Design of Polymer Processing Activities for Pre-College Students

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Abstract

Plastic products play an important role in daily life. To support manufacture of the massive quantity of polymer products generated every day, the plastics industry currently employs over 900,000 workers and has more than 13,000 establishments in United States\(^1\). However, polymer manufacturing processes are not well-known or widely understood by the general public. Helping pre-college students gain experience with common polymer processes affords a fun and useful way to prepare them to be better consumers and potential product designers and manufacturers. This paper presents activities and exercises that introduce students to plastic thermoforming, casting, and extrusion processes that can be completed in a typical science or project-friendly classroom. To highlight the multidisciplinary nature of polymer product realization, science and mathematics applications such as geometric measurements, volume, mass, density, and estimation are embedded into the activities. These activities and exercises are intended for students at the middle school level and above, but some can be easily adapted for groups as young as pre-kindergarten children.

Keywords: Pre-College, plastics, casting processes, thermoforming process

Background

Plastic products find their way into the life of a typical person starting at birth, if not before. Informal education regarding manufacture of plastic products can be obtained various ways, from the Crayola Experience\(^2\) to Play Doh extrusion toys such as its Fun Factory\(^3\) to simple casting and injection molding toys such as Mattel’s Creepy Crawlers ThingMaker and Hot Wheels Car Factory\(^4, 5\). These enjoyable experiences may pique the interest of youth but generally do not provide much insight into the integration of mathematics, science, and technology that results in plastics processing. The following exercises were developed to:

- Introduce students to differences between thermoplastic and thermosetting plastics
- Develop basic processing vocabulary in context (mold, pattern, cavity, draft angle, parting line, sprue)
- Form connections between mathematics and product/process requirements (volume, mass, surface area, draw ratio, area ratio)
- Provide practice with 3D printing for molds while improving understanding of thermal property constraints

Adaptations of several of these processes have been implemented in informal education settings with children of all ages (e.g., Purdue University at the Indiana State Museum) with no attempt to incorporate mathematics. For this paper, the students are assumed to be enrolled in middle school, high school, or college and doing the activities as part of an ongoing class or STEM club.

Thermoplastic and thermosetting plastics
Plastics and other polymers consist of materials that have a base molecule, the mer, which is the base and repeat unit of polymer structure and bonds with many other mers to form a much larger polymer molecule (Figure 1). Thermoplastic and thermosetting comprise the two major categories of plastic materials. Most of their fundamental differences in properties and performance result from their chemical structures. Thermoplastics have secondary bonds (van der Waals forces, see Figure 2) between molecular chains while thermoset molecules are joined by cross-linking primary, covalent bonds. Secondary bonds are the bonds with no electrons sharing or transfer and they weaker than primary bonds. They can be classified as van der Waal’s forces, including hydrogen bonds. Unlike strongly bonded crosslinked thermosetting polymer chains, the chains of thermoplastics are long, linear and weakly bonded. These easily broken bonds allow thermoplastics to be reshaped and/or recycled, often at relatively low temperatures. Thermosets cannot be reshaped or recycled, and require relatively high heat to form only once. Completion of the crosslinking takes time (to cure or finish hardening), typically requiring more time than thermoplastics need to cool and solidify. These molecular differences mean thermoplastic products are less dense, have lower stiffness, and lower resistance to chemicals compared with thermosetting products.

Figure 1: Monomer (base unit) and polymer molecules

Figure 2: Weak intermolecular van der Waals bonds and strong intramolecular (covalent) bonds atoms
Processes Overview and Vocabulary

Casting and forming processes generally involve putting material in liquid form into a mold that consists of a cavity that is the inverse or negative of the intended part. The cavity may result from constructing a mold around a physical pattern, from additive manufacturing processes, or from machining. For ease of mold construction and to facilitate part removal, these molds often have two sections. Material enters the mold’s cavity via a main channel (sprue), with additional channels (gating) in molds with more than one cavity. Even with very high quality, low-tolerance two-part molds, a parting line is produced on the part where the two mold faces meet. The mold sections are typically designed with a positive draft angle to allow them to be pulled away from the part. For thermoplastic materials, the mold must account for sufficient cooling for the part to solidify, so most molds are made of metal.

Thermoforming and hot-dip casting molds work somewhat differently. For thermoforming, one-piece molds with positive draft angles provide convection cooling on their open side, allowing molds to be made of many materials if they contain holes for drawing a vacuum or introducing pressurized air, as shown in figure 5. Hot-dip casting products are formed by coating the outside of the mold (mandrel). Figure 4 shows two simple mandrels for hot dip casting. The mandrel material must tolerate heating and allow its polymer coating to cool and cure.

Vacuum thermoforming

As a simplified type of thermoforming, the vacuum thermoforming process is commonly applied to fabricate products from thermoplastic sheets. This process cannot be applied to thermosetting materials since the plastic must first be formed into sheeting. From cookie trays to toys and boat hulls, vacuum thermoformed thermoplastic products play an important role in daily life, as shown in figure 5. This process requires a combination of control of pressure, time, and temperature to properly heat thermoplastic sheeting until it becomes pliable, then stretch it into its mold shape by drawing a vacuum, and subsequently cooling until the sheet returns to force. Some commonly thermoformed thermoplastic materials include polystyrene (PS), high impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS), polyethylene (PE), PVC, and acrylic (PMMA).
Figure 3: Thermoforming machine with mold in place. Vacuum holes are clearly visible.

Figure 4: Hot dip casting mandrel can be easily exchanged.
This vacuum thermoforming activity introduces students to a simple version of the industrial manufacturing process and gives hands-on experience with processing plastic materials. A compact vacuum forming machine is recommended for this processing exercise. One of the options is approximately 8” wide, 10” deep, and 12” high (200 mm by 250 mm by 300 mm)\textsuperscript{11}. A square plate, 4 inches (100 mm) on a side can be produced by this particular machine model, starting with thermoplastic sheeting at a minimum size of 5” x 5” (127 mm by 127 mm). For this
activity, small quantities of PS and copolyester (PETG) plastic sheets are available in a choice of thicknesses and colors at many hardware stores. Polylactic acid (PLA) sheeting works well for thermoforming but may require purchase in bulk.

The vacuum thermoforming process entails installing a piece of sheeting over the mold in a manner that will allow a seal to form between the mold and sheet when heat and pressure. About a minute is needed to heat the machine to the temperature of softening (not melting) the plastic sheet and develop sufficient pressure for the vacuum to draw. Drawing the vacuum and giving the plastic time to cool takes another 20-30 seconds when making a small plate like those shown in Figure 3.

If forming the sheet occurs at an overly low temperature or for an insufficient amount of time, a half-spherical, bowl-shaped plate will be produced instead of a square one. Reshaping is required and can be done for this case. As long as the round bottom sheet stays locked in the mold to ensure its location has not changed, simply repeat the process at the correct temperature and forming time to obtain the intended product. Students will observe that the half-sphere shape softens and returns to flat sheet and then forms to the mold shape. This process demonstrates the thermoplastic materials’ characteristic ability to be reshaped.

Related processing measures of draw ratio and areal draw ratio may be calculated after obtaining several dimensions of the plate product or its mold. Draw ratio can be used to determine if the vacuum should be sufficient to stretch the sheet into its new shape without additional means (e.g., plug assist), while areal draw ratio can be combined with sheet thickness to ascertain the likely final thickness or the appropriate initial thickness. Working from the instructor-provided equations and definitions, students may use their values to help summarize the advantages and disadvantages of this hands-on plastic processing experience.

This thermoforming exercise can be enhanced and connected to other STEM disciplines in numerous ways. By observing and counting the short processing cycle time, students can estimate and calculate the labor cost involved in its completion. To incorporate minor design aspects, students can identify or possibly make small mold inserts, as shown in figure 3 (flat shape, made of any material that can withstand the thermoforming temperature and pressure). These inserts can be loaded on the plate mold to get more interesting parts with relatively complex geometry. By examining the final product’s shape, surface texture, dimensional details and mold features, the students can gain inspection insight. If the process is repeated with variations in time, pressure, material thickness, and temperature, the students get the experience of controlling the thermoforming process and relating their process changes to physical results.

**Casting: expandable foam bead**

Expandable foam bead casting relies on heat and moisture to cause foam beads to expand to approximately triple their original volume, filling a mold cavity and forming pressure bonds with the adjacent beads. Cheap picnic coolers, insulated disposable cups, packaging, and many similar products are manufactured this way. This can be done in nearly any location due to its simplicity. The basic equipment requirement is a heating element and a pot for boiling water plus a two-part mold that allows moisture and heat ingestion to the beads in the mold cavity. Polystyrene bead should occupy about one third of the cavity volume prior to heating. The partially filled mold
halves are tightly closed to prevent the escape of the foam beads, and then submerged in boiling water for approximately 10 minutes.

Finding the cavity volume affords students an opportunity to identify and apply one or more problem-solving strategies. They may choose to determine the volume by filling the cavity the water then measuring the water’s volume, by measuring the dimensions and calculating volume via equations for standard shapes, approximating the cavity as a set of layered sections, relying on graphics software with a solid model of the mold, and/or perhaps numerous other approaches. In addition, science and mathematics elements could be incorporated through a check of density from the volume and mass if a mass balance scale is available.

**Casting: chemical foam**

In chemical foam casting, a cellular material is formed through a chemical reaction that liberates a gas within the polymer mixture. The gas causes the polymer to expand, or foam. Examples of products produced by chemical expansion of plastics are cushioning/shock absorbing materials, insulation (thermal, acoustical), toys and other consumer goods. Both rigid and flexible cellular materials are produced, as are open and closed cell foams. Open cell foam materials connect to other cells in the component with gaps in the plastic, allowing transfer of gas and liquid between cells. Conversely, closed cell foam materials connect without gaps, allowing no liquid transfer between cells and only permitting gas transfer via diffusion through the cell walls. Both formations have multiple industrial applications.

Typical materials used for chemical foam casting include polyurethane, epoxy, silicone, polystyrene, and isocyanate. The mold material options are broad. As long as the liberated gas vents, the mold material does not react with the polymer material, and the mold shape facilitates part removal (i.e., incorporates radii, is largest at the opening), the mold and its materials will probably be acceptable. Simple choices are a hollow two-piece metal sphere shape, small disposable loaf pan, or small recyclable food storage container. A 3-D printed mold designed by students might also be a good choice. For ease of part removal, the mold cavity should be coated with mold release of some sort.

Chemical foam comes with two significant exposure-based safety concerns. Figure 6a shows the chemicals and required lab materials. Gloves are required for the process due to chemical exposure concerns, and a well-ventilated space is needed for the process, assuming the foam of choice is a two-part polyurethane resin kit or another similar chemical. Students carefully measure each of the two parts (by mass or volume) into disposable cups. The components must be quickly and thoroughly mixed, with the two parts at their specified ratio and limiting stirring time to about 30 seconds for many foams. The mixture is then poured into the mold. Depending on the volume and material, the wait time will differ. Expect to wait about 12-15 minutes before demolding, and check the foam remaining in the mixing cup to know when it has finished its initial reaction. The foam will continue to cure following demolding, so any handling in the hours immediately following processing should be done with care. After demolding, students will get a cream color foam ball as in Figure 6b.
To prepare the right quantity of two parts of resin, students need to figure out the quantity of each part according to given foam ratio. This necessitates students applying equations to calculate the volume of different geometries and connecting material density to mass. For a given mold, students must measure the size before volume calculation. For a 3D-printing design, the volume can be calculated during the design process and confirmed by the computer aided design software. By measuring the mass of the final product and knowing its volume, students can experimentally determine the material density and compare their results to published property data. Unit conversion exercises in length, mass, and volume can also be practiced.

**Casting: hot dipping**

Dipping is a common polymer molding and coating process, where a usually preheated metal mandrel or other substrate is submerged into liquid plastic (such as plastisol) at room temperature then hung inside an oven for post heating. The final product will be a thin coating in the shape of the mandrel which can be removed after cooling, or sometimes, the mandrel may be the product that is to be coated. The typical material used in this lab is vinyl. The hot dip molding process is applied extensively in the metal, rubber, and plastic industries. Plastic and rubber dip products have a smooth surface and water-resistant, such as tool handle grips, coin purses, overshoes, electrical insulation parts, and rubber gloves.¹²,¹³

Hot dipping activity resource requirements are vinyl plastisol, metal mandrel molds, and an appropriate oven. A convection countertop oven can be used to instead of a laboratory oven if its
internal height is sufficient to allow mandrels to hang as they heat, nominally at least 6 inches (150 mm). The required heating temperature for vinyl plastisol is 400 °F so the oven should be able to reach a temperature of at least 450 °F. The vinyl plastisol can be dyed to different colors by adding colorant if desired.

The hot dip process must be completed in a well-ventilated area. To prepare for the hot dip process, mandrels preheat in the oven while students stir the vinyl plastisol dispersion thoroughly to avoid unequal surface coating. The preheated mandrel gets dipped in the vinyl for about one minute, then is hung in the oven. When the oven opens, chlorine will be in the emitted air so students should avoid inhaling as they open the oven. The hot baked mandrel should be cooled in cold water for about 3-5 minutes before demolding. If the part must be cut to remove it from the mandrel, instructor intervention is recommended. Figure 7a shows the sample products baked in the oven and Figure 7b shows the demolding processes as below.

As students acquire hands-on experience and techniques in the process of hot dip casting, a few enhancements may be incorporated. The dipping and baking times can be adjusted to show how these variables affect the product. For example, students may dip and bake some products once and others twice, then measure the wall thickness for single dip and double dip parts. Different colors of plastisol can help distinguish multiple dipping easily, affording another means of making the process interesting. By measuring the mass of the final product and calculating its volume, students can determine the density of the plastic material.

**Casting: Do-It-Yourself (DIY) two-part polyurethane**

If space and equipment are particularly limited, a basic casting process using a DIY two-part polyurethane resin could be implemented in any well-ventilated room. This exothermic material can be formed in molds of many materials, including PLA, if sufficient cooling time is provided. Calculation of volume of each chemical component will be necessary. The components should be added to a disposable container such as a cup, stirred until the chemical reaction causes the container to feel warm, then poured into the lightly coated mold for curing approximately 10 minutes. Demolding is easier if petroleum jelly or a similar coating covers the mold.
Safety in the lab

For all the activities discussed in this paper, students are required to wear safety glasses, long pants, and long sleeve shirts (preferably cotton). Loose clothing or jewelry is unacceptable. Longer hair must be tied back. Students should be made aware of any particular safety hazards associated with the materials and/or processes prior to taking action. Students should operate equipment only under close supervision and should not remove any safety guards. Good ventilation is required in the room for these activities. Furthermore, use of a fume hood is preferable if available.
Combinations, enhancements, and more math opportunities

By designing or choosing the mold style and part geometry they like, students’ motivation to learn and express their creativity will be enhanced. The mold can be as simple and common as something from daily life, like a cookie cutter, cup with lids, or lunch box. For two-part molds used for chemical foam and expandable foam bead, a vent hole is required. For chemical foam, the vent(s) must be on top during the process so the foam will not block the vent. For expandable foam bead, the vent hole must allow ingress of moisture while keeping the beads in the mold. Although this sounds difficult (and can be), often simple solutions like tightly wrapping the mold in aluminum foil are effective.

Many students enjoy 3D printing, which can be incorporated into thermoforming and DIY casting as one-part molds, and into chemical foam and expandable foam bead as two-part molds. The CAD design could be the students’ choice or assigned by the teacher. Simple geometries like a cylinder, sphere, or football mean the instructor may require students to calculate the volume by equation and verify their values with the software. By knowing the volume of the mold and measuring the part’s mass, students can calculate the density of the material using in the lab.

Integration can also be practiced in volume calculation. A non-regular shape may need integration to find the volume. Multiple layers will be separated along vertical axis. Each relatively thin layer’s volume will be calculated and all the value will be summed up at the end to get the total volume. An example is shown in appendix C.

Evaluation

These activities were developed for two purposes: to ensure plastics processes can be integrated into an introductory materials and processes course that is offered in multiple locations which have varying amount of laboratory infrastructure, and to familiarize pre-college students with common plastics processes as a means of attracting them to pursue degrees in engineering technology (while making them more informed consumers, et cetera). The corresponding outreach programs were first offered in November 2015 as part of an informal education program for participants of all ages at the Indiana State Museum, with no effort to determine the program’s effectiveness at attracting pre-college students to engineering technology. Many of the initial participants were at the preschool and early elementary school level and only able to complete the process of DIY casting into simple thermoformed molds while under one-on-one supervision. More comprehensive versions of these plastics processing sessions were provided to high school juniors in spring 2016. Data on their applications to attend the sponsoring institution, the college that administers most of the engineering technology programs, and their selection of engineering technology majors are presented in Table 1, combined with data from previous outreach programs that did not involve plastics processes. It is impossible to definitively state that the processing activities are the reason students are selecting engineering technology major, but there is a clear link between attendance at these outreach programs and knowing that engineering technology is the student’s preferred major. Nearly students who were admitted to engineering technology at the institution offering the programs have opted to enroll in one of the engineering technology majors. These activities have similarly improved student learning of materials and processes at the university freshman level.$^{16}$
Table 1: Technology-based Outreach Programs & Matriculation in Engineering Technology

<table>
<thead>
<tr>
<th>YEAR</th>
<th>ATTENDANCE</th>
<th>APPLIED</th>
<th>ET apply</th>
<th>ET admit</th>
<th>ET enroll</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>104</td>
<td>75</td>
<td>11.5%</td>
<td>66.67%</td>
<td>87.50%</td>
</tr>
<tr>
<td>2015</td>
<td>103</td>
<td>65</td>
<td>8.7%</td>
<td>66.67%</td>
<td>100.00%</td>
</tr>
<tr>
<td>2016*</td>
<td>58</td>
<td>42</td>
<td>8.6%</td>
<td>100.00%</td>
<td>not complete</td>
</tr>
</tbody>
</table>

Key:
- **attendance** = participation in an outreach program for Juniors
- **Applied** = submitted a college application
- **ET apply** = applied to an engineering technology major
- **ET admit** = admitted to an engineering technology major
- **ET enroll** = matriculated to an engineering technology major

* 2016 attendance was lower due to administrative transitions, and was nearly matched by spring only 2017 headcount.

References:

### Appendix A – Resource requirements

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment</th>
<th>Mold</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoforming</td>
<td>Small thermoforming machine - $120</td>
<td>Small parts can be loaded in the existing mold as an extra mold</td>
<td>Plastic sheets like PS, PETG, and PLA ($8 – letter size)</td>
</tr>
<tr>
<td>Chemical foam</td>
<td>A stand to hold the mold during processing (can be homemade simply)</td>
<td>Two-part mold, metal, or plastic - $60 (3.5” diameter metal ball)</td>
<td>Polyurethane pour foam(2 parts) kit - $40 (2quarts)</td>
</tr>
<tr>
<td></td>
<td>Digital weight scale - $15</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Gloves - $5 (box)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Popsicle sticks - $2 (50pcs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paper cups (4oz and 8oz) - $5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mold release spray - $10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expandable foam</td>
<td>A 10-12inch stockpot with lid - $25</td>
<td>Metal two half-part molds- $33 (4” tall)</td>
<td>Polystyrene bead- $15 (5lbs)</td>
</tr>
<tr>
<td></td>
<td>Electrical burner - $25</td>
<td>Foil molds (baking goods section, normal below $3 each)</td>
<td></td>
</tr>
<tr>
<td>Hot dip casting</td>
<td>A conventional toast oven (around $50)</td>
<td>Metal mandrels - $6 (2” diameter or side length)</td>
<td>Vinyl (plastisol) - $9 (quart)</td>
</tr>
<tr>
<td></td>
<td>Coloring powder (may come with the order of Vinyl)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIY casting</td>
<td>One-part mold of choice</td>
<td>Gloves, petroleum jelly, cotton swabs, disposal cups ~$15</td>
<td>AlumiRes (RC-3), $32</td>
</tr>
</tbody>
</table>

All the prices listed are estimated and/or approximated, and should not be assumed to be current. For purchasing certain materials and equipment, possible sources are:

- [http://www.iasco-tesco.com](http://www.iasco-tesco.com)

Appendix B – Equations

Density: \( \rho = \frac{m}{V} \), while \( m \) is mass, \( V \) is volume

Mass can be measured by digital scale.

Surface area (A):

1. Rectangle surface: \( A = \text{length} \times \text{width} \)
2. Triangle surface: \( A = \frac{\text{Base length} \times \text{Height}}{2} \)
3. Circular surface: \( A = \frac{\pi d^2}{4} = \pi r^2 \), while \( d \) is diameter, \( r \) is radius of the circle

Volume (V):

1. Cylinder: \( V = \text{surface area of one end} \times \text{height} = \pi r^2 h \)
2. Cube: \( V = \text{height} \times \text{length} \times \text{width} \)
3. Sphere: \( V = \frac{4}{3} \pi r^3 \)

Draw ratio:

1. Rectangle shape: \( \text{Draw Ratio} = \frac{\text{Part Depth}}{\text{Part Width}} \)
2. Cylinder shape: \( \text{Draw Ratio} = \frac{\text{Part height}}{\text{Diameter}} \)

Areal Draw Ratio: \( \text{Areal Draw Ratio} = \frac{\text{Surface Area of Part formed}}{\text{Footprint}(\text{Area of the sheet within clamps})} = \frac{\text{Part Area}}{\text{Sheet Area}} \)

\( \text{Initial Sheet Thickness (estimated)} = \text{Areal Draw Ratio} \times \text{Final Thickness (part)} \)
Appendix C – Example volume of revolution for an arbitrary solid shape

If a solid is resulted from revolving a region about a given line, it is called a solid of revolution and the given line is called the revolution axis. The volume of a solid of revolution can be calculated by using a disc method.

1. Set the center line be the revolution axis x and divide equally 10 segments along the line. Each segment has length h and the left end of the total length is point O and the right end point is A which marks at 10h.

2. Draw y-axis normal to x-axis and through starting point O.

3. Draw the revolved region (Fig 5) from O to A.

4. Measure the y axis value r from x=1h to 10h.

5. Use the cylinder volume equation to calculate each segment volume as a cylinder: \( V = \pi r^2 h \), eg, \( V_1 = \pi r_1^2 (1h) \)

6. Add all the individual volume and get the total volume of the solid of revolution

Figure C1: Revolved region, which is below the blue line