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Education in Plastics Manufacturing: Aluminum Mold Making and Injection Molding

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ABSTRACT

Plastics are ubiquitous in the modern world with both positive and negative consequences. Students will benefit from understanding how plastics are manufactured. They will be more aware of the material and have a better appreciation for the need to recycle. Injection molding is one of the primary plastics manufacturing methods and hobby scale injection molding machines can be used to educate students about plastics and polymers. Furthermore, it is possible to create custom injection molds from aluminum using similar hobby scale tools. In this article, experiences introducing injection molding in the classroom and experiences with mold making as a senior design project are presented. Suggestions and procedures for using the injection molding machine and for creating custom aluminum molds are covered.

KEYWORDS

Injection Molding, Mold, Plastics, Polymer, Aluminum, Milling Machine, Hobby Scale, Recycle, Senior Design, Education in Plastics Manufacturing

INTRODUCTION

Plastics are so common in modern life that it’s easy to forget they were developed recently. In 1950, the total plastics produced around the world amounted to 1.5 million metric tons per year (MMTPY); by 1989 that figure had increased to 100MMTPY, by 2006 it reached 245MMTPY, and in 2015 it was 380MMTPY[1,2] . The enormous amount of plastics produced is testament to their importance, but they are often taken for granted. For example, of all the plastics that people have discarded over the years, only 9% have been recycled, the rest have either been incinerated or sent to landfills[1]. There is clearly a need for increased awareness of plastics, and hands-on plastics manufacturing experiences will help meet this need.

Current US standards, such as Project 2061 by the American Association for the Advancement of Science (AAAS) and the Next Generation Science Standards by the National Research Council (NRC), do not have specific benchmarks for plastics at the high school level[3–5]. Project 2061’s Benchmarks for Science Literacy includes a middle school benchmark, 8B/M6, that specifically addresses synthetic materials, such as plastics[3], but there are no similar high school standards. Undergraduate engineering students are more likely to learn about plastics, but curriculum standards in the US are focused on broad outcomes rather than specific content[6], so exposure will depend on the program.

Education about plastics has not kept up with the growing importance of the plastics industry. One possible explanation is that the US made a pivotal investment in science during the 1950s and 1960s which had a lasting effect on curriculum[7–10]. Though the potential importance of plastics was known by education leaders[11], plastics production was at a comparatively low level at that time and did not have the same relevance as it does now.

In addition to the work described here, there are other examples of polymer and plastics demonstrations and activities[12–17]. Torres describes teaching plastics manufacturing at the undergraduate level[16] and Powers describes the use of injection molding in a senior design project[17]. Two articles by Joseph Castka describe early examples of plastics manufacturing activities, but the materials and methods may not be practical in the modern setting[18,19]. Alfredo Mateus described a low cost demonstration of blow molding[20]. Ferdinand Rodrigues described demonstrations for extrusion, blow molding, compression molding, and vacuum forming[21]. Low cost 3D printers offer another way to introduce plastics manufacturing, but they print slowly which limits the opportunity for hands-on experiences by students in a lab class. Additionally 3D printing currently accounts for a small segment of industrially manufactured parts[22]. Injection molding, on the other hand, is one of the chief industrial manufacturing methods for thermoplastics. Herein can be found useful information for those interested in using an injection molding machine in a classroom, lab, or project.

A hobby scale injection molding machine (IMM) that costs around $2000 to $3000 offers a relatively inexpensive way to introduce students to plastics manufacturing. In recent years more manufacturers have started offering IMMs around this price point but the lack of off-the-shelf molds limits their usefulness. While it is relatively easy to make new plastic objects with a 3D printer, making a new plastic object with an IMM requires the creation of a new mold. There exists a large difference in skill requirement between operating an IMM compared to making a custom mold. Necessarily much of this article and the supplemental material is focused on the mold making aspect of plastics manufacturing due to the technical challenges associated with it.

Figure 1. A custom aluminum injection mold that creates a ball-and-stick model of polyethylene

Aside from making the mold, the actual process of injection molding is fast and easy to learn. The author's initial effort to introduce education in plastics manufacturing was done while teaching high school juniors and seniors. The students had no difficulty learning to use the IMM, and because it produces parts very quickly it could be incorporated into lessons without diverting much class time away from the learning objectives aligned with the mandated curriculum. For example, the author used a custom mold for a toy wheel to allow high school students to make their own balloon powered cars for studying momentum in a physics class[23]. For undergraduate engineering majors, a hobby scale IMM could be incorporated in a similar way, for example students could use it to make their own dogbone specimens for tensile strength testing. Alternatively, in a course such as materials science an IMM could be introduced as part of the main learning objectives as a low cost way to expand the plastics section of the course with hands-on activities. In the above cases, it would be desirable and/or necessary to have custom molds. In this article the process of designing a custom mold that makes a ball-and-stick model of polyethylene (Figure 1) is describe. Such a mold could be used, for example, in a materials science class for the students to create their own model of a polymer in order to demonstrate molecular scale phenomena in plastics.

The author's experience teaching undergraduate students about plastics manufacturing has been primarily through senior design projects on mold making. Due to the amount of work involved senior design was deemed the best venue. The students had all previously taken courses on CAD modeling and CNC machining which prepared them for their projects.

MATERIALS AND METHODS

Injection Molding Machine

The IMM used in this work was a Model 150A Plastic Injection Machine (LNS Technologies, Scotts Valley, CA) with Quick Release Toggle Mold Clamp (LNS Technologies). The PID temperature controller was adjusted to 238°C (460°F), for use with virgin polypropylene pellets with melt flow index of 12 (Birch Plastics, Houston, TX). The IMM, loaded with pellets, was preheated 10 minutes prior to use. To operate the IMM, plastic pellets were added to the hopper; the mold was positioned and locked in place with the clamp, and the lever arm was manually pulled to apply pressure and inject plastic into the mold. Several shots were generally required to warm up the mold; these initial shots did not fill the mold cavity completely but the heat from the plastic warmed the mold and complete parts could then be made. The warm mold allowed the plastic to fill the cavity completely before solidifying.

CNC Milling Machine

The author's initial work took place at the high school level without access to a machine shop, as such this section covers the use of a low cost hobby scale CNC milling machine for mold making. At the university level, a machine shop with professional tools will most likely be available. Molds made by the author's senior design students used a HAAS Mini Mill located in the Mechanical Engineering machine shop. Details on the use of the hobby scale mill are included for those who may be interested, such as faculty wishing to add a small machine shop to their lab or to create a "lab on a cart" arrangement that includes a mill and an IMM on a mobile platform.

The custom mold was made from 6061 aluminum bar stock, 2”x1/2” (50.8 mm x 12.7mm) in profile, cut to 3” (76.2 mm) lengths with a chop saw before being machined with a desktop CNC mill. The CNC mill was a Taig model 2000 HD-ER micro mill (Taig Tools, Chandler AZ). MachIII software (Newfangled Solutions, Livermore Falls, ME) is used to control the CNC mill. A UC100 USB Motion Controller (CNC Drive, Pécs, Hungary), a USB to serial port adapter, was used to connect the PC running MachIII to the CNC mill. A variety of end mills and collets were used ranging from 1/8” (3.175 mm) diameter to ¼” (6.25 mm) diameter. End mills included flat, ball and tapered variety. Raceways were lubricated using standard automotive transmission fluid and WD-40 (WD-40 Company, Budd Lake, NJ) was applied to the end mill and aluminum workpiece during milling as lubricant to prevent overheating.

CAD/CAM Software

Fusion360 (Autodesk, San Rafael, CA) CAD/CAM software was used to create a 3D model of the mold and to simulate toolpaths. Fusion360 was also used to create G-code, ascii-text commands readable by the MachIII software.

Ancillary Tools and Equipment

The IMM and CNC Mill were both bolted to a heavy duty workbench on caster wheels creating a “lab on a cart” that could be moved from classroom to classroom as well as outdoors. A number of useful tools were housed on the workbench/cart: 45°-90° quick layout tool for squaring the mill, calipers for precise measurement of parts, adjustable wrenches, screw drivers, hex keys, pliers, and personal protective equipment (PPE). Additionally, a shop vacuum was attached to the cart, allowing quick and easy cleanup of metal shavings from the milling machine and spilled plastic pellets from the IMM.

RESULTS AND DISCUSSION

Engineering Senior Design Use

The author has mentored two engineering senior design projects in consecutive years utilizing a hobby scale injection molding machine. Students were able to design and fabricate their own molds and successfully manufacture plastic parts. Students showcased skills in CAD/CAM, machining, work design, and quality control.

Learning objectives included the ability to plan the mold design based on requirements, to select proper tooling to machine the mold cavity, to make aligned mold cavities in a two-part mold, to use CAM software to create files for CNC machining, to use CNC machining tools to create aluminum molds, to develop work procedures for using the mold with the IMM, to develop quality control procedures, and to collect and analyze data to verify project requirements were met. Deliverables included CAD/CAM files, the injection mold, examples of plastic parts made with the mold, work procedures, quality control procedures, verification data and test results, as well as a report and presentation. Grading was based on progress assessed during weekly meetings, general quality of work, and thoroughness of verification testing to demonstrate that requirements were met. The senior design teams that worked on mold making projects indicated that it was a challenging but positive experience resulting in an increase of knowledge, skills, and confidence.

The supplemental material includes a guide which may be of use to senior design students to help them understand special considerations in mold design such as avoidance of undercuts, placement of the parting line, placement of runners and gates, and ensuring alignment of cavities in the mold halves. It also includes an overview of CAD/CAM concepts necessary for mold design. The guide may also be of use to instructors interested in making custom molds for their classes.

Classroom Use

Students at the undergraduate and even the high school level can benefit from the molds made by senior design projects, as described above. Partnering with STEM teachers at local high schools would be an excellent way to provide real-world requirements for the molds made by senior design teams, as well as creating a means to introduce education in plastics manufacturing at the high school level. Molds from the senior design teams may also be designed for use in courses within the department.

The author used the IMM for classroom activities with 12 groups of students over two consecutive years. The IMM was so easy to operate that most students were able to run it after a 3-5 minute introduction. A complete cycle of injection, removal of the part from the mold, and setup for the next shot could be done in a minute or less, making it possible for all students to get hands-on experience within one or two class periods.

Students worked in teams with the following roles: hopper filler, injection lever operator, clamp operator, and mold remover. Students were challenged to work together to develop a process that would allow them to operate the IMM as quickly as possible. Each team had to go through cycles of designing and testing potential work processes until arriving at an efficient one. It's worth pointing out that this usually took no more than 5-10 minutes to complete. Initially students tend to defer to the lever operator as the leader and wait for that person to direct the others resulting in a slow process. With more experience students act according to the stage of the process without needing instruction and resulting in increased speed, but usually some rate limiting steps emerge. Difficulty removing the part from the mold, difficulty clamping the mold, and getting in each other's way are common problems. Other problems include not applying enough force to the lever and loading the hopper without spillage. Proposing solutions and testing them as a team usually resulted in an optimized work process relatively quickly.

Classroom activities started with a brief presentation describing plastics and emphasizing their importance in the modern world. The presentation was followed by a class discussion where students were asked to share experiences of their own relating to plastics. Because only one IMM was used, after the discussion students were divided into teams in order to take turns using the machine.

Learning objectives associated with the presentation and discussion included recognizing that plastics are relatively new materials, that manufacturing of plastics has been increasing exponentially over the years, that plastics are used in many important (even lifesaving) products, that most plastics are not biodegradable, that thermoplastics soften when heated and are generally recyclable, that thermoset plastics undergo a chemical reaction called curing and are usually not recyclable, that plastics are made from polymers, that different types of plastics have different physical and chemical properties and cannot normally be recycled together, common types of plastics and their uses, and common methods of plastics manufacturing including extrusion, thermoforming, 3D printing, and injection molding.

Learning objectives associated with the hands-on experience include being able to operate the IMM, being able to communicate with team members to coordinate a manufacturing process (injection molding), being able to propose strategies for process improvement, and familiarity with manufacturing by injection molding. Students also learned about recycling, which is described below.

Assessment was done informally when the IMM was used to support other course learning objectives; when the IMM was the main focus of the lesson, pre- and post-activity quizzes were also given. The quizzes included matching questions to assess student knowledge as well as survey questions to determine student opinion regarding plastics. The pre- and post-assessments used identical questions with scrambled matching order. Informal assessment involved asking the students to talk about their experience and to explain how they were able to improve the process. In some cases, students needed to be encouraged to develop a faster process by challenging them to beat a particular cycle time such as 90 seconds or 60 seconds; the instructor can assist them by asking detailed questions about the bottlenecks and how they can be improved. Student can be asked to provide a write-up or short report explaining their process improvement activities.

Recycling

The IMM provides an excellent opportunity for students to get hands-on experience recycling plastics with no additional work required. The injection molding process generates waste plastic through failed injection attempts, sprues removed form parts, and spilled pellets. Students often want to throw this material away, and are interested to learn that it can be recycled. Small pieces can simply be placed back into the hopper and can be used as-is to make new parts. Larger pieces may not be immediately recyclable within class-time because they need to be cut or ground down in order to fit into the IMM. Assessment for recycling activities are similar to those described in the Classroom Use section.

With access to a plastics granulator, recycling activities could be expanded to include plastics from consumer products or other sources. Students could learn how pigments combine when different colored plastics are mixed and about challenges relating to color sorting. Students could also learn about the need for separating plastics by type, for example, separating the caps from water bottles. Currently hobby scale granulators are not widely available but a number of companies are developing them.

Hazards

At injection temperature, polypropylene release fumes which are a nuisance and can be harmful upon long term exposure. Reported cases of serious adverse effects were for asthma sufferers exposed over years through their workplace[24,25]. Fumes result from polymer degradation and the most concerning compounds released are acetaldehyde, formaldehyde, and acetone[26]. The concentrations should remain below the Occupational Safety and Health Administration (OSHA) permissible exposure limits as long as the IMM is operated at the appropriate temperature with adequate indoor ventilation or outdoors[26–29].

In addition to standard laboratory precautions, including wearing safety glasses, students should wear leather work gloves to protect against contact with hot surfaces and accidental pinching or gouging while using pliers to remove parts from molds.

Mold Making

A model of the object is made with CAD software and a Boolean subtraction operation is used to create the mold cavity. Runners and gates, pathways through which heated plastic travels, are created in the same way. Care must be taken to avoid creating undercuts in the mold that would trap the plastic part and prevent it from being removed. Through trial and error the workflow in Box 1 was developed.

Box 1. Workflow for Making an Injection Mold

1) Visualize the part
2) Decide on parting line location, no overhangs, flat parting line
3) Consider milling tools before specifying dimensions
4) Pencil and paper sketch with key dimensions
5) CAD model of part
6) CAD model of gates, runners and pins
7) Boolean operations to make CAD models of molds
8) CAM milling tools setup
9) CAM workpiece setup
10) CAM toolpaths
11) CAM simulations
12) CAM post processing
13) G-Code editing
14) CNC Controller simulation
15) CNC setup (setting origin)
16) CNC milling
17) Polishing (optional; can remove machining marks)
18) Set Alignment Pins

While working on Box 1 steps 1-7, it is important to consider not only what can be made with the CAD program, but what can be made with the milling machine. Students should keep in mind the diameter of the end mill and avoid designing grooves and cavities that are too small to be machined. Box 1 Steps 8-11 require feed and speed values for the end mill; Table 1 lists data used by the author with the Taig CNC milling machine. These data are conservative; the author found milling slowly avoided broken end mills and was more cost effective than optimizing for rapid milling.

Table 1. End Mill Feeds and Speeds Used for Aluminum Mold Making with Hobby Scale Machine[a]

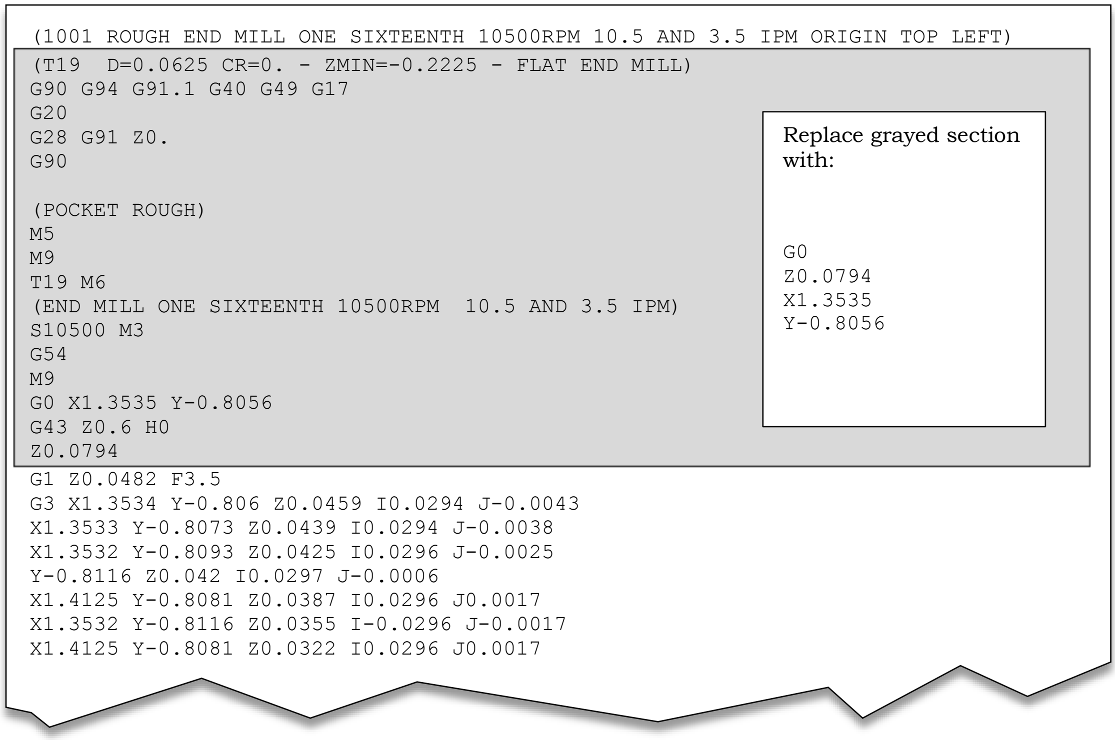
Diameter (inch)	Diameter (mm)	Number of Flutes[b]	Speed (RPM)	Feed Rate (inch/min)	Feed Rate (mm/min)	Feed Rate for Plunge Cuts[c] (inch/min)	Feed Rate for Plunge Cuts[c] (mm/min)
1/32 - 1/16	0.79375-1.5875	4	10500	21	530	7.0	180
3/32 - 1/8	2.38125-3.175	4	6500	13	330	4.3	110
5/32 - 3/16	3.96875-4.7625	4	4300	8.6	220	2.9	74
1/4	6.35	4	2900	5.8	150	1.9	48
1/32 - 1/16	0.79375-1.5875	2	10500	10.5	267	3.5	89
3/32 - 1/8	2.38125-3.175	2	6500	6.5	170	2.2	56
5/32 - 3/16	3.96875-4.7625	2	4300	4.3	110	1.4	36
1/4	6.35	2	2900	2.9	74	1.0	25

[a] Applies to flat end mills and ball end mills used on 6061 aluminum

[b] Flutes are the cutting edges on the end mill

[c] Plunge cuts occur when drilling downward

Box 1 Steps 12-13 required customization to work with the MachIII software that controls the Taig CNC milling machine. Figure 2 shows how the G-code generated with the “CNC Router Parts (Mach3Mill)/cncrouterparts” post processor configuration was manually edited.



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(1001 ROUGH END MILL ONE SIXTEENTH 10500RPM 10.5 AND 3.5 IPM ORIGIN TOP LEFT)
(T19  D=0.0625 CR=0. - ZMIN=-0.2225 - FLAT END MILL)
G90 G94 G91.1 G40 G49 G17
G20
G28 G91 Z0.
G90

(POCKET ROUGH)
M5
M9
T19 M6
(END MILL ONE SIXTEENTH 10500RPM  10.5 AND 3.5 IPM)
S10500 M3
G54
M9
G0 X1.3535 Y-0.8056
G43 Z0.6 H0
Z0.0794
G1 Z0.0482 F3.5
G3 X1.3534 Y-0.806 Z0.0459 I0.0294 J-0.0043
X1.3533 Y-0.8073 Z0.0439 I0.0294 J-0.0038
X1.3532 Y-0.8093 Z0.0425 I0.0296 J-0.0025
Y-0.8116 Z0.042 I0.0297 J-0.0006
X1.4125 Y-0.8081 Z0.0387 I0.0296 J0.0017
X1.3532 Y-0.8116 Z0.0355 I-0.0296 J-0.0017
X1.4125 Y-0.8081 Z0.0322 I0.0296 J0.0017
```

Replace grayed section with:

```
G0
Z0.0794
X1.3535
Y-0.8056
```

Figure 2. The asci-text G-code created by the Fusion360 post processor that needs to be edited in order to work with the MachIII software used by the Taig CNC mill.

For a more detailed explanation of the mold making process, please see the supplemental material.

Ball-and-Stick Model

The ball-and-stick model shown in Figure 3 has two parts that must be separated and snapped together to make a model single-monomer unit. The two pieces have 0.01inch (0.254 mm) clearance between them in the CAD model but uneven cooling and warpage results in a tight fit for the physical model. A hemisphere and detent is used to hold the piece in place. Multiple monomer units attach together to make the model polymer. Attachment is achieved by creating a hollow sleeve on one model covalent bond and a prong on another. The sleeve is made by inserting a 3/32” (2.38mm) diameter aluminum rod that creates the cavity. The rod is inserted from the bottom along a hole that follows the part line. After plastic injection the rod is carefully twisted free from the part for reuse.

Working together students can assemble a polymer long enough to visualize molecular scale phenomena such as entanglement of polymer chains and crystallinity. They can also demonstrated the relationship between random-walk, polymer structure, and entropy. By rotating each monomer unit the overall shape of the polymer can be changed and the backbone of the polymer resembles a random walk in 3-dimensions. Rotating the monomers to maximize the distance from the head to the tail of the polymer requires one specific configuration, a straight line with the backbone following a zig-zag pattern. Shorter distances measured directly from head to tail can be achieved through many different configurations. In this way it can be demonstrated that a more compact polymer structure tends to have higher conformational entropy than a stretched out polymer structure.

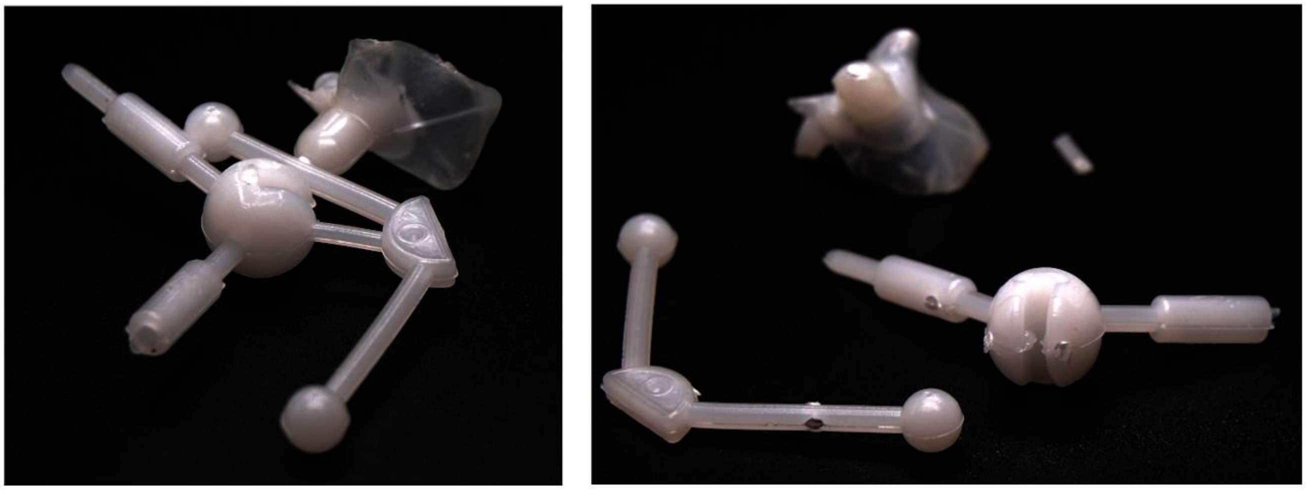

Figure 3. The injection molded plastic part as removed from the mold (left) and after being trimmed apart (right). The two pieces clip together to form one monomer. Multiple monomers can be attached together to form a polymer.

CONCLUSION

The hobby scale IMM is easy to learn and fast to operate. It is reasonable to plan activities to engage all students in a class or lab over just one or two sessions. Challenging students to develop a workflow to produce parts quickly is an opportunity to exercise process skills which can be expanded upon by asking them to write or talk about their experience. Students will spill pellets and create plastic waste from failed parts; all of these can be placed back into the hopper for immediate recycling. Experiencing plastic recycling firsthand can be the seed for a writing assignment, presentation or class discussion. The mold described here, for use in making a polyethylene ball-and-stick model, can be used to engage students in learning about plastics and to create demonstrations of polymer behavior.

Mold making requires more time and more advanced skills; it is most appropriate for a senior design project. The requirements for the senior design project can be based on custom molds needed for other courses or for local high schools interested in teaching students about injection molding. Making custom molds provides students with valuables skills and experience for their future engineering career.

As the manufacture of plastics continues to grow, it is important to include more opportunities to educate students, at all levels, about these amazing and relatively new materials. The low cost and abundance of plastic products, especially recyclable disposable products, leads many to undervalue its importance and global impact. Educational opportunities, such as those with an inexpensive hobby-scale IMM describe here, can help students better understand plastics and better appreciate the role plastics play in their lives.

SUPPLEMENTAL MATERAIL

Creating an Aluminum Injection Mold.pdf

DECLARATION OF CONFLICTING INTERESTS

The Author declares that there is no conflict of interest.

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REFERENCES

1. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. *Sci Adv* 2017; 3: e1700782.

2. *"The Compelling Facts about Plastics. An Analysis of Plastics Production, Demand and Recovery for 2006 in Europe.* PlasticsEurope (APME).

3. Benchmarks Online ~ Project 2061 ~ AAAS. *Project 2061*, http://www.project2061.org/publications/bsl/online/index.php (accessed 20 October 2020).

4. Council NR. *Next Generation Science Standards: For States, By States*. The National Academies Press. Epub ahead of print 15 August 2013. DOI: 10.17226/18290.

5. Cersonsky RK, Foster LL, Ahn T, et al. Augmenting Primary and Secondary Education with Polymer Science and Engineering. *J Chem Educ* 2017; 94: 1639–1646.

6. Akera A. Setting the Standards for Engineering Education: A History [Scanning Our Past]. *Proc IEEE* 2017; 105: 1834–1843.

7. George E. DeBoer. 28. The History of Science Curriculum Reform in the United States. In: Norman G. Lederman, Sandra K. Abell (eds) *Handbook of Research on Science Education, Volume II*. Routledge, 2014.

8. *Taking Science to School: Learning and Teaching Science in Grades K-8*. Washington, D.C.: National Academies Press.

9. Barrow LH. A Brief History of Inquiry: From Dewey to Standards. *J Sci Teach Educ* 2006; 17: 265–278.

10. Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. 20.

11. Hurd, Paul D. Science literacy: Its meaning for American schools. *Educ Leadersh* 1958; 16: 13–16.

12. Mc Ilrath SP, Robertson NJ, Kuchta RJ. Bustin' Bunnies: An Adaptable Inquiry-Based Approach Introducing Molecular Weight and Polymer Properties. *J Chem Educ* 2012; 89: 928–932.

13. Iler HD, Rutt E, Althoff S. An Introduction to Polymer Processing, Morphology, and Property Relationships through Thermal Analysis of Plastic PET Bottles. Exercises

Designed to Introduce Students to Polymer Physical Properties. *J Chem Educ* 2006; 83: 439.

14. Bopegedera AMRP. Tie-Dye! An Engaging Activity To Introduce Polymers and Polymerization to Beginning Chemistry Students. *J Chem Educ* 2017; 94: 1725–1732.

15. Erk KA, Rhein M, Krafcik MJ, et al. Demonstrating the Effects of Processing on the Structure and Physical Properties of Plastic Using Disposable PETE Cups. *J Chem Educ* 2015; 92: 1876–1881.

16. Torres FG. Some Remarks on the Teaching of Polymer Processing to Mechanical Engineering Students. *Int J Mech Eng Educ* 2002; 30: 155–164.

17. Powers LM, Summers JD. Integrating Graduate Design Coaches in Undergraduate Design Project Teams. *Int J Mech Eng Educ* 2009; 37: 3–20.

18. Castka JF. Demonstrations on the preparation and molding of plastics. *J Chem Educ* 1943; 20: 253.

19. Castka JF. Demonstrations on the preparation and molding of plastics—Part II. *J Chem Educ* 1944; 21: 38.

20. Mateus ALML. Polymer Processing Demonstrations Using PET Bottles. *J Chem Educ* 2019; 96: 1696–1700.

21. Rodriguez F. Classroom demonstrations of polymer principles. Part V: Polymer fabrication. *J Chem Educ* 1992; 69: 915.

22. Attaran M. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Bus Horiz* 2017; 60: 677–688.

23. Mini Grants, Major Benefits: South Houston High School - Education in Plastics Manufacturing, https://www.youtube.com/watch?v=FUsMfQoI-4s (2018, accessed 18 October 2020).

24. Malo JL, Cartier A, Pineault L, et al. Occupational asthma due to heated polypropylene. *Eur Respir J* 1994; 7: 415–417.

25. Lee JS, Kwak HS, Choi BS, et al. A Case of Occupational Asthma in a Plastic Injection Process Worker. *Ann Occup Environ Med* 2013; 25: 25.

26. Frostling H, Hoff A, Jacobsson S, et al. Analytical, occupational and toxicologic aspects of the degradation products of polypropylene plastics. *Scand J Work Environ Health* 1984; 10: 163–169.

27. CDC - Immediately Dangerous to Life or Health Concentrations (IDLH): Acetaldehyde - NIOSH Publications and Products, https://www.cdc.gov/niosh/idlh/75070.html (2018, accessed 18 October 2020).

28. CDC - Immediately Dangerous to Life or Health Concentrations (IDLH): Formaldehyde - NIOSH Publications and Products, https://www.cdc.gov/niosh/idlh/50000.html (2018, accessed 18 October 2020).

29. CDC - Immediately Dangerous to Life or Health Concentrations (IDLH): Acetone - NIOSH Publications and Products, https://www.cdc.gov/niosh/idlh/67641.html (2018, accessed 18 October 2020).

30. Zhu W, Fan X, Brake N, et al. Engineering Design and Manufacturing Education through Research Experience for High School Teachers. *Procedia Manuf* 2018; 26: 1340–1348.