2006-2264: USING HANDS-ON LABORATORY EXPERIENCES TO UNDERSCORE CONCEPTS AND TO CREATE EXCITEMENT ABOUT MATERIALS

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Hands-On Laboratory Experiences to Underscore Concepts and to Create Excitement about Materials

Abstract

It is universally acknowledged that laboratories and demonstrations add information and interest to science and engineering courses. Constraints are time, space and cost. We have developed a series of hands-on laboratories coordinated with our "Introduction to Principles and Properties of Materials" course, taken as a Basic Engineering elective by most of the engineering majors in the McCormick School of Engineering and Applied Science at Northwestern. These activities are conducted in 50-minute weekly sessions with approximately 40 students in each section. Our objective is for students to handle materials and to make qualitative observations and quantitative measurements. The experiments described herein are easily and inexpensively duplicated, allowing individuals or small groups to work independently. We describe the following representative activities in detail: the observation of work hardening and recrystallization in copper tubing; measurement of temperature-dependent resistivities of metals and semiconductors; exploration of the glass transition in inorganic and organic materials; measurement of LED I-V curves with a simple circuit; and quantitative determination of the effect of surface flaws on the strength of glass.

Introduction

Laboratory exercises provide a great opportunity to expose students to "real materials" in an active learning environment. Such exercises also provide a means to satisfy important learning objectives, such as the application of material discussed in lectures ("an ability to apply knowledge of math, science and engineering") and the ability to conduct experiments, analyze and interpret data.[1] We have developed a series of experiments which we believe meet these objectives and add an element of fun to the introductory materials course. These exercises were developed in the process of teaching, experimenting with materials, discussing the course with students and colleagues, and making many trips to the local hardware store and chemistry stockroom. We are certain that many of these activities are not unique to our curriculum, and we acknowledge inspiration from others using similar hands-on learning techniques, especially Professor Arthur Ellis and coworkers at the University of Madison[2] and participants at the Materials Educators conferences.[3] In this paper we document some of the experiments we have developed for use with relatively large classes.

The MSE 201 "Introduction to Principles and Properties of Materials" course has an enrollment of approximately 40 students in each of two sections taught in the fall, winter and spring quarters. This course satisfies a Basic Engineering requirement for most (approximately 75%) engineering undergraduates at Northwestern, and is taken by those majoring in Biomedical, Civil, Computer, Electrical, Industrial and Mechanical engineering in addition to Materials Science and Engineering. A separate but similar course, MSE 301, is taught for Chemical and Biological Engineering majors once each year. Both classes use the current edition of "Materials Science and Engineering: An Introduction" by William D. Callister.[4] A draft of a new text by Y. W. Chung[5] was used for the most recent sections of 201, taught during Winter Quarter of 2006.

Each section meets four days a week for 50 minutes. Typically, three days are devoted to lectures and the fourth to lab exercises that complement the material covered that week. We use a separate laboratory facility, equipped with multiple bench tops and sinks, for these sessions. The lab space accommodates about half of each section enrollment, so students spend about 25 minutes in lab and 25 minutes at demonstrations done nearby. Write-ups, typically two pages in length, are sent to the students at least one day before the activity. Given the limited time available, student promptness and preparation are important; class members cooperate in this.

Our primary objective is to provide hands-on exercises that capture important material concepts and yet can be completed in 20-25 minutes. Most importantly, each student participates, either individually or in groups of two or three. A secondary objective, when results are quantifiable, is to have students manipulate "real" lab data in a short homework exercise that is handed in and evaluated. These assignments address measurement uncertainties and experimental errors, and provide a basis for educating (or reminding) students about graphs, tables, significant figures, etc.

Representative Experiments

1. Cold Working and Annealing Copper Tubing

Objective

Each student feels the effect of cold working a metal, and the subsequent softening that occurs after heating.

Theory

Plastic deformation of metals is accomplished by the motion of dislocations, which occurs at low force or stress if the crystals are regular. Dislocations are also created during plastic deformation; these structural imperfections make the material more resistant to further deformation, in this case the straightening step. Dislocations are high energy defects that can be removed by *annealing* the material at temperatures close to half the melting temperature (through the processes of recovery, recrystallization, and grain growth). The melting temperature of Cu is 1360 K, so annealing effects are rapid above 680 K or ~400 °C. The propane torch can heat the specimen substantially above 500°C.

Materials and supplies

- Copper refrigeration tubing (¼ in. diameter, 0.025 in. wall thickness), cut into ~ 8 in. lengths. (One length for each student.)
- Propane torches at each station/sink (1 for every 3-4 students)
- Pliers to hold tubing in flame.

Procedure

Each student is supplied with a length of copper tubing, then requested to grasp it near one end and bend it moderately (through about 20-30°). Here they get a qualitative sense of "yielding". When asked to straighten the tubing, each student immediately feels the increased resistance, which is further enhanced for those able to bend and straighten the piece more than once. Most students are surprised and impressed by the large force required for straightening. The tubing is long enough so each student can try a second time, now knowing what to expect, using the other end of the piece. After experiencing the effect of cold-work on the copper, students use pliers to hold the worked region(s) in the flame of a propane torch. The tubing is heated until it is red hot, then cooled completely under cold water until it can safely be handled. Each student bends the piece once again to sense the effect of annealing. The exercise is complemented with projected micrographs of microstructure evolution, primarily recrystallization.

Deliverables: none for this exercise.

2. Temperature-dependent Resistivity of Metals and Semiconductors

Objective

Students measure resistance as a function of temperature for different materials: metal, semiconductor and "unknown" (pencil lead).

Theory

Differences in resistivity vs. temperature distinguish semiconductors from metals. Metal resistivity increases with increasing temperature due to increased phonon scattering, while semiconductor resistivity decreases with increasing temperature because of increased charge carrier concentration. Since the geometries of the metal wire and pencil lead are known, students convert their measured resistance R to resistivity ρ. The resistance of the semiconductor (unknown geometry) changes exponentially with 1/T: $R \propto \rho \propto \exp(E_g/2kT)$, assuming intrinsic behavior. Students evaluate the bandgap E_g of the semiconducting material by plotting lnR vs. 1/T (Kelvin^{-1}).

Materials and Supplies

- 1 meter lengths of thin wire (steel, 0.2 mm diameter, for example), space wound on cardboard frames that can easily be submerged in liquid nitrogen. 1 wire for every 1-3 students.
- Pencil leads (Pentel Hi Polymer 0.7 mm x 60 mm)
- Thermistors (Radio Shack part # 271-110 (old) or comparable metal-oxide thermistor)
- Multimeters or ohmmeters (Tenma model 72-5095 digital multimeters, for example, and cables with alligator clips).
- Thermocouple or thermometer to measure water temperature
- Beakers containing water at for example 0 ^{o}C and 50 ^{o}C; hot plates are useful.
- Beakers containing styrofoam cups filled with liquid nitrogen
- Cadmium-sulfide photocells (Radio Shack part #276-1657) – optional part of this lab.

Procedure

Students first record the (series) resistance of the multimeter leads, then the resistance of the meter-long steel wire at room temperature. All values are entered in Table 1 (see below). The wire, coiled on its cardboard support and with leads attached, is next submerged in liquid nitrogen and the resistance measured again. Since the wire is thin, it warms and cools quickly, so the students may test that the results are reproducible as they re-warm, then re-submerge the wire. The series resistance is subtracted and the values are normalized for the wire geometry to calculate the material's resistivity at room temperature and at liquid nitrogen temperature. The room temperature value is later compared to that in the text.

The second sample is a commercially available thermistor, or metal-oxide semiconductor. The resistance between the two leads of this device is measured at room temperature, in warm water, and in ice water (not in liquid nitrogen!). First, students observe that the magnitude of the semiconductor resistance is much larger than that of the steel wire. Next, the students observe that the resistance of the thermistor *increases* as it is cooled, in contrast to the behavior of the metal.

Finally, students investigate an "unknown," in this case a 60mm length of pencil lead at room temperature and in liquid nitrogen. This material is classified as a semiconductor based on the observed temperature-dependent resistivity, indicated in Table 1. A fourth sample, a CdS photoresistor, may be added. In this case, students observe a decrease in resistance when visible light (photons with energy equal to or greater than the bandgap) is used to promote carriers from the valence band to the conduction band.

Deliverables

Thermistor: Students are asked to use their three data points to plot ln(R) vs. 1/T(K), as indicated below, and use the slope to determine the (apparent) bandgap of this material.

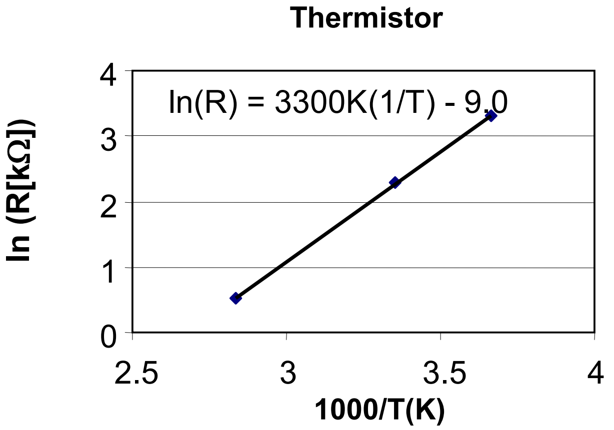

Figure 1. Plot of the natural log of the measured resistance vs. inverse temperature for the Radio Shack thermistor. In the case, the slope, 3300 K, equals E_g /2k, hence E_g = 0.57 eV.

Steel wire and "unknown" graphite: Students are asked to compute resistivity of the two materials, and complete the table below. They are asked to compare their experimentally determined resistivity for steel wire at room temperature with "book values" and discuss why differences might exist.

Table 1. Measured resistance and calculated resistivities for steel wire and pencil lead at room temperature and 77K.

	Temperature	Resistance (Ω)	ρ (Ω m)
Series resistance	RT	*0.2*	*xxxxx*
Steel wire	RT (~298 K)	*7.0-0.2=6.8*	$2.1 \times 10^{-7*}$
Steel wire	LN_2, 77K	*3.6-0.2=3.4*	1.1×10^{-7}
Graphite	RT (~298 K)	*1.2-0.2=1.0*	6×10^{-6}
Graphite	LN_2, 77K	*1.8-0.2=1.6*	10×10^{-6}

* Compare to 1.6×10^{-7} *Ω-m,* table B.9 of reference 4.

3a. Glass transitions - Inorganic materials

Objective
Students feel the rapid decrease in rigidity of an inorganic glass when heated above the glass transition temperature.

Theory
At room temperature this glass is a disordered elastic solid that fractures in a brittle fashion. In a narrow temperature range above T_g the material transforms to a viscous liquid that may be bent or pulled into a thin fiber. The low thermal conductivity of glass allows students to heat it, to work it and to hold it without tools, in contrast to metal (Cu from earlier lab).

Materials and Supplies
- Borosilicate glass stirring rods (4 mm diam. x 125 mm; Kimble-Kontes Glass part # 40500-125)
- Propane torch

Procedure
Students hold a glass stirring rod at each end and heat the center section using a propane torch until it is hot enough to be worked. The abrupt "softening" that accompanies heating above $T_g \approx 550\ ^{o}C$ is readily perceived. Almost all enjoy the exercise and try to create various figures by bending and fusing the rods.

Deliverables: none for this exercise.

3b. Glass transitions - Organic Materials

Objective
Students explore the behavior and properties of elastomers above and below T_g.

Theory

Non-crystalline organic macromolecules (polymers) have glass transition temperatures considerably lower than inorganic glasses, typically from -70 °C to 150 °C. Below T_g they are glassy, and above T_g they are rubbery, with retractive forces coming from coil deformation.

Materials and Supplies

- Triangular pieces of rubber sheet (1/16 inch thick)
- Balsa wood (dimensions: ~3 inch wide x 4 inch wide x ¼ or 1/8 inch thick)
- Happy and Unhappy Balls (Edmund Scientific Company part # WW6974500)
- Beakers containing styrofoam cups filled with liquid nitrogen
- Hammer
- Tongs or pliers to hold rubber sheet

Procedure

Rubber nails

Cool a rubber "nail" by holding it in liquid nitrogen with a pair of tongs. The material is now a rigid glass. Use the glassy nail to join two pieces of (soft) balsa wood before it returns to its rubbery state at room temperature. Hints: Align the nail with the grain of the wood; use repeated soft taps to avoid shattering your "nail." Have everyone in your group contribute a nail through the boards.

Glass/Rubber ball

The glass transition is demonstrated very effectively, both visually and aurally, using an elastomeric ball with $T_g \approx -50\ ^oC$.[6] When the room temperature neoprene ball – rubbery – is dropped onto a hard surface, it bounces to nearly the drop height with a characteristic "thud." After the ball is cooled for ~ 20 seconds in liquid nitrogen, the glassy ball will bounce, but with a "click" sound corresponding to contact between two hard surfaces. As the ball is warmed toward its glass transition, the bounce height clearly diminishes and the "click" becomes less pronounced. In the vicinity of T_g the "leathery" material has no bounce and the impact sound is a "whop." Once above its glass transition temperature the ball recovers elasticity and bounce, and the sound again corresponds to the thud of rubber on a hard surface.

Deliverables: None for this exercise.

4. Measurement of I-V curve for an LED

Objective

Students use a simple circuit to generate an I-V curve for a light emitting diode (LED). The correlation between current and light intensity is obvious.

Theory

A p-n junction does not have a "conductivity" because Ohm's law is not obeyed. Under a reverse bias (positive electrode to the n doped side) the current passed by the diode is very small (minority carriers). For positive bias (positive electrode to the p doped side), the current increases non-linearly, becoming appreciable when the bias voltage V_b exceeds a critical value

V_c. For many diodes, the energy lost during recombination of electron and holes during conduction is emitted as light; the light intensity parallels the current in a "light emitting diode".

While the I-V characteristics of a diode are often established with a (commercial) curve tracer, we use a simple circuit based on a voltage divider and two multimeters.

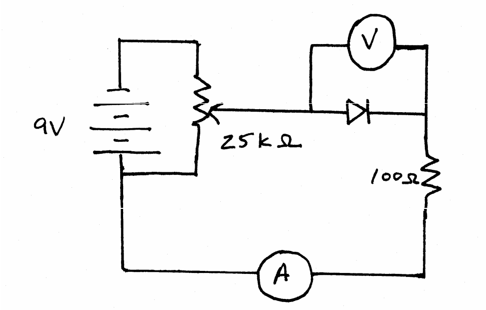

Figure 2. Voltage divider circuit diagram.

<u>Materials and Supplies</u>

- LED (for example, DigiKey clear round flat top LED, P380); note that the flat-top LEDs may be easily viewed under a stereomicroscope.
- 9 volt battery
- Circuit board with 100 Ω series resistor and 25 kΩ potentiometer, as in Fig. 2
- Two multimeters, or one ammeter (.001 – 100mA) and one voltmeter (0-9V)

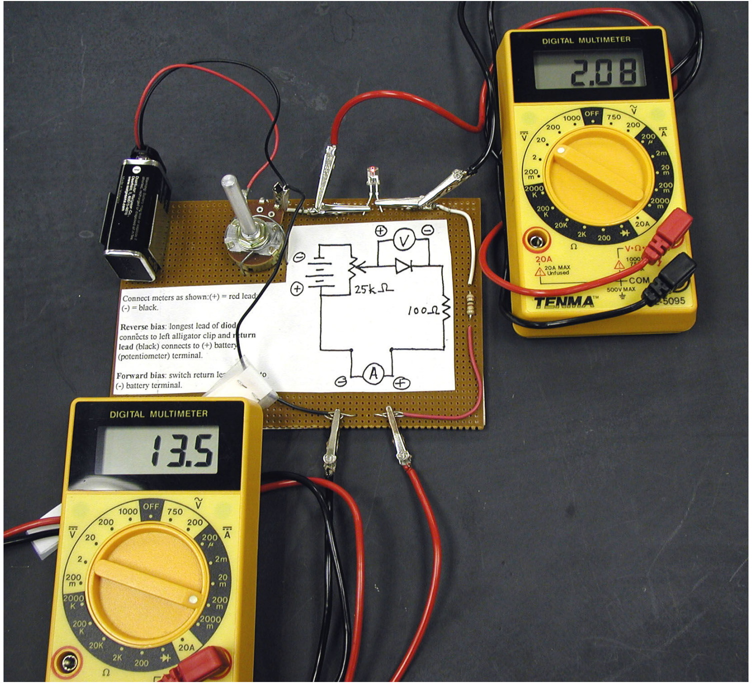

Figure3: Voltage divider circuit and meters. The LED is on at a forward bias of 2.08V and a current of 13.5 mA.

Procedure

Students in groups of two or three are provided with the voltage divider circuit, an LED, and two multimeters, one serving as an ammeter in series with the circuit, the other as a voltmeter in parallel with the diode. The students are instructed to record approximately 10 values of current as a function of forward bias, from 0 to ~ 3V, paying particular attention to the region where they first observe light emission from the LED. It quickly becomes evident that the I-V behavior is non-Ohmic. Then they measure about three values in reverse bias, from 0 to -9V.

Deliverables

Students are asked to plot the I-V curve on a single set of axes, as shown in Figure 4, and comment on the magnitude of the turn-on voltage.

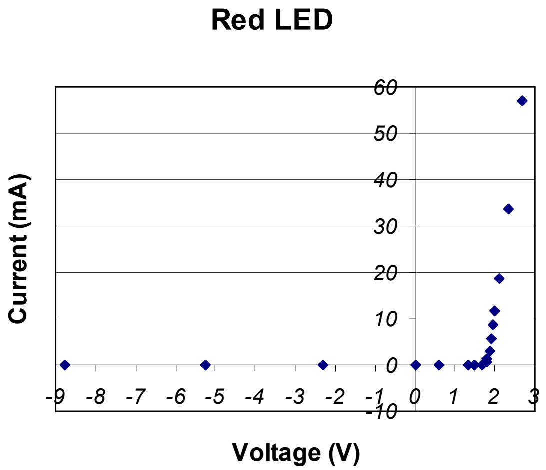

Figure 4. I-V curve for Red LED, measured using the 9V voltage divider circuit. The critical voltage, V_c is about 1.8 V.

5. Brittle Fracture and Surface Flaws

Objective

Students measure the effect of surface flaws on the flexural strength of glass using a simple bend test apparatus.

Theory

Conventional soda-lime glass is an exemplary brittle material for which the breaking stress σ_b is well accounted for by flaw size *a* and the plane-strain fracture toughness K_{IC}. In this course we assume the geometrical factor Y = 1. Here we demonstrate that increasing the flaw size will reduce the tensile stress at which fracture occurs, according to:

$$K_{IC} = Y\sigma_b\sqrt{\pi a}$$

A related experiment uses the environment (water) to lower K_{IC}. The Si-O-Si network in the glass is disrupted by formation of Si-O-H bonds at the surface, and the material effectively "unzips."

As it is difficult to perform conventional tensile tests on most brittle ceramic materials, we employ the bending mode, as illustrated below. Note that when loaded, the top of the plate is in compression and the bottom is in tension.

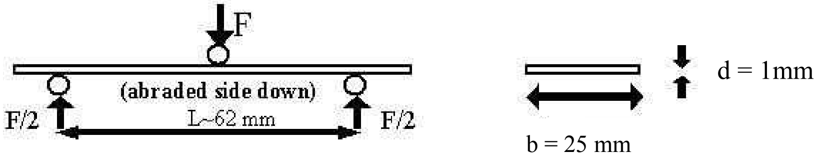

Figure 5. Schematic three point bend test apparatus for microscope slides.

For a sample with a rectangular cross-section tested on a three-point bend apparatus, the tensile breaking stress, termed the flexural strength, σ_{fs}, is:

$$\sigma_{fs} = \frac{3F_bL}{2bd^2}$$

Here F_b is the load at break, L is the distance between supports, b is the width and d is the thickness of the rectangular cross-section.[4]

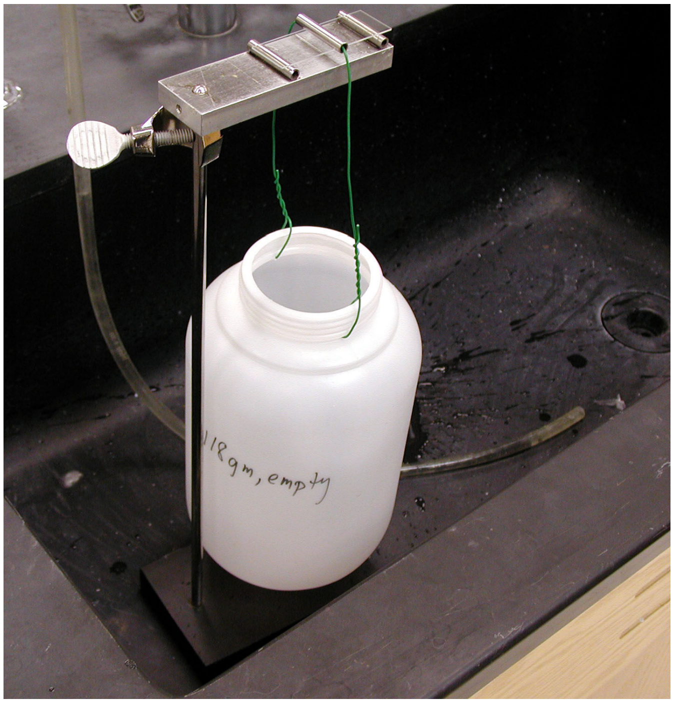

Figure 6. Three point bend test apparatus, using Al sample mount, a one gallon bucket and ring stand. (Note the bucket is not touching the bottom of the ring stand.)

Materials and Supplies

- 75 mm x 25 mm x 1mm glass microscope slides

- Ring stand with sample mount for microscope slide: aluminum block, with two ¼ in. diameter support rods
- One gallon plastic bucket with third "load rod" on the handle
- 180 grit SiC paper (small sections, ~ 1 inch square)
- Beaker (ca. 400 mL).

Procedure

Students first load a pristine slide (no intentional flaws) onto the two support rods, then hang the bucket with the loading rod/handle over the center of the slide. They increase the deforming force by pouring water into the bucket until the slide breaks. By recording the volume of water and adding the weight of the empty bucket, they determine F_b in grams, then later convert to Newtons to establish σ_{fs} in MPa.

Next, these students abrade the center 2-3 millimeters of a second slide with 180 grit paper, rubbed perpendicular to the long axis of the slide. The slide is loaded onto the base supports with the abraded side down. Then the (appreciably lower) force to fracture is determined as with the pristine slide. It is important that all samples are dry, even though water is used in the experiment.

A third slide is abraded in the same manner as described above, but it is loaded with the abraded side up. Hence the abraded side is in compression. The load to fracture will be greater for this test that for the case when the flaws were in tension, often approximating that for the pristine slide.

If time permits, students are asked to abrade a fourth slide, and intentionally wet the abraded region prior to loading, face down, on the apparatus. They observe that the maximum load is less when the abraded region of the slide is wet, due to stress corrosion cracking.

Note that the experimental procedure could be modified so students measure stress to fracture for a series of grits, and subsequently plot σ *vs.* $a^{-1/2}$; however, the procedure using a single grit size works best for our short time period.

Deliverables

Students are asked to complete the following table with their measured values and compute the flexural strength of "pristine" and "abraded" slides, as well as the estimated inherent flaw size in the "pristine" slide, as follows:

Table2. Sample data for three point bend test on glass slides.

Container weight = 118 g (Add to obtain total load)	Vol (ml)	Total load (gm)
A. Pristine slide:	*2800*	*2918*
B. Flawed slide down (tension):	*900*	*1018*
C. Flawed side up (compression):	*2 900*	*3018*
D. Repeat b, but **WET** the abraded region	*600*	*718*

Calculations to be handed in at next lab:

1. Use the appropriate equation to calculate the "flexural strength" obtained with this three point bend experiment for the sample in part A. Sample dimensions are d = 1 mm, b = 25 mm, and L = 62 mm between support points. Your answer should be in MPa, and you will need to convert F_b from g to N.

Example for A:

$$\sigma_{fs} = \frac{3(2800+118)\ gm * 9.80556\ m/sec^2 * 0.062\ m}{2\ (0.025m)(0.001m)^2} = 110\ MPa$$

[Two significant figures.]

2. Use your flexural strength from experiment B to calculate K_{IC} for the microscope glass material (let Y = 1). Compare your K_{IC} to the value for soda-lime glass in Table 8.1 of the text. Use your K_{IC} to calculate flaw size a (mm) in the pristine glass slide.

Example for B:

$$\sigma_{fs} = \frac{3(900+118)\ gm * 9.80556\ m/sec^2 * 0.062\ m}{2(0.025m)(0.001m)^2} = 40\ MPa$$

[One significant figure.]

$$K_{IC} = Y\sigma\ sqrt(\pi\ a) = 1.0\ (40\ MPa)\ sqrt(3.14 * 80 \times 10^{-6}m) = 0.6\ MPa\ m^{-1/2}$$

[value in text is 0.7-0.8 MPa $m^{1/2}$]

$$a_{pristine} = (0.6\ MPa\ m^{-1/2}/120\ MPa)^{2}\ \pi = 8\ \mu m$$

Assessments

Students are asked to evaluate the labs at the end of the term by scoring each according to educational value (useful in understanding the course material, *3*, somewhat useful, *2*, or unnecessary, *1*) and interest (interesting in their own right, *3*, somewhat interesting, *2*, and boring, *1*). In the survey these hands-on activities are grouped with demonstrations done for the overall topic covered in a particular week. The summary in Table 3 covers four sections taught in different years by different lecture instructors; K. Stair was the laboratory coordinator for all. Be aware that small changes are made from time to time. Nevertheless, the results appear internally consistent. Each lab is assessed as being between "useful" and "somewhat useful" and between "interesting" and "somewhat interesting". Conductivity and Optoelectronics have the lowest interest appeal, and the Polymer lab the highest. The Ceramics lab scores high on both content and interest. Reasons for these evaluations are considered below.

Class members are also requested to specify their favorite and least favorite labs, and given space to add additional comments. Be reminded that there are at least three additional laboratories in each quarter that are not described here. Some students cited a particular exercise, while others cited the corresponding lab topic. As mentioned above, a very popular lab is the “Polymers” in which students experience the glass transition temperature of elastomers, plastically deform a semicrystalline polymer film, use Silly Putty to explore viscoelasticity, and observe the polymerization of nylon. One student commented that the glass transition exercise in this lab was a “Good way to see how temperature influences properties and T_g!” In general, the favorite lab exercises are those involving qualitative observations made while handling materials: cold working copper tubing, cooling rubber to produce "nails," and heating glass stirring rods above T_g. The latter was the single most popular exercise; it is often difficult to get students to stop "experimenting" and go on to the next activity. The least favorite labs involved multimeters to quantify the resistance of materials or the I-V curve of the LED. They likely feel rushed, being unfamiliar with the multimeters used in the quantitative exercises. We did not survey students directly about their reasons for these choices, although one student offered that the resistance measurements were "redundant," another that the I-V behavior of the LED "didn't show me much qualitatively until I plotted the graphs." (The instructors happily observe that this comment underscores the value of plotting data.) One student indicated the polymer and conductivity labs were favorites because "I was surprised by some of the results." Another wrote that the conductivity lab was a favorite because it was "very interactive." Clearly, most students prefer labs where the hands-on experience provides an immediate result.

Table 3: Summary of student responses from one section in Fall 2003, three sections in Fall 2005, and two (combined) sections in Winter 2006:

Lab topic	Useful (out of 3)	Interesting (out of 3)	Favorite (# students/ #responses)	Least favorite (# students/ #responses)
Metals (#1. Cu tubing)				
Fall 2003	2.4	2.3	0/9	0/9
Fall 2005	2.6, 2.7, 2.4	2.7, 2.7, 2.2	5/20, 5/28, 1/24	0/20,1/28,1/24
Winter 2006	2.5	2.4	9/52	2/52
Conductivity (#2. Resistivity)				
Fall 2003	2.3	1.9	0/9	2/9
Fall 2005	2.4, 2.2, 2.3	2.3, 2.0, 2.1	2/20, 0/27, 2/23	1/20,6/27,4/23
Winter 2006	2.4	2.2	1/52	3/52
Polymers (#3a. glass transition – organics)				
Fall 2003	2.9	3.0	9/9	0/9
Fall 2005	2.6, 2.5, 2.4	2.8, 2.9, 2.8	2/17, 8/28, 9/24	0/17,0/28,1/24
Winter 2006	2.4	2.7	12/45	0/45
Ceramics (#3b. inorganic glass transition and #5 three point bend test)				
Fall 2003	2.4	2.9	3/9	0/9
Fall 2005	2.6, 2.7, 2.5	2.8, 2.7, 2.4	6/19,13/28,3/23	0/19,1/28,0/23
Winter 2006	2.4	2.6	13/52	0/52
Optoelectronics (#4. IV curve of LED)				
Fall 2003	2.3	1.9		
Fall 2005	2.2, 2.3, 2.3	2.1, 2.0, 2.1	1/20,0/26,2/23	5/20,4/26,4/23
Winter 2006- this exercise combined with Conductivity lab; no separate scoring.				

At the end of the Winter 2006 term, we also asked students to respond to how much the lab exercises helped their learning in three areas, scored from 0 - 5:

Understanding measurement uncertainties	2.1
Data plotting	2.4
Significant figures	2.2

The values to the right indicate the average response of 49 students. A number of students responded with “0,” adding that they already felt competent in these areas, based on previous experience. Nonetheless, the non-zero average indicates that many students felt these lab exercises contributed to developing these skills. It should be noted that in these particular sections, each lab exercise was graded out of 10 points, and points were deducted for incorrect significant figures and poorly plotted data, as well as incorrect calculations. Since some of the quantitative exercises were done early in the term, the point deduction effectively captured student interest, and we observed improvement in their attention to such details as the term progressed.

It should also be noted that a change in the course text did not appear to make much difference in student response to the laboratories. This suggests the exercises are easily adapted for classes on the subject, in general, and not dependent on a particular text.

Conclusions

The introductory materials course at Northwestern covers a large number of topics in the ten week quarter. Students benefit from the informal laboratory sessions described here in a number of ways. The most obvious - and we believe the most important - is that the students like the change of pace as well as the opportunity to have fun! There is no doubt that we all enjoy heating with a torch, chilling in liquid nitrogen, and breaking materials. Many students added general survey comments such as “I really liked all the labs in this course. I wish my other courses were like this,” “Far more interesting and useful than labs in most classes,” and “Overall, labs were useful and fun to go to.”

Although there is some distribution in the student response to individual laboratory topics, on average the students rated the value of each exercise between “useful” and “somewhat useful,” and the interest generated between “interesting” and “somewhat interesting.” Students also indicated that the course was effective in helping them learn about measurement uncertainties, how to plot data, and use of significant figures.

Our sense is that students appreciate the opportunity to work with materials and make relatively simple qualitative or quantitative observations. Experiencing these phenomena in lab enhances the learning process throughout the course. In addition, it is important that students learn that measurements have finite precision, experimental errors can be made, and even informal reports should be clear and objective, etc. Simple measurements on real materials are used to obtain data that establish properties with remarkable accuracy. Our hope is that students feel empowered by their ability to generate real numbers that correspond closely to “book values,” thereby relieving some of the mystery that can accompany the first exposure to the properties of materials.

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