Exploring Plastic Foam Processing and Properties

Wei Dai Vian
Purdue University, Kokomo
wdai@purdue.edu

Nancy L. Denton
Purdue University, West Lafayette
dentonnl@purdue.edu

Abstract

Polymer foam products are part of daily life and highly accessible to people of all ages. Manufacturing processes for these products, however, are typically unknown but can pique the interest of secondary students and college freshmen searching for a major. This paper describes two laboratory modules where students make two types of foam packing materials and test for common properties. The first module introduces fundamental concepts of chemical expansion foam plastics and foam bead casting, and provides hand-on experience with both types of foam casting materials and processing techniques. Determination of approximate foam material properties through simple product testing and calculations comprises the second module's activities. A third project-oriented module incorporates learning from the processing module to implement a small-scope student design project. The paper describes the three instructional modules and discusses lessons learned through their implementation.

Background

Efforts to attract young adults to STEM career fields are ubiquitous to engineering and technology education. For students entering college, these efforts expand to address retention as well as recruiting. Reducing attrition in engineering and engineering technology affords substantial progress toward meeting national goals of graduating 10,000 new engineers annually.[1] Consistent with a Purdue University College of Technology educational policy implemented in fall 2011, a discipline-based gateway course was introduced to provide new and/or curious students to authentic experiences that expose them to the learning and skills of the major.[2] For the mechanical engineering technology (MET) and manufacturing engineering technology (MFET) programs, MET 14400 Materials and Processes II meets this policy requirement. In addition, the course is a direct prerequisite for MET 24500 Manufacturing Systems for both majors. The course description and learning objectives are provided in Appendix 1. One key intention of the course is to help Explorers (students who have not declared a major) determine if they have identified their preferred major; another is to retain students in the MET and MFET majors. To satisfy both of these intentions, students need to have a good understanding of what they will learn in these majors and how this learning will be applied in the workplace. The foam modules presented here contribute much toward achieving these intentions for new college students who may not have previously considered the role of materials testing and processing in product generation. The processing and testing modules also work well with pre-college students who may be exploring their career options. For all three modules, equipment and workspace requirements are minimal, allowing implementation of these simple processing and testing modules in a variety of educational settings.

Processing Modules Overview

Polystyrene foam beads expand with the introduction of heat. By limiting the expansion to the volume within a mold, and subsequently quench-cooling the mold and foam, the beads form pressure bonds. As long as molds are available, expandable foam bead can be readily cast into a variety of small shapes. The basic equipment requirements are a hot plate, a stock pot, tongs, a bucket of cooling water, and small metal two-part mold(s), plus safety glasses or goggles for personal protection. To make a product, the pot should contain an ample amount of boiling water. Sufficient expandable foam bead to fill one of the mold halves approximately two-thirds full is added, the mold sealed, and the mold placed in the pot for at least 10 minutes. When heating time is up, the mold gets transferred immediately to the cooling water to quench and retain its expanded form. When the mold has cooled enough to handle, the mold halves can be separated to access the product.[3]

The chemical expandable foam processing setup is a bit different, but also is quite simple. Two matched chemicals must be mixed in appropriate proportions to produce an exothermic foaming reaction; the new liquid is then added to a vented mold with sufficient conduction to facilitate cooling throughout the reaction. As the foam forms, the mold halves are clamped to ensure pressure from the reaction does not force them apart. The time to fully react will vary. Since the mold must stay intact until the foam has solidified, a small quantity of chemical foam mixture should be left in the mixing container and observed to learn when the reaction is finished. Two cautionary notes should be made. A potential addition would be to incorporate chemical reaction equations into the module, assuming a reasonable approximation of the chemical composition of each component can be found. Many chemical foams include a toxic component, so gloves should be worn and work should be done in a well-ventilated area. And, the shelf life of some foam components is brief. Check for color change prior to beginning processing.[4]

If desired, either or both of the processing modules can be performed independent of testing and design modules. In that case, the choice of foam product shape(s) is up to the instructor and the constraints set by the mold(s). To facilitate the testing module, three foam products should be molded by each of the two processes. The products are a thin bar 6.0” by 1.5” by 0.5”; a block 5.0” by 3.0” by 2.5”, and a 3.0” diameter ball, as shown in figures 1-3. If many students are participating, colorant may be a helpful addition to the chemical foam process.

Testing Module

The following experiments reinforce concepts and/or provide general insights into the behavior of the foams and the products made in the Processing Module. While precision of the data and results is limited, the students should be encouraged to adopt good measurement techniques and practices.

Figure 1: 3.0” diameter expandable foam bead ball with mold halves

Figure 2: Chemical foam block with its disposable plastic mold

Figure 3: Expandable foam bar and part of mold, prior to cutting to test size

To begin their experimental work, the products should be thoroughly observed for color, shape, pore size, odor, and any other quantities that students identify. Products must be measured for initial mass (or weight) and volume to prepare for subsequent testing.

Closed or Open Cell Foam Test

The first test is to determine if the foams are closed-cell or open-cell. Closed-cell foams essentially have fully-formed adjacent bubbles that prevent liquid transmission and absorption, while some bubbles in open-cell foams have burst and allow liquid absorption.

For testing, both balls will be submerged in a bucket of room temperature water. A digital scale and timer complete the equipment needed. Submerge the balls for 60 seconds; remove the balls and allow them to drip for 30 seconds, then measure the balls' masses (or weights) for comparison with their initial values. The open-cell foam experiences a large jump in weight and will retain substantial liquid; the closed-cell foam has a much smaller change, as shown in Table 1. (The mass change for the closed-cell foam is due primarily to surface water. To further verify the closed-cell condition, the experiment could be continued. The next step would be to gently wipe the likely closed-cell foam product to remove surface moisture, then re-measure its mass. The 16.8 gram increase corresponds to a water layer of slightly less than 1.0 mm covering the surface of the ball).

Table 1: Closed or Open Cell Foam Test Sample Data

Product	Mass before submerging, grams	Mass after submerging, grams	Foam Type, based on mass change
Chemical foam ball	48.1	114.4	Open-cell
Expandable foam bead ball	56.6	73.4	Closed-cell

Some additional calculations to incorporate to enhance the scientific connection of the foam modules include determination of density of each ball before and after the water submerge test. Chemical reactions of the chemical foam component parts might be analyzed, if sufficient molecular information can be obtained.

Bouncing, Energy-absorbing Test

Foams are frequently employed for their energy-absorbing characteristics. In this experiment, the Law of Conservation of Energy is applied.[5] Kinetic and potential energy are balanced, so energy absorption can be calculated from the change in potential energy on rebound in a simple marble-dropping test. Equipment consists of the foam blocks, mass scale, marbles, a clear cylindrical tube for controlling the marble's path, and a meter stick or other means of determining the vertical travel distance as the marbles rebound. Potential energy is the energy at each vertical relative maximum height, beginning from the marble's drop position.

$PE = mgh$ Where: m = marble mass in kg; g = 9.81 m/s^2, and h = marble position height in meters

$\Delta PE = mg\Delta h$ Where: Δ indicates a difference in two values (energy and height)

The potential energy of the marble is determined at height h_o, prior to its drop. Using careful observation or perhaps multiple student photos of the peak location, the potential energy at the end of the first bounce, at height h_1, is also determined. The difference in potential energy represents the approximate energy absorbed by each foam block. The open-cell foam should absorb energy more readily than the close-cell foam.

Axial Deformation Test

This experiment requires additional part and stand preparation, but offers a path for obtaining the modulus of elasticity for each foam material when there is no access to a tensile tester and/or standard size dog-bone specimen. The brick specimens should be cut into thin bar shapes and their new dimensions carefully measured and recorded. A small hole will be needed at one end of the bars for adding known mass; and a stand that lets the bar hang freely during testing must be devised. For 6.0” bar lengths, the center 3.0” length needs to be marked with two thin dark lines. Weight will be added via a small cup (e.g. 3 fluid ounce paper cup) that can be suspended from the end of the bar while remaining somewhat level when marbles are added.

The basic relationships for axial stress and strain combine to provide an equation for axial deformation that includes the modulus of elasticity of the material.[6]

$$\delta = \frac{FL}{AE} \qquad and\ E = \frac{FL}{\delta A}$$

Where: δ = axial deformation; F = applied load = mg; L = original length; A = cross-sectional area, and E = modulus of elasticity.

For the axial deformation test, the two key variables during the experiment are change in length under load and mass of the cup and all marbles that it holds. With the bar installed in its stand, marbles are added until there is a visible, measurable change in length between the marked lines. The new length should be measured and recorded, then the cup of marbles can be removed and measured for mass (or weight). Students use their length change, mass, and previously obtained dimensions to estimate the modulus of elasticity for each foam. (Testing more than one specimen per foam is recommended). While it is possible to compare the foam modulus of elasticity values to published values, it is important to note that foam modulus values vary with density. For example, for polystyrene expandable foam bead, the initial modulus values range from 2 MPa to near 14 MPa.[7] This added layer of complexity in the testing analysis may be challenging for some audiences, especially pre-college students. The instructor should be prepared to address the variability of polymeric properties if comparisons to published property values are undertaken.

Product Design Module

In fall 2014, a pilot product design project module was implemented for small cohort of gateway course students in four groups. The assignment was to develop a simple plastic item which would be manufactured using one of five processes. Each process came with its own set of constraints. Products made with the foam processes were limited in volume and mass, primarily. Two of the student teams chose chemical foam casting for their product (and no teams chose expandable foam bead). Design challenges the teams addressed included scaling their products to conform to a mass limit of 90 grams and properly locating vents so the foam would not prevent outgassing as it expanded. The prototype products were a very small pillow/cushion appropriate for a doll-house bed or basic packaging, and a flying disk. Both teams required at least a second iteration to make a reasonably viable product due to misunderstandings regarding venting.

Summary

Foam materials offer a relatively inexpensive way to introduce pre-college and new college students to manufacturing processes, product testing, and product design concerns. The approaches discussed in this paper can be implemented with equipment found in most middle school and high school science classroom laboratories. The implementation approach can be customized effectively for audience age, time available, and existing resources. For example, foam products can be made in advance to allow testing to occur without student processing, or processing and product development can be done without the testing module.

Based on the authors' experience, two important lessons learned are as follows. First, students will ignore design constraints whenever possible. Adapting product designs to meet specified constraints (or working with customer to modify constraints) is a key facet of engineering design of products and processes. Second, for outreach programs, younger students respond very favorably and have a high level of engagement when the product(s) they encounter are the same types of items they use every day, such as a foam ball.

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These processing and testing modules were previously presented at the 2012 National Educators Workshop.

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Appendix 1 MET 14400 Materials and Process II, Lecture 2 hours; Lab 2 hours; 3 Credits

Course Description: An overview of structures, properties, processing, and applications of polymers, composites, laminates, biomaterials, green materials, nanomaterials, and pharmaceuticals commonly used in industry is presented. Problem solving skills are developed in the areas of materials selection, evaluation, measurement, and testing. This course serves as the gateway for the MET and MFET programs.

Specific goals for the course:

1. Differentiate between the structure and characteristics of the major thermoplastic and thermoset polymers.
2. Understand the terminology pertaining to industries involving polymers or alternative materials.
3. Identify major traditional polymers and alternative materials used in the production of consumer products.
4. Conduct material property tests using standard methods and instrumentation.
5. Research polymeric materials and processes using various resources.
6. Describe key design considerations for gating systems, molds and other process equipment components.
7. Identify and describe the major molding, forming, shaping and joining processes used in the manufacture of polymeric products.
8. Display safe and environmentally sound methods of working with polymeric materials and processes.
9. Understand the concepts of lean manufacturing, sustainability, and product life cycle management with regards to polymers and alternative materials and processes.
10. Describe how fibers and matrices are combined to form composites and explain why composites are used.
11. Describe the fabrication techniques used to produce particulate, laminar, and fiber-reinforced composites.
12. Describe biomaterials and biomedical device manufacturing concepts.
13. Identify green materials and green manufacturing strategies.
14. Describe the key difference between traditional manufacturing and industries such as pharmaceutical and biomedical device.
15. Perform objective quality inspection, analyze basic material and manufacturing-related defects, and recommend appropriate modification that would be likely to reduce or eliminate the defects and/or provide for more efficient design and manufacturing.