manufacture a working Stirling engine. This project intends to give students first-hand experience with a wide range of processes, and the satisfaction of producing a working mechanical device. Previously, students were required to produce test specimens using several processes, measure some attribute of these specimens, analyze their results, and then report their findings. This new project eliminated the previous labs, providing a means for students to increase their design/problem solving skills, communication skills, and abilities to work as part of a team. This project also encourages self-learning, and greatly improves student's confidence. Many students who enter this project have little or no experience in a machine shop. However, all students leaving this course could produce a simple prototype of their own designs.

We have successfully produced 14 Stirling engines in the past four quarters using student teams with as few as 8 members. Although a project of this type requires slightly greater resources than the previous labs, student enthusiasm and motivation has improved markedly. In addition, students are now introduced to a wide range of manufacturing related issues including tolerances, quality, assemblability, manufacturability, etc., that previously were not covered.

We have found that a relatively large number of basic manufacturing processes can be illustrated using a project of this type, and interesting exercises can also be developed. Our students were required to write detailed process plans, which were then published as web pages. We found that subsequent lab sections benefited greatly from these plans, eliminating costly errors, and improving quality. Successful implementation of a similar lab could be accomplished within a shorter time period by initially employing similar processes described here and employing these exercises.

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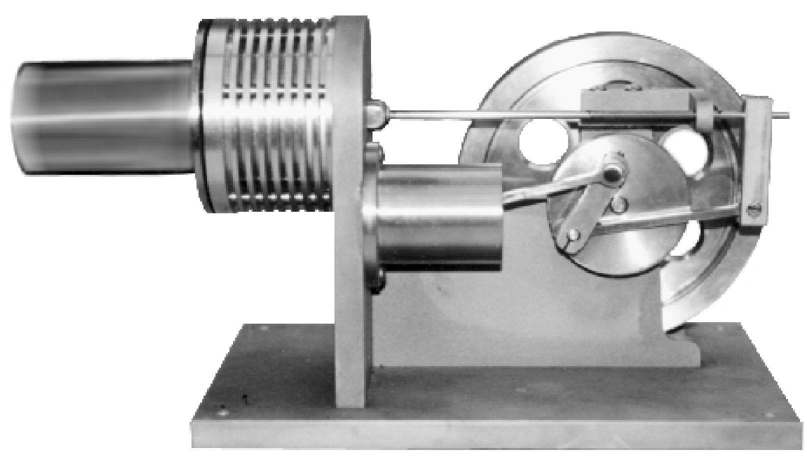

Figure 1 - Photograph of the Stirling engine produced for this project.

Table 1 - Course schedule.

Week	Topic
1	Safety, Hand Tools, Small Equipment
2	Lathe
3	Milling Machine / Parts Assigned
4	Complete Process Plan / Begin Part production
5	Part production / Injection Molding
6	Part production / Brazing
7	Part production
8	Part production / Casting lab
9	Assembly

Table 2 - Manufacturing processes used to produce the Stirling engine.

Milling (traditional and CNC)
Drilling / Tapping
Turning (including boring, grooving, parting)
Sand Casting
Injection Molding
Brazing
Rapid Prototyping*
Wire EDM*

* optional

Table 3 - Manufacturing related issues that were added to the labs.

• Metrology
• Part layout techniques
• Writing process plans
• Generating CNC codes using commercial software