Session 3264

# Using Everyday Materials to Examine Characteristic Mechanical Properties of Metals, Polymers, and Ceramics

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## Introduction

This paper will describe an active laboratory exercise designed to introduce key mechanical properties of metals, polymers, and ceramics. The materials investigated are common and everyday in the sense that they can be found in the desk, classroom, or refrigerator of a student, i.e., in his or her life. The exercise is presented as a "real-world" project, in which the students are newly hired employees, asked to review their knowledge of mechanical properties in materials and report their recommendations in a memorandum to their project manager. This active laboratory exercise is part of a sophomore-level materials science course that is designed into the mechanical engineering curriculum at Union College. The course also partially fulfills a writing requirement that all Union students must fulfill before graduation. The emphasis on mechanical properties makes relevant the understanding of materials science to the processing and design issues in mechanical engineering.

## Background

The materials science course at Union College is taken by all mechanical engineering majors during their sophomore year. A chemistry prerequisite is required before taking this course. The course meets every week for three one-hour lectures and one two-hour laboratory session with the lecturing professor. The objectives of the course, as listed in the course syllabus, are outlined as being:

- To provide a comprehensive introduction to materials science – the interrelation of structure, properties, processing, and performance of modern, engineering materials.
- To present the principles formulated in the science of materials that allow mechanical engineers to understand the nature and behavior of a wide variety of materials that we use everyday.
- To describe the information engineers need to anticipate the properties of materials not yet studied or developed.
- To give students gain hands-on experience and knowledge of several methods of materials characterization and processing through laboratory assignments, and build an intuitive appreciation for the phenomenon being discussed in lecture.

Other laboratory sessions include working with software provided by the textbook[1] to explore crystallography and crystal structures of ionic solids, performing tensile and compression testing of materials, exploring the temperature dependence of elastic behavior in silicone high-bounce balls, the heat treatment of steel, and microstructural observation of heat-treated steel using the scanning electron microscope (SEM). This laboratory session was created in part through ideas generated from reading about the suggested demonstrations listed in the textbook and tailoring them to the objectives of this course. It either uses similar experiments that have been used individually in the demonstration of mechanical properties, or ideas and materials that seem quite intuitive, or "everyday", in the demonstration of mechanical properties, but it is the *collection* of these tests, performed by the students, that provides a highly effective pedagogical experience. Stress and Strain, for example, are introduced first to the students as a "hands-on" phenomenon, *experimentally,* then it is reinforced as a textbook concept in lecture, and again as a machine-tested observation that is quantified by a set of data (via tensile and compression testing). This laboratory session, usually conducted in the third or fourth week in the ten-week long term, presents the students with a scenario and a document, as shown as in Fig. 1.

**Dear New-Hire,**

Welcome to AH Materials, Inc. As part of your new-hire orientation, you are given this assignment to learn about specific mechanical properties of various types of materials. These properties will help you focus on future project designs of products you will be manufacturing for AH Materials, Inc.

On the table is a collection of common and maybe not-so-common objects and materials that have interesting mechanical properties. You will be investigating the mechanical behavior of each of these items. It is a good idea to read through the entire set of directions for each object or material before beginning your experimental work. It is important for you to carefully observe experimental events and record your observations in your lab notebook. Both verbal (written words) and non-verbal (figures, drawings) are important here. You are required to turn in a memorandum reporting the materials and properties investigated, the possible applications for the properties examined, and the significant conclusions you made from this exercise.

[signature]
President, CEO
AH Materials, Inc.

Figure 1: Example of memorandum given by the president of a materials company (a.k.a. professor) to new employees (a.k.a. students) for the testing of various materials.

Procedures

The procedures for each test are provided in the document following the memorandum. New employees are encouraged to work with a fellow new-hire during this process but to keep an individual record in their laboratory notebooks of their observations. The first test investigates *elastic deformation, plastic deformation, and fatigue* of metal paper clips. The new employees take a metal paper clip and bend the inner loop away from the outer loop, slightly so that the paper clip returns to its original shape. The force applied is suggested to be the same amount of force used to slip the metal paper clip around a few pieces of paper. The new employees then take the inner loop of their metal paper clip and bend it 180º backwards so that each clip looks like an “S”. They then examine the area in the middle of the “S” with a magnifying glass. The new employee then repeats this exercise with a smaller-sized metal paper clip and records the observations and differences between the two sizes. What is demonstrated here is elastic deformation – a type of deformation in which the object returns to its original shape after the forces have been removed. This type of deformation is unique in the realm of mechanical behavior because all materials undergo elastic deformation. The new employee is also asked in the new-hire document to address the following specific questions related to elastic deformation in their memorandum to the president of the company:

a) Draw a stress-strain curve, and label the axes and the modulus of elasticity. Describe the loading and unloading as it applies to bending these metal paper clips. What are the factors involved in ensuring elasticity with these metal clips (or, what makes the paper clip **not** return back to its original form)?

The new employees then take the two ends of the “S” and bend them back and force relative to each other a few times, keeping count of the number of times before the metal paper clip breaks. When the paper clip does break, the new employees are asked to quickly put the middle of the “S” to their upper lip and record any observations. In addition, they are to examine and record the area at which the break occurs using a magnifying glass. What is demonstrated is plastic deformation – a type of deformation in which the object undergoes a permanent shape change, or fracture, and evolution of energy is usually involved in the deformation. This test also illustrates the mechanical property of ductility, in which a material is capable of undergoing plastic deformation before fracture. In this case, the number of bends the metal paper clip can withstand before fracture is a comparable measure of ductility. The new employees must also address the following question in their memorandum:

b) What would be the case if the metal paper clips had no ductility? Sketch the curve plotting Stress as a function of Number of Bends for a brittle paper clip that fractures at its first bend and for your metal paper clip.

The next experiment involves the exploration of strain rate sensitivity and creep on a polymeric material, namely Silly Putty®. The new employees are asked to make a cylinder about 50 mm long and 10 mm in diameter from the Silly Putty®. Then they grab the ends of the cylinder and slowly pull it until the original length is doubled. The time is recorded for this process so that rate at which the material was pulled can be calculated. This is then compared to a cylinder of the same dimensions of Silly Putty® being pulled with a sharp yank. The new employees are asked to look at the area of fracture, record, and compare differences between the slowly pulled sample and the quickly pulled sample. This demonstrates *strain rate sensitivity* in a material. The rate of deformation (straining) can greatly affect how a material deforms. This is true of many polymers at ambient temperatures, some metals at high and low temperatures, and a few ceramics at high temperatures.

To investigate the phenomenon of *creep*, in which plastic deformation is a function of time and amount of load on a material, the new employees reshape their Silly Putty® into a cylinder, and using a blunt knife, create a section in the middle of their sample in which the diameter is reduced by 2 mm. While the sample is horizontal, the new employees then carefully attach another glob of Silly Putty® to one of the cylindrical sample. Holding the other end of the sample and carefully turning it vertically, the new employees observe and record the process of creep, how it deforms the Silly Putty® and the time it takes for creep to cause the sample to break apart and fail. To be more accurate about this phenomenon, data points are collected by stopping the creep action every two seconds by placing the sample horizontally on a table and measuring the amount of elongation per time interval. A plot of elongation as a function of time is requested to be reported in the memorandum to the company president. What is demonstrated here is that Silly Putty® creeps easily, and similarly, understanding of creep deformation is key to design of applications, at ambient and high temperatures, in aeronautical and mechanical engineering.

The next experiment investigates *inhomogeneous deformation* in polyethylene beverage holder rings. Low-density polyethylene is used to hold six-pack packaging of beverages (soda, beer) and cans (pet food, soups). The new employees are asked to draw a picture of their polyethylene ring before deformation. Then they pull the plastic ring along a horizontal axis away from each other (a tensile test). They observe if the amount of force exerted to start the deformation is different than the amount of force to continue the deformation. They also observe if the deformation is local or uniform in all locations of the plastic ring. The new employees are asked to draw a picture of their polyethylene ring after deformation. What is demonstrated is a kind of *inhomogeneous deformation* – one part of the sample deforms locally and this local deformation continues to move throughout the entire sample before fracture. In polymers, this is called *cold drawing*; in metals, this is called *local necking* or *Luders band formation*.

*Anelastic deformation*, or time-dependent elastic deformation is demonstrated with the use of licorice sticks, namely Twizzlers®. The new employees are asked to gently pull the opposite ends of a stick of licorice and observe that the licorice will deform a bit and then almost immediately return to its original length. If the licorice is pulled harder elastically, more time is required before the sample returns to its original shape. This mechanical property is important when it is desirable for a material to absorb energy upon impact, or for the strain on the material to *lag* the stress. The damping of a material contributes to its time-dependent anelastic property. The piece of licorice also demonstrates *ductile fracture* because it will stretch, or plastically deform over a measurable length, before breaking.

Finally, the new employees are asked to investigate the mechanical properties of chalk. Taking a piece of chalk and pulling it without producing any bending or twisting confirms that many ceramic materials require a considerable amount of normal stress in tension to break. However, pulling the chalk when a notch is made laterally into it will easily break it. This demonstrates the sensitivity and tensile weakness of ceramic materials in the presence of internal microcracks and pores and external cracks due to processing or wear. In addition, the inability of the chalk to strain, or plastically deform, before fracture shows that they are brittle materials, so notches act as stress concentration regions. The regions near the notch reach the breaking strength with little overall stress on the sample. Once a crack forms at the notch (the notch itself is a macroscopic crack), it propagates through the ceramic quickly.

Procedure for Writing a Memorandum

During the laboratory session, the format and purpose of a memorandum is explained to the students. It is discussed that in contrast to laboratory reports, memos are generally written to inform the reader of new information or by persuading the reader to take an action. The most important feature of a memo is that it is concise yet complete and informative, not more than two pages with attachments.

In this scenario, the audience is the professor, also the "company president" who has asked her students, the newly hired employees, to perform the task of testing and observing the mechanical properties of different materials. She wants the new employees to present key results, and make recommendations for applications of the specific class of materials investigated and specific mechanical result tested. She wants to be treated as a "skeptical employer", who will believe a recommendation only if it is backed up concisely and carefully with "bottom-line" data. Fig. 2 outlines the format given to the students for the preparation of a memorandum.

<u>Heading</u>: The heading segment follows this general format:

TO: (audience's names and job titles)
FROM: (your name and job title - "authenticate" memo with your handwritten initials here)
DATE: (date experiment was completed, date memo was prepared)
SUBJECT: (concise description of what the memo is about)

<u>Purpose</u>: State the main purpose of the correspondence in this opening paragraph. Include the context and problem, the specific assignment or task, and the objective of the memo. This section should be short (1 paragraph) and used to remind the reader of the issue, problem, or situation that is addressed in the memo.

<u>Recommendation</u>: This section provides a brief statement of the key results or recommendations you have reached. These will help your reader understand the key points of the memo immediately. (i.e include a statement like "*I recommend that materials with good ductility be used for XXXX " or "I measured the creep rate to be XXXX.")*

<u>Discussion</u>: The discussion section is where you include all the detailed information that you have gathered to support you ideas. Keep these two things in mind:

- Begin with the information that is most important. This may mean that you will start with key findings or recommendations. Think of an inverted pyramid. Start with your most general information and move to your specific or supporting facts.
- Briefly describe any experiments you performed or calculations that you made.
- Provide supporting data to give the reader confidence in your recommendations. (one or two key attachments)

<u>Closing</u>: After the reader has absorbed all of your information, you want to close with a courteous ending (offer of further assistance) that states what action you want your reader to take.

<u>Attachments</u>: Make sure you document your findings or provide detailed information whenever necessary. You can do this by attaching lists, figures, tables, etc. at the end of your memo.

Figure 2: Format for a memorandum.

## Discussion and Conclusion

This active laboratory exercise was not only fun but constructive in teaching sophomore-level students fundamental mechanical properties of everyday materials. The early placement of the laboratory exercise in the quarter allowed for the students to be introduced to mechanical properties as hands-on, experimental phenomena first, which were then reinforced with classroom definitions of these terms. This laboratory exercise introduced simple testing of stress and strain that is emphasized in later laboratory sessions on tensile testing (of metals and polymers) and compression testing (of wood and fiberglass composite) using a load frame. This laboratory exercise was a useful reference point, pedagogically, as the professor could refer to the "paper clip" or the "chalk" experience to elaborate upon the mechanisms for deformation, i.e. dislocations, or the differences between brittle and ductile fracture in class, for example. In discussing polymers in lecture, she could refer to the "licorice", "Silly Putty®" or "polyethylene ring" experiences to illustrate how polymer structure and degree of crystallinity in a polymer affected its response to mechanical stress.

Similar sets of experiments have been created and tailored for specific objectives of other courses in materials science. F. Xavier Spiegel presented a paper on a set of experiments to explore the relationship between the processing and mechanical properties of metals and alloys[2]. His set of experiments included one exercise on the bending of metal paper clips until fracture to demonstrate fatigue. In the laboratory exercise presented in this paper, the bending of metal paper clips was used to demonstrate plastic deformation and ductility simply, upon which mechanical design, lifetime, and wear issues can be built in upper-level courses. Similarly, a proposed addition to this experiment would be for the students to observe variations in size of the metal paper clip upon repeated bending, or a comparison of the mechanical response of a polymeric paper clip, and a polymer-coated metal paper clip, to that of a plain metal one. Henry Petroski[3] also used metal paper clips to illustrate strain-hardening and associated brittle fracture of metals[a]. F. Xavier Spiegel also presented papers on the brittle, elastic, anelastic behavior of chewing gum, licorice, and a plastic beverage container, from which the experiments in this laboratory session were inspired[4,5].

This laboratory session was also a beneficial exercise in the written communication of scientific information. The memorandum format facilitated students to "think outside of the box", in terms of applying their investigated results to possible materials or design applications. Assessment of memos were based heavily on the student's ability to draw together key conclusions from each test and make insightful recommendations, as a new-hire, based on the experimental findings. Fig. 3 shows an example of the evaluation sheet that was used to grade each memo. In addition, student response via end-of-the-term course evaluations on this laboratory session showed that it was successful in being a fun introduction to mechanical properties of everyday materials. General comments in response to the question of "the usefulness of the laboratory to learning the subject matter" included "very useful, all were useful", "always pertinent to what we were learning, fun too", and "the labs definitely made you think about what you were learning – she [the professor] never made them too difficult which was wonderful as we could pay much more attention to the lab itself." Common responses to the writing component of laboratory sessions and the improvement of writing were "amount of writing was a good level", "my lab writing

[a] This video by Petroski was shown on the first day of class.

improved greatly in terms of ME [mechanical engineering] lab writing", "better", "in a science manner, improved".

In summary, the laboratory exercise presented in this paper illustrates an effective, hands-on way for mechanical engineering students to understand the importance of materials science, in specific mechanical properties of materials, in their field. The various activities in this exercise were geared for the sophomore level and tailored for a mechanical engineering program. The set of experiments provided a reference point during discussions in lecture on specific materials or specific mechanical properties. It also met the goal of the liberal arts environment of Union College to develop students with a skilled ability to communicate effectively in written form. A compilation of experiments, presented with an industrial scenario, proved to be a good way to focus on engineering phenomena, technical writing, and fulfillment of college-wide writing degree requirements.

**Evaluation of Memorandum**

| | |
|---|---|
| Heading (10 pts) | _____ |
| Clarity of Subject Line (10 pts) | _____ |
| Opening (10 pts) | _____ |
| Recommendation/Communication of New Information (15 pts) | _____ |
| Discussion (15 pts) | _____ |
| Closing (10 pts) | _____ |
| Attachments (10 pts) | _____ |
| Proofreading (10 pts) | _____ |
| Intellectual Creativity (10 pts) | _____ |
| **Total (100 pts)** | _____ |

Additional Comments:

Figure 3: Evaluation Sheet for Student-Written Memorandum.

## Bibliography


1. Callister, William D., Jr. Materials Science and Engineering, An Introduction, 6th Edition. John Wiley & Sons, 2003.

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3. When Engineering Fails [videorecording], Henry Petroski, British Broadcasting Corporation, 1997.

4. Spiegel, F.X., "Demonstrations in Materials Science from the Candy Shop", *NEWU 94*, 189-191.

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