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Using Mechanical Testing of Disposable Plastic Cups to Illustrate Processing-Structure-Property Relationships in an Introductory Materials Laboratory Course

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A hands-on activity was implemented in a sophomore-level materials engineering laboratory to illustrate how the structure and properties of polymeric materials are directly influenced by the method of processing. The mechanical properties of specimens cut from the walls of poly(ethylene terephthalate) cups, oriented parallel and perpendicular to the thermoforming direction, were measured in tension. The parallel sample displayed greater elastic moduli, yield stress, and predominantly ductile deformation behavior compared to the relatively weaker and more brittle perpendicular sample. This observed mechanical anisotropy was related to the processing-induced orientation of polymer molecules within the cup. Students' learning outcomes were assessed and it was found that processing-structure-property relationships were communicated most effectively by encouraging the students to describe their ideas through molecular-scale sketches and further challenging them to design their own hypothesis-driven experiments as compared to a traditionally prescribed lab activity.

Introduction

Processing-structure-property relationships are central to the field of materials engineering. To introduce students to this important paradigm, a hands-on activity was designed and implemented in an introductory, sophomore-level materials engineering laboratory course at Purdue University (West Lafayette, Indiana). The objective of the activity was to illustrate how the molecular-level structures and macroscale properties of disposable plastic cups are directly influenced by the method of processing in a way that does not require the use of sophisticated manufacturing equipment or time- and energy-intensive plastic melt processing laboratory tasks. Thus, this activity is well suited for any engineering or science laboratory course in which materials are discussed.

In this document, we first summarize the scientific background related to the processing, structure, and properties of disposable plastic cups. Second, the logistics of the activity and representative experimental results are described in detail. Third, we report the two different methods that were used to implement this activity with identical groups of students, how the methods were assessed for effectiveness, and the quantitative results of our assessment. It was found that students displayed an enhanced understanding of polymer processing-structure-property relationships when specifically instructed to draw sketches that indicated how the processing method impacted the cup's structure and further challenged to describe their processing-structure ideas in the form of a hypothesis, which was tested during the activity.

Scientific background

Many common disposable plastic cups are composed of poly(ethylene terephthalate) or "PETE", displaying the familiar #1 recycling code on the base of the cup.[1] Plastic cups are typically processed by a molding method known as thermoforming, in which a thin sheet of PETE is heated and expanded into a cup-shaped mold cavity by either applying a vacuum or mechanical pressure.[2] This processes causes significant stretching of the sheet, as shown in Figure 1. The shape is then cooled, released from the mold, and trimmed from the sheet, forming a stand-alone, solid plastic cup.

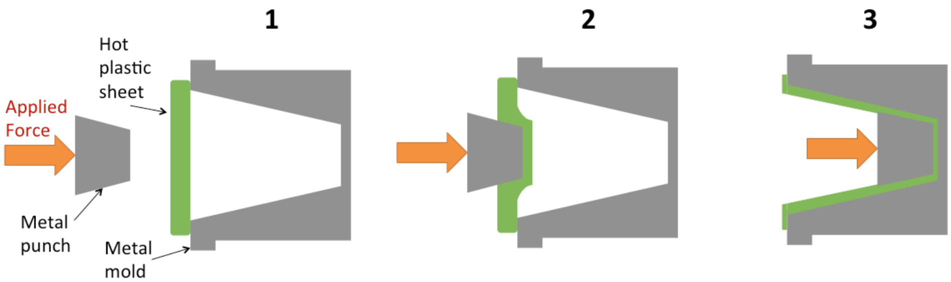


Figure 1: Side-view schematic illustrating the three basic steps in a mechanical thermoforming process used to make a cup from a hot plastic sheet.

As described in a recent study[3], the thermoforming-induced stretching of the PETE sheet to form the cup's walls actually has a measurable impact on the cup's mechanical properties. Specifically, the mechanical strength of the cup's wall was found to be anisotropic, displaying high stiffness, strength, and ductility when tested in a direction parallel to the long-axis (*i.e.*, height) of the cup and reduced mechanical properties and ductility when tested in a perpendicular direction. This idea is illustrated schematically in Figure 2. The increased strength that was observed during tensile testing of "parallel" specimens compared to "perpendicular" specimens was due to the molecular-level differences between the specimens, ultimately induced by the thermoforming process. For parallel specimens, the applied tensile force was supported by the relatively strong covalent bonds within polymer chain (with energies ranging from 30 to 100 × 10^{-20} J). For the perpendicular specimens, only relatively weak van der Waals forces between neighboring chains (with bond energies of ~ 1 × 10^{-20} J) resisted the applied tensile force.[4–6] Thus, by conducting mechanical measurements on specimens cut in different directions from the walls of a disposable plastic cup, students can collect direct evidence of how the cup's properties are impacted by its structure and processing.

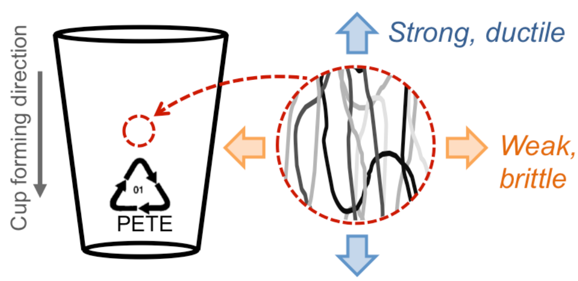


Figure 2: Schematic of processing-induced alignment of polymer chains within the walls of a plastic cup and the resulting mechanical anisotropy when tested in different directions, "parallel" and "perpendicular" to the long-axis of the cup.

Activity logistics

Students were provided with safety glasses, scissors, markers, and digital calipers. A selection of clear, 12-oz., PETE disposable cups was purchased from a local grocery store and provided to the students. Students cut specimens from the walls of the cups (Figure 3), using templates adapted from ASTM standards, included in Appendix A.[7] Specimens were

Figure 3: Students cutting specimens from the PETE cups and loading specimens into the tensile testing machine.

oriented parallel and perpendicular to the long-axis (height) of the cup. After measuring the dimensions and labeling their specimens, a benchtop mechanical tester (MTestQuattro; ADMET, Inc., Norwood, MA, USA) was used by the students to deform their specimens in tension at a fixed deformation rate of 0.5 mm/s until failure was observed. Engineering stress-strain curves were constructed from the resulting data, and the students determined the Young's modulus (E), yield stress (σ_y), and strain at failure (ε_f) for each specimen. A full list of materials, step-by-step instructions, discussion questions and a glossary of engineering terminology is publically available.[8] While only one deformation rate is investigated here, activity extensions could be performed to investigate the effect of rate on the deformation response. As many polymeric materials are viscoelastic, deforming the specimens at a greater rate is expected to lead to a more brittle, elastic response overall while deforming the specimens at a reduced rate is expected to cause a more ductile, viscous response.

Activity results and discussion

Table 1 reports the average mechanical properties of the parallel and perpendicular PETE samples, and representative stress-strain curves are shown in Figure 4 (with the full data set shown in Appendix B). In general, the parallel specimens displayed greater stiffness and strength compared to the perpendicular specimens. Parallel specimens consistently deformed in a ductile manner, exhibiting relatively large deformation magnitudes following yielding and large ε_f values. An image of a parallel specimen following fracture is shown in Figure 5.

Interestingly, a disparity was observed in the deformation response of the perpendicular specimens. As shown in Table 1, data for the perpendicular specimens is divided into brittle and ductile responses. Of the total perpendicular specimens that were tested, 80% experienced ductile behavior with significant post-yield elongation (ε_f = 3.2) and 20% experienced brittle fracture with relatively little post-yield elongation (ε_f = 0.2). Representative stress-strain curves of two perpendicular specimens are shown in Figure 4 as solid and dashed red curves, highlighting the differences in the mechanical responses of ductile and brittle specimens respectively. Additionally, images of perpendicular specimens that displayed ductile and brittle fracture are displayed in Figure 5. Brittle fracture occurred in the center of each gauge section, almost immediately upon applied tensile force. The ductile specimens began to elongate and neck (*i.e.*, reduce in width) shortly after the test was started, slowly stretching until failure.

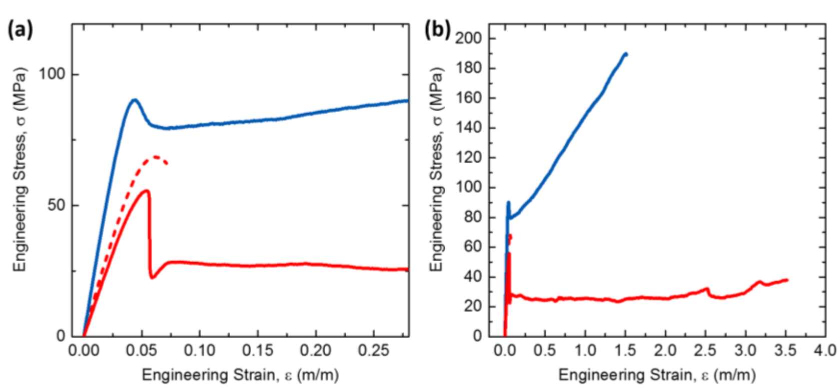


Figure 4: Representative stress-strain curves of a parallel specimen (shown in blue) and two perpendicular specimens (shown in red). Small-strain behavior is magnified in (a) while full deformation responses are shown in (b).

Table 1: Averages (± 1 standard deviation) for the mechanical properties of parallel and perpendicular PETE specimens. The values for the perpendicular sample are further divided into ductile and brittle categories based on the varying mechanical responses observed during testing.

PETE Sample	**Young's Modulus, E (GPa)**	**Yield Stress, σ_y (MPa)**	**Strain at Failure, ε_f**
Parallel	2.8 ± 0.5	83.7 ± 5.4	1.6 ± 0.3
Perpendicular	1.6 ± 0.4	62.0 ± 4.1	1.4 ± 1.7
Ductile (80%)	1.3 ± 0.1	57.7 ± 2.7	3.2 ± 1.0
Brittle (20%)	1.8 ± 0.4	66.7 ± 3.8	0.2 ± 0.1

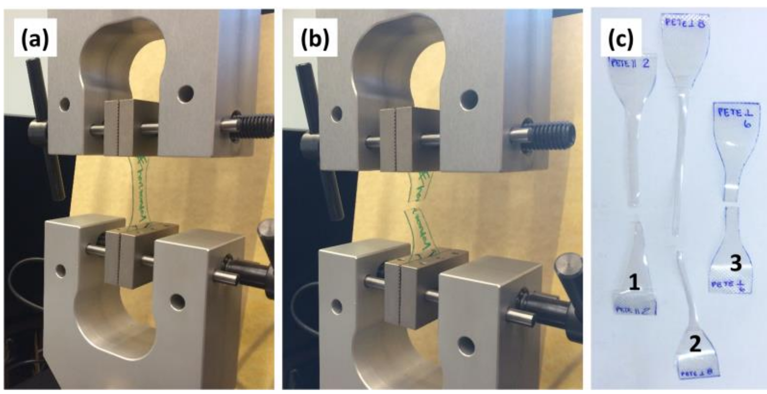


Figure 5: (a) Perpendicular PETE specimen, prior to start of testing and (b) the specimen following testing, displaying brittle failure. In far-right image (c): post-failure examples of (1) a ductile parallel, (2) a ductile perpendicular, and (3) a brittle perpendicular specimen.

As described in detail in a previous publication, the mechanical anisotropy displayed by these experiments was most likely due to processing-induced alignment of the polymer chains in the thermoforming direction.[3] During mechanical testing of the parallel specimens, the applied force was supported at the molecular level by the relatively strong covalent bonds in the polymer backbone. This allowed for a relatively stiffer and stronger response to applied tensile forces in comparison to the perpendicular specimens. The force applied to the perpendicular specimens was only resisted by relatively weak van der Waals interactions acting between neighboring polymer chains, as opposed to the strong covalent bonds within the backbones of the chains.

Two methods of activity implementation

This activity was designed by the course instructor (K. A. Erk) and implemented by 1 graduate student teaching assistant (TA; J. J. Nash) during a 2-hour laboratory activity with sophomore students in materials engineering at Purdue University (44 students total). To determine the most effective instructional method, the students were divided into two groups – Group A and B, summarized in Table 2 on the following page.

Table 2: Summary of the activity implementation and assessments performed for two groups of undergraduate students (sophomores in materials engineering at Purdue University).

	Group A (26 students) **"Traditional"**	**Group B (18 students)** **"Hypothesis-Driven"**
Lab handout	Full written description of lab activity, including relevant background information and in-lab instructions (Appendix C)	None
Pre-lab lecture	Review of content from lab handout, including discussion of: 1. The features of polymer stress-strain curves 2. How polymer chains can be aligned by external forces 3. The types of bonding in polymeric materials (*i.e.*, strong covalent bonds within chains and weak van der Waals forces between chains) 4. How chain alignment can increase mechanical strength 5. Main processing steps to manufacture a plastic cup by thermoforming (communicated by a video and accompanying schematic in handout)	Same 5 areas of emphasis as Group A. Followed by completion of a worksheet by each student that involved sketching, developing a hypothesis, and proposing a plan to test the hypothesis. (Appendix D)
In-lab	Students completed the lab activity using the instructions provided in the lab handout. The TA reiterated the instructions. Following data collection, students completed an in-lab worksheet (Appendix E).	At the start of the lab session, the TA led a group discussion by asking the following questions: 1. Think back to the pre-lab lecture and the microstructure sketches that you drew of the PETE cup. Can you formulate a hypothesis about the cup's microstructure? 2. How can you "test" your hypothesis experimentally, to see if your ideas about the cup's structure are accurate? 3. What outcomes/results do you expect from your proposed experiment? The TA helped the students to outline their experimental plan and provided the students with the materials and equipment to complete their plan. Following data collection, students completed an in-lab worksheet (Appendix E).

The relationship between a polymer chain's molecular structure and its resulting mechanical properties – *i.e.*, the fact that externally applied forces can be used to preferentially align polymer chains, which then leads to increased mechanical strength – was discussed with both groups. Group A was exposed to this idea by a more "traditional" route: a laboratory handout was generated (see Appendix C) that fully described the connection between chain alignment, bonding differences, and impact on mechanical strength as well as described how polymer cups were manufactured by thermoforming. This content was also reviewed in a pre-lab lecture and a video on thermoforming was shown. Also included in the lab handout was a set of activity instructions, describing how different specimens of plastic cups would be mechanically tested in lab to relate the mechanical properties of the cups to its molecular-level structure.

For Group B, no written lab handout or activity instructions were provided. Instead, the same material was presented in the pre-lab lecture with one addition: after discussing structure-property relationships and viewing the thermoforming video, students were given a worksheet (see Appendix D) that asked them to do the following:

- draw a sketch to illustrate the cup's structure, considering both the micro- and molecular-scale,
- develop a hypothesis about the cup's structure, and
- propose a method to test the accuracy of the hypothesis.

During the lab activity, the students in Group A followed the instructions provided in their lab handout, whereas the students in Group B decided upon a group hypothesis and then developed a plan to test that hypothesis during the lab session, with only minimal guidance from the lab TA. Following data collection, all students were provided with an in-lab worksheet (see Appendix E) that asked them to summarize their mechanical results and then summarize the "relevant processing-structure-property relationship for a PETE disposable cup". The in-lab worksheet was collected and responses were independently analyzed by the course instructor and TA, focusing on the breadth, depth, and accuracy of the terminology in the students' responses.

It is important to note that there was no discussion with any students about how the structure and properties of the cups were directly influenced by its processing. This idea was not described in the lab handout provided to Group A, in the pre-lab lectures presented to both groups, or during the actual lab sessions. Thus, by analyzing the students' responses on the in-lab worksheet from Group A and Group B, differences in the students' understanding of the processing-structure-property relationships of plastic cups can be directly attributed to the method of implementation for the two different groups.

Implementation assessment methods and results

Pre-lab worksheet – Group B only

Responses from the worksheet completed by students in Group B during the pre-lab lecture (Appendix D) were analyzed by the course instructor. In the first question on the worksheet, all students included a sketch, the majority of which accurately communicated the effect of the thermoforming process on the structure of the cup (*i.e.*, showing processing-induced alignment of the individual polymer chains within the walls of the cup). In the second question, over 80% of students correctly hypothesized that the alignment of the chains was a direct result of processing. Finally, in the last question that asked the students to propose a "test" for their hypothesis, "to see if [their] ideas about the cup's structure are accurate…", 83% of students proposed to conduct a test to determine the cup's mechanical properties by using specimens cut in different directions. Interestingly, 25% of students proposed to perform optical microscopy to determine if the polymer chains were aligned, illustrating an important misconception that should be addressed in the future, as polymer chains cannot be directly viewed with optical microscopy.

In-lab worksheet – Groups A and B

Students' responses on the in-lab worksheet (Appendix E) were analyzed separately by the course instructor and TA. Each analysis was conducted following the same protocol. First, a selection of key phrases was determined for each question in the worksheet (see Table 3). One point was assigned for each key phrase that was accurately described in a student's response. For each student, the total points earned for each question was calculated and normalized by the maximum number of points available (dependent on the analysis, see Table 3). The averages and standard deviations for all normalized responses in Groups A and B are reported in Table 4.

Table 3: Key phrases that were used to code and analyze students' responses to the in-lab worksheet (Appendix E).

<table>
<tr><th>Two Independent Analyses</th><th>Key Phrases for Question 1:
"For the PETE disposable cups, use the space below to summarize the mechanical results that were measured during the lab."</th><th>Key Phrases for Question 2:
"Considering the cup's mechanical properties that were measured during lab, use the space below to summarize the relevant processing-structure-property relationship for a PETE disposable cup."</th></tr>
<tr><td>Analysis 1:
conducted by graduate TA</td><td>Maximum points: 3
- Parallel stronger than perpendicular specimen
- Parallel stretched more than perpendicular specimen
- Parallel ductile and perpendicular brittle</td><td>Maximum points: 6
- Polymer chain alignment along thermoforming axis/parallel direction
- "van der Waals bonding"
- "Covalent bonding"
- High mechanical property magnitudes of parallel due to polymer chain alignment
- Mechanical property magnitudes of parallel direction are greater than those of the perpendicular direction
- Parallel was more ductile and perpendicular was more brittle</td></tr>
<tr><td>Analysis 2:
conducted by course instructor</td><td>Maximum points: 3
- Parallel stronger than perpendicular specimen
- Parallel stretched more than perpendicular specimen
- Parallel ductile and perpendicular brittle</td><td>Maximum points: 9
- "Processing"
- Thermoforming/stretching of the polymer film to form a cup
- "Structure"
- Polymer chains are aligned/parallel/oriented in parallel direction
- "Properties"
- Mechanical property magnitudes of parallel direction are greater than those of the perpendicular direction
- Parallel was more ductile and perpendicular was more brittle
- Relevant forces are mentioned (covalent, van der Waals)
- Total response was accurate</td></tr>
</table>

Table 4: Averages (± 1 standard deviation) for normalized responses to the in-lab worksheet for Group A and B.

Average Scores For:	Analysis	Group A	Group B	p-value
Question 1: "For the PETE disposable cups, use the space below to summarize the mechanical results that were measured during the lab."	1	0.70 ± 0.19	0.65 ± 0.18	0.38
	2	0.74 ± 0.14	0.73 ± 0.16	0.83
Question 2: "Considering the cup's mechanical properties that were measured during lab, use the space below to summarize the relevant processing-structure-property relationship for a PETE disposable cup."	1	0.34 ± 0.22	0.46 ± 0.21	0.074
	2	0.58 ± 0.27	0.74 ± 0.21	0.033

For Question 1, there was no appreciable difference between the average scores for Group A and B from both analyses. This indicated that all students had a reasonably accurate understanding of the mechanical data that was obtained during the lab activity, *i.e.*, the parallel PETE specimens were mechanically stronger and stretched to a greater extent than the perpendicular specimens.

For Question 2, two-sample hypothesis testing was conducted to compare the scores for the two groups. Assuming a significance level of 0.1 for both analyses, it was found that Group A and Group B had statistically significant average scores in comparison (see p-values in Table 4). This indicated that Group B, with the greater average score, had accurate responses to Question 2 that included more key phrases from Table 3 compared with Group A.

When taking a closer look at the students' responses to Question 2, it was found that Group B students were able to more strongly connect the anisotropic mechanical properties observed during testing to the processing-induced alignment of the polymer chains. Additionally, of the Group B responses to Question 2, 85% of the students used a sketch (see Figure 6) to illustrate the processing-structure-property relationship whereas only 50% of students' responses in Group A included a sketch.

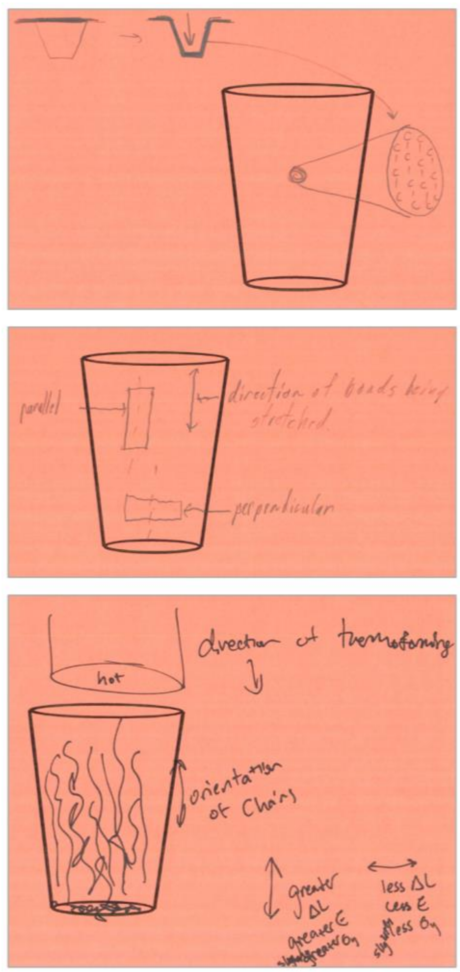


Figure 6: Examples of sketches from Group B students' in-lab worksheet (Appendix E).

This increased level of processing-structure-property comprehension of Group B compared with Group A is explained by considering the main differences in the groups (from Table 2):

1. In their lab handout, the students in Group A were provided with a full written description of the molecular-level structure (including the 2 bonding

types) which was also reinforced in the pre-lab lecture. Group B was only exposed to this content in the pre-lab lecture.

2. In their pre-lab lecture, Group B was provided with a worksheet that required them to sketch the cup's microstructure and develop a testable hypothesis about the cup's structure.

3. During the lab activity, Group A followed the instructions provided in the lab handout while Group B designed their own experiment based on their independently developed hypothesis.

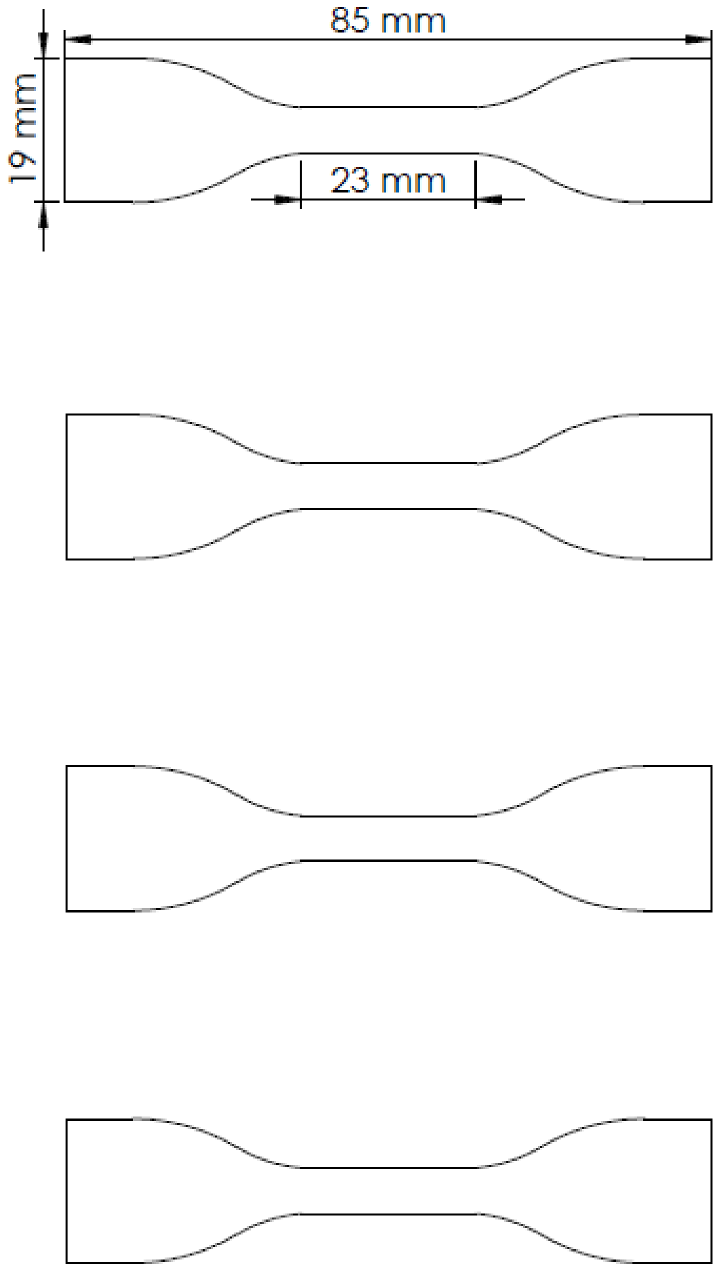
One area where the students in Group A slightly outperformed Group B was in identifying the molecular-level forces that exist in the cup. In answering Question 2 of the in-lab worksheet, Group A (38%) specifically mentioned the strong covalent bonding within polymer chains and the relatively weaker van der Waals forces between neighboring chains. Only 23% of students in Group B directly mentioned these forces. The increased performance of Group A in this instance was most likely due to the complete written description of these forces that was provided in their lab handout (which was not provided to Group B). In the future, the deficiency of Group B in identifying these forces could be remedied by asking them to indicate the important molecular-level forces in the cup's structure on the pre-lab worksheet.

Conclusions

This hands-on laboratory activity utilized an everyday material (a disposable plastic cup) to effectively communicate advanced processing-structure-property relationships for polymeric materials. Learning outcomes were enhanced by encouraging the students to communicate their ideas by molecular-scale sketches and further challenging them to design their own hypothesis-driven experiments. Instead of the traditional "prescribed" lab activities accompanied with thorough lab handouts and significant TA involvement – common in introductory engineering curriculum – this activity demonstrates that it may be possible to achieve the same learning outcomes through a more open-ended, hypothesis-driven approach, where control of the activity is largely placed in the student's hands.

(1) Lepoittevin, B.; Roger, P. Chapter 4: Poly(ethylene Terephthalate). In *Handbook of Engineering and Speciality Thermoplastics: Volume 3: Polyethers and Polyesters*; Thomas, S., Visakh, P. M., Eds.; Scrivener Publishing LLC, 2011; pp 97–126.
(2) Klein, P. W. *Fundamentals of Plastics Thermoforming*; Morgan & Clapool, 2009.
(3) Erk, K. A.; Rhein, M.; Krafcik, M. J.; Ydstie, S. "Demonstrating the Effects of Processing on the Structure and Physical Properties of Plastic Using Disposable PETE Cups," *J. Chem. Educ.,* 92 (11) 1876-1881 **2015**. doi: 10.1021/acs.jchemed.5b00082
(4) Sperling, L. H. *Introduction to Physical Polymer Science*, Third.; John Wiley & Sons, Inc., 2001.
(5) Mark, H. Strength of Polymers. In *Polymer Science and Materials*; John Wiley & Sons, Inc., 1971; pp 231–246.
(6) Jones, R. A. L. *Soft Condensed Matter*; Oxford University Press, 2002.
(7) ASTM D638-14: Standard Test Method for Tensile Properties of PlasticsTitle. ASTM International: West Conshohocken, PA 2014.
(8) Public web site of K. A. Erk., https://soft-material-mechanics.squarespace.com/teaching-outreach/

Appendix A: Printable dog bone templates with dimensions. Based on ASTM D638-14.[7]



Appendix B: Stress-strain curves for a full representative PETE data set.

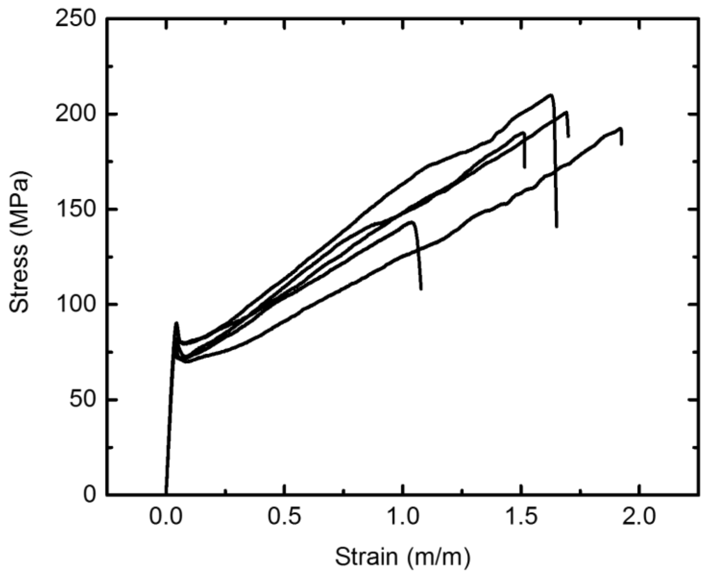


Figure B-1: Representative engineering stress-strain curves from a sample of 5 parallel specimens cut from disposable PETE cups.

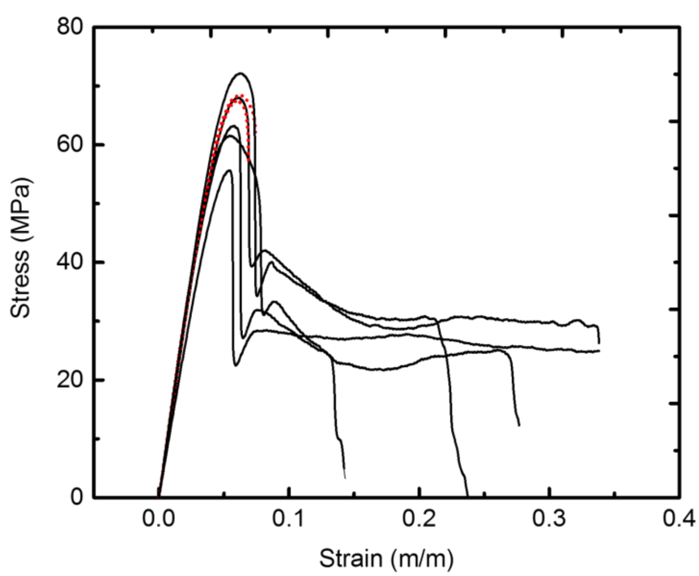


Figure B-2: Representative engineering stress-strain curves from a sample of 9 perpendicular specimens cut from disposable PETE cups. Black solid lines indicate the specimens that displayed ductile behavior while red dashed lines indicate the specimens that displayed brittle behavior.

Appendix C: Handout provided to Group A, including instructions for the in-lab activity.

Mechanical Properties of Polymers

Instructions: Before your lab session, read this lab handout. Bring your safety glasses and wear proper safety attire.

Plastic materials are composed of a tangled collection of polymer molecules or "chains". Each polymer chain is made of a series of repeating units that are connected by covalent (chemical) bonds in an end-to-end fashion to form one long, flexible, string-like polymer molecule (see Figure 1).

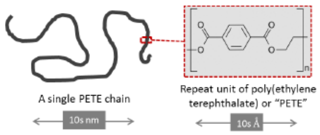


Figure 1: Simple schematic of a polymer chain (left), illustrating the chemical structure of PETE (right) and the relative length scales.

Plastic objects contain millions of polymer chains, tangled together in a similar fashion to a tangled collection of spaghetti noodles (see Figure 2). When a force is applied to the collection of chains, the chains can move and reorient in response to the applied force. If the applied force is great enough in magnitude, the long axis of the molecules can reorient in the direction of the applied force (as shown in Figure 2). Chain reorientation takes less energy and is thus more likely to occur when the plastic is heated.

The long axis of the aligned molecules can store elastic energy within its covalently bonded "backbone", resulting in a strong mechanical response from the deformed collection of aligned chains. Thus, a plastic material in which the chains are aligned is very strong in response to forces applied parallel to the chain alignment direction but can behave in a mechanically weak manner in response to forces applied perpendicular to the chain alignment direction. This is because only the relatively weak Van der Waals interaction forces between the different chains act to resist forces applied perpendicular to the alignment direction as compared to the relatively strong covalent bonds in the chains' backbones that resist forces applied parallel to the alignment direction.

When a block of plastic is heated to a high temperature and becomes mechanically soft, it can be molded and processed into a variety of different physical forms, such as plastic cups, plastic forks, and plastic cords. A quick online search for "How plastic forks (or cups or cords) are made" will result in a number of videos that illustrate different industrial plastic processing techniques, such as sheet extrusion, injection molding, compression molding, and thermoforming.

1

Mechanical Properties of Polymers

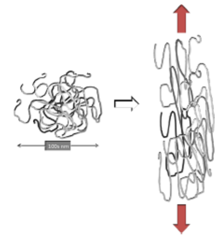


Figure 2: Simple schematic of the microstructure of a plastic material, composed of a tangled collection of polymer chains (left). When the chains are exposed to a tensile force (red arrows), the chains can reorient and align in the direction of the applied force (right).

Focusing on disposable plastic cups, cups are commonly manufactured by a process known as thermoforming (see Figure 3). In Step 1, a heated film of plastic is positioned above a cooled metal mold containing a cup-shaped cavity. In Step 2, a metal punch is brought into contact with the hot plastic by applying a downward force and the plastic subsequently deforms around the punch. Typically, this process is also assisted by a vacuum to aid in mold-filling. In Step 3, the punch is pushed further into the plastic, causing the plastic film to stretch and deform, ultimately filling the mold and creating the cup. After the cup is formed in Step 3, it is cooled and removed from the mold. There are excellent videos of this process at the industrial scale available online.

Thermoforming Steps

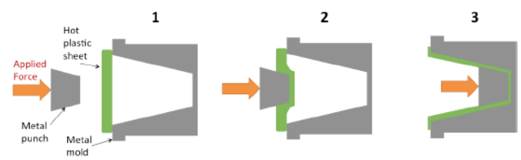


Figure 3: Simple schematic (side-view) illustrating a thermoforming process to make a plastic cup.

2

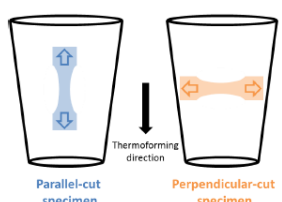
Mechanical Properties of Polymers

Lab Activity Instructions

Material and Equipment List: clear plastic cups; scissors; permanent markers; dog-bone style template for tracing of the specimens; digital calipers; mechanical tensile testing machine; laptop or in-classroom computer with spread-sheet software for data recording and analysis.

Tasks: Your TA will help you to perform the following tasks during this lab activity,

(1) Determine the mechanical response of different specimens of plastic cups deformation in tension: "parallel-cut" and "perpendicular-cut" specimens (see schematic below).
(2) Relate the mechanical response of the different specimens to the molecular-level structure and thermal properties of the plastic cups.



Notes: With help for your TA, you will prepare the specimens from each cup, measure and record the specimens' dimensions, perform the mechanical tests, and analyze the resulting data (by making stress-strain plots, calculating the Young's modulus, and determining the yield stress and strain at failure for each specimen). Make sure you keep an accurate list of what specimens were tested and the testing conditions (such as temperature, strain rate).

3

Appendix D: Worksheet provided to Group B during the pre-lab lecture.

Pre-Lab Lecture Worksheet

Name: ___________________________

(1) Knowing that PETE cups are made via thermoforming, use the space below to draw a sketch of what you think the cup's structure looks like. Consider both the micro-scale structure and the molecular-scale structure.

(2) Think about why you drew the structure the way you did in Question (1). Can you formulate a **hypothesis** about the cup's structure? ***"I hypothesize that…."***

(3) How can you "test" your hypothesis, to see if your ideas about the cup's structure are accurate?

Appendix E: Worksheet provided to both Group A and Group B during the lab activity.

Individual In-Lab Worksheet

Name: ___________________________________

(1) For the PETE disposable cups, use the space below to summarize the mechanical results that were measured during the lab.

(2) Considering the cup's mechanical properties that were measured during lab, use the space below to summarize the relevant processing-structure-property relationship for a PETE disposable cup.