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Laboratory Experiment for Improving Understanding of Grain Refinement in Aluminum Castings

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Laboratory Experiment for Improving Understanding of Cold Working in Aluminum Castings

Abstract

Cold working is applied widely in metal forming when manufacturing metal components to improve mechanical properties, reduce energy usage, increase dimensional precision, etc. Understanding this type of technique is valuable to those who design and manufacture components. As such, cold working is introduced to students of engineering technology (ET) in their first semester at xxxxxx University. To enhance course content understanding and improve learning efficiency, a lab-based group experiment that utilizes a materials-based cold working technique for aluminum castings was designed and implemented in a Materials and Processes course.

In this instructor-designed project, students manufactured pure aluminum tensile specimens using sand casting followed by cold rolling. The specimens were tested to find the effects of cold rolling on hardness and tensile strength. The students calculated the amount of aluminum required for the casting, estimated the solidification time of the casting with Chvorinov's rule, and completed most aspects of the specimen casting, rolling, preparation, and property testing processes. The final deliverable of the experiment was a professional quality laboratory report comparing and analyzing several mechanical properties. Students' cold forming and sand casting-related learning outcomes achievement versus their previous exams and the outcomes of previous students are presented and linked to ABET Engineering Technology Accreditation Committee student outcomes.

Keywords: Cold working, cold rolling, casting, materials and processes, group project, laboratory

Introduction

The cold working process plastically deforms metal at temperatures below its recrystallization temperature[1]. Through strain hardening, the metal's strength and hardness are increased by rearranging the material's microstructure with no heat treatment[1,2,3]. Cold rolling, one of the most common cold working processes, is used to manufacture sheet metal, strip, and foil products[1,2.] It results in a smoother surface finish, improves dimensional accuracy, and increases mechanical properties at room temperature[6,7].

Therefore, it is valuable and essential to introduce cold working manufacturing processes to students in engineering technology programs[9]. Performing cold working experiments helps students understand the relationship between process parameters and the material's resulting microstructure and mechanical properties. To help improve ET students' course content understanding and hands-on experience, an enhanced group laboratory project that utilizes a cold working technique for aluminum castings was implemented in a Materials and Processes course in XXXXXX university xxxxxx campus.

This experiment showed that about one-third of the students initially had difficulty using common foundry, joining, and hot/cold working process terms. The previous semester's course learning outcomes assessment showed that students struggled to determine which basic cold forming processes can effectively execute a given manufacturing task. This designed lab project involved the manufacturing processes of sand casting and cold rolling with corresponding property tests. This required students to collect experimental data, complete analytical calculations and compare testing results, providing opportunity to better connect these processes to application. Learning outcomes assessments for this semester all showed learning improvement and will be discussed in this article.

XXXXXX University xxxxxx campus is a statewide campus; all students are commuters. In general, there are 10-20 students in the Materials and Processes I class. This course introduces structures, properties, processing, and applications of metals commonly used in industry and develops problem-solving skills in the areas of materials selection, evaluation, measurement, and testing. At the end of the semester, the final exam was used to assess the learning objectives of this course. By comparing two semesters' learning objective assessments, overall this lab project corresponds to XXXXX University's overarching goals for its undergraduate programs.[9]

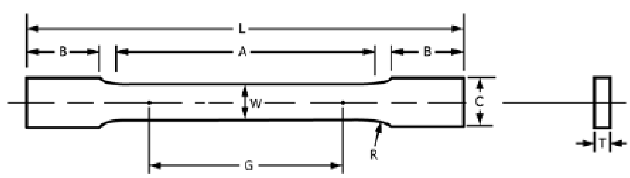
Methodology

Materials and Processes I is a 3-credit course required for freshmen in the mechanical engineering technology program at XXXXXX University and serves as a selective for manufacturing and industrial engineering technology students. Students in the Fall 2021 class at statewide campus xxxxxx worked on this new designed project in the lab session. The eleven students in this course were divided into four groups of two to three people each. Fundamental knowledge of cold work and sand casting was introduced in the lecture setting prior to this lab project.

Three two-hour weekly lab sessions were provided to complete the lab processes and project report. Lab processes included 3-D printing the pattern for casting their tensile specimens, creating their sand mold, sand casting of their tensile specimens, cold rolling their tensile specimens, and testing the specimens for mechanical properties. The cast product is a tensile tester which follows ASTM E8M[4] standard dimensions. Students obtained dimensional and mechanical property test data, then calculated, analyzed and compared their experimental and analytical property results, and discussed their findings in their lab reports.

Project Details

Four pure (99.9% purity) aluminum tensile test specimens were sand cast using a match plate in the lab and were subjected to hardness and tensile tests before and after cold rolling. The specimens' patterns were 3D-printed ABS parts and mounted on the side of an aluminum plate. The dimensions of the pattern follow the subsize specimen from ASTM E8M[4], as shown in figure 1:



Dimensions			
	Standard Specimens		Subsize Specimen
	Plate-Type, 40 mm [1.500 in.] Wide	Sheet-Type, 12.5 mm [0.500 in.] Wide	6 mm [0.250 in.] Wide
	mm [in.]	mm [in.]	mm [in.]
G—Gauge length (Note 1 and Note 2)	200.0 ± 0.2 [8.00 ± 0.01]	50.0 ± 0.1 [2.000 ± 0.005]	25.0 ± 0.1 [1.000 ± 0.003]
W—Width (Note 3 and Note 4)	40.0 ± 2.0 [1.500 + 0.125, -0.250]	12.5 ± 0.2 [0.500 ± 0.010]	6.0 ± 0.1 [0.250 ± 0.005]
T—Thickness (Note 5)		thickness of material	
R—Radius of fillet, min (Note 6)	25 [1]	12.5 [0.500]	6 [0.250]
L—Overall length, min (Note 2, Note 7, and Note 8)	450 [18]	200 [8]	100 [4]
A—Length of reduced parallel section, min	225 [9]	57 [2.25]	32 [1.25]
B—Length of grip section, min (Note 9)	75 [3]	50 [2]	30 [1.25]
C—Width of grip section, approximate (Note 4 and Note 9)	50 [2]	20 [0.750]	10 [0.375]

Figure 1: Dimensions of the tensile test specimens

Each group of students produced four tensile specimens by sand casting. Figures 2 and 3 show the sand cast molds and match plates. The pure aluminum ingots were purchased and pre-melted by the lab technician. Students used Chvorinov's rule[1] to estimate the aluminum's solidification time:

$$t_s = B\,(V / A)^n$$

where t_s is solidification time in minutes, V is volume of casting, A is surface area of casting, and B is mold constant (assumed to be B=16 min/in^2 in this lab). After the cast parts were de-molded and cooled, the students checked part surfaces for shrinkage. The dimensions and masses were measured and recorded so students could calculate the density (ρ) of the aluminum using the equation,

$$\rho = \frac{mass}{Volume}$$

The calculated density value for each cast aluminum specimen was compared to published density data for pure aluminum.

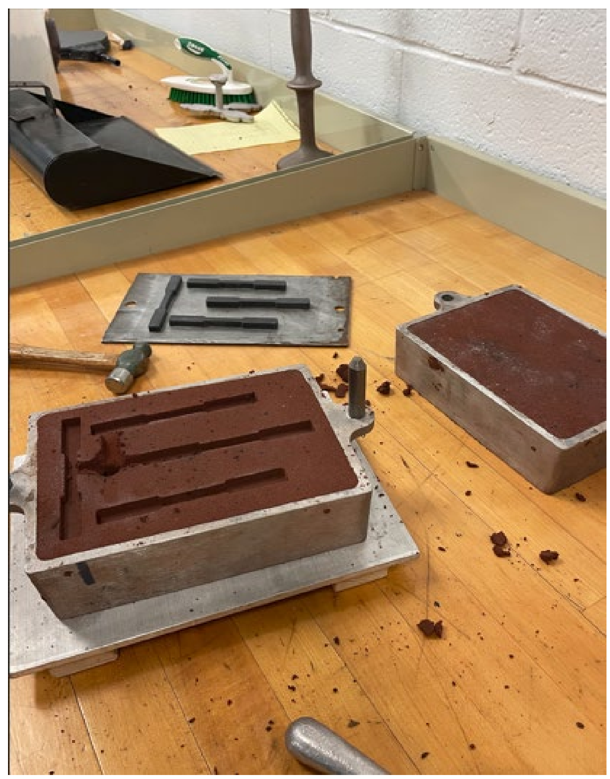


Figure 2 (L): Match plate for sand casting; figure 3(R) Sand Mold

After labeling the cast specimens Number 1-4, as shown in figures 4 and 5, specimen #1 was hardness tested by using Rockwell scale H at five different locations at the two ends in accordance with standard ASTM E18[5]. Next, tensile testing of specimen #1 occurred.

Specimen #1 represented 0% of cold work and its property test results served as baseline values for the remaining specimens.

Figure 4: Cast tensile specimen (Front view)

Figure 5 Cast tensile specimen (top view)

Specimens No. 2, 3, and 4 were cold rolled from their original thickness to different final thicknesses based on length, giving them different amounts of total deformation or cold work. After rolling to their final thicknesses, specimens #2, #3, and #4 were hardness tested and tensile-tested. Specimen #2 was cold-rolled one inch longer than #1. Specimen #3 was one inch longer than #2, and specimen #4 was one inch longer than #3. The cold-rolled specimens are displayed in figure 6; figure 7 shows one of the specimens as it undergoes the cold-rolling process. After rolling, specimens No. 2-4 were measured for dimensions (length and width), hardness tested, and tensile strength tested. Students recorded data and discussed the results in the report.

Figure 6 (L): cold-rolled specimens after tensile tests;
Figure 7 (R): Specimen in cold rolling

The result of the tensile testing was imported into the EXCEL file. A stress versus axial strain chart was created for each tensile test, where strain € is the ratio of change in length to original (gage) length. Students located the yielding strength and tensile strength for each specimen, then compared the estimated strength values with published tensile strength data. The engineering stress was calculated by:

$$\sigma = \frac{F}{A}$$

σ is the engineering stress (tensile), F is the tensile force, and A is the cross-section area.

Students then determined the modulus of elasticity (E; also called Young's modulus). Students picked two points from the linear portion of their stress-strain plot to find the value of E. The equation used to calculate the modulus of elasticity was:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

the ratio of the change in stress divided by the change in strain. Finally, the percentage elongation was calculated by:

$$\frac{l_f - l_0}{l_0} \times 100\%$$

Where l_f is the final gage length after pulling and l_o is the original gage length of 2.00 in (50.6 mm) before tensile testing.

The students compared hardness, tensile strength, modulus of elasticity, and percentage elongation values for the four specimens to consider the effects of cold-rolling on cast aluminum. In addition, they matched their property results to published property values. Finally, students created data and results tables to support their conclusions regarding their lab results and lab experience (discussion and summary) in the lab report.

Results and Discussion

All four groups completed this lab project successfully and on time. In their report summaries, two groups mentioned this hands-on project experience helped them extend their understanding of the process and application of sand casting and cold working. All groups discussed the direct relationship between cold work and mechanical properties based on their data and analysis. By casting the specimens in the lab, one group of students noted that this project helped them apply theoretical knowledge to a real case and made the subject matter more engaging and memorable.

Students also discussed the issues they found through this lab. For example, the small surface area at the ends of the specimens may have affected Rockwell hardness test results. Students observed that the shrinkage porosity in the sand casting affected the flatness of the specimen. They also noted it was difficult to flatten the curvy parts after cold rolling, one of the major tensile testing concerns for the cold-rolled parts.

Learning objective assessments

The course of Materials and Process I at XXXXX University has explicit and implicit objectives. The explicit Core Learning Outcome Objectives (CLOO) for this course are shown in Table 1. Student success in this course is assessed by a combination of lab reports, homework, and exams, where exams constitute the formal assessment. Students are expected to demonstrate a comprehensive understanding of the course material and be able to apply their knowledge in practical situations. This course's learning objectives were assessed by midterm and final exams. This designed group project ties directly to CLOO 2-7. CLOO 2 and 4 match the ABET student outcomes(SO)[10] 1 for engineering technology baccalaureate degree programs. CLOOs 6 and 7 match ABET SO 3. CLOO 3 matches ABET SO 4 and CLOO 5 matches ABET SO 5. The midterm and final exams have four multiple choice items on each of CLOO 2 and 4, six multiple choice items on each of CLOOs 3 and 5, 18 multiple choice items on CLOO 6, and eight multiple choice items on CLOO 7. The items are equally weighted. Students who answer at least 75% of the items correctly are considered to have attained the related CLOO.

Table 1 listed the results of assessments for Fall 2021 and Fall 2020. Except for item 10, which is assessed qualitatively rather than on exams, fall 2021 students demonstrated a higher learning success rate than the fall 2019 students for every one of the thirteen course CLOOs.

With only one data set, it is not appropriate to attribute the improvement in CLOO attainment solely to this cast aluminum cold working project. However, the initial CLOO attainment increases suggest this project is likely to directly improve student understanding of CLOOs 2, 3, and 5, and may indirectly improve student learning for CLOOs 4, 6, and 7.

Table 1 Learning Objective Assessments for Materials and Processes I

	CLOO	F2020	F2021	ABET SO#
1.	Use phase diagrams and metallographic specimens to explain the compositional and property differences between alloys of ferrous and non-ferrous metals, including determining what phases are present, their compositions and amounts.	44%	58%	
2.	Use stress-strain diagrams to determine material properties of both ferrous and non-ferrous metals.	62%	85%	1
3.	Conduct material property tests using standard methods and instrumentation.	62%	67%	4
4.	Identify brittle and ductile failure types and describe the effect of temperature and surface defects on impact toughness.	52%	84%	1
5.	Communicate with colleagues in their field using common terms of foundry, joining, powder metallurgy, hot/cold working, and the ceramic fabrication industries.	76%	81%	5
6.	Describe key process variables when working with molten metal.	65%	81%	3
7.	Identify and differentiate between common single-use and multi-use mold processes by describing processes and listing advantages and disadvantages of each process.	71%	75%	3

8.	Describe the common fabrication processes for amorphous and crystalline ceramics.	63%	70%	
9.	Describe a typical powder metallurgy manufacturing process and explain its advantages and disadvantages.	62%	91%	
10.	Identify the basic material removal processes: turning, boring, drilling, reaming, milling, sawing, broaching, shaping, and grinding and determine the material removal processes that can effectively execute a given manufacturing task.	None	None	
11.	Determine the basic cold forming processes that can effectively execute a given manufacturing task.	92%	100%	
12.	Describe and differentiate between the hot working processes of rolling, forging, and extrusion and predict the results of heat treating metal alloys.	31%	38%	
13.	List advantages and disadvantages of joining processes including common fusion and solid-state welding processes and integral, discrete, and shrink/expansion fastener systems.	45%	70%	

Conclusions

This project-based instructional approach corresponds to XXXXX University's overarching goals for its undergraduate programs for engineering technology students. The knowledge and experience gained through student completion of various team projects during their freshmen through junior academic years is expected to form a strong foundation for the senior capstone project (an implicit goal of most courses within the engineering curricula). At the capstone level, students undertake an often unstructured, broadly-defined, real-world problem. Many of these capstone projects entail solving manufacturing process issues for production facilities. Students' growth in their ability to connect process decisions to their effects on materials through this lab experience should strengthen their readiness to tackle industrial processing concerns. Similarly, this project contributes to aspects of four of the five ABET ETAC Criteria 3 Student Outcomes.

By participating in this lab project, freshmen gained experience in critical thinking and connecting theory to practice. This can help them in their academic pursuits and future careers. Students developed their critical thinking skills by breaking down complex tasks into smaller parts, evaluating information, and using logic and reasoning to make analysis. They also took the theories they have learned in the classroom and used them in a real-world situation of manageable complexity. This can enhance the students' ability to identify and solve real-world problems, experiment with new ideas, and reflect on the results of their work.

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