AC 2010-1276: STUDENT UNDERSTANDING OF THE MECHANICAL PROPERTIES OF METALS IN AN INTRODUCTORY MATERIALS SCIENCE ENGINEERING COURSE

Rebecca Rosenblatt, Ohio State University

Rebecca Rosenblatt is a graduate research associate in the physics department working towards a PhD in physics education at The Ohio State University. She is currently investigating the evolution of student understanding of force, velocity, and acceleration, and she is working on this project to identify and address student difficulties in learning materials science.

Andrew Heckler, Ohio State University

Andrew F. Heckler is an Assistant Professor of Physics at Ohio State University. His original area of research was in Cosmology and Astrophysics. In the past eight years, he has focused on Physics Education Research, studying fundamental learning mechanisms involved in learning physics, the effects of representation on learning and problem solving, and the evolution of physics understanding during and after a physics course. As part of the education component of an NSF MRSEC center, he is also leading a project to identify and address student difficulties in learning materials science.

Student Understanding of the Mechanical Properties of Metals in an Introductory Materials Science Engineering Course

Abstract

We report on initial findings of a project to identify, study, and address student difficulties in a university-level introductory materials science course for engineers. Through interviews of over 80 students and testing of over 300 students, we examined in detail student understanding of the mechanical properties of metals. Here we describe a number of student difficulties in understanding macroscopic properties of metals and the effects of simple processing on these properties. For example, many students have difficulty with basic definitions of mechanical properties. These difficulties include the notion that yield strength is independent of the cross sectional area of the material, the difference between the strength of a material and the stiffness of that material, and the actual definition of yield strength and Young's modulus. Further, only half of the students recognized that drawing a metal through a tapered hole increases its strength and only half again of these students could give a simple, correct explanation as to why. All of these results are after traditional instruction that explicitly covered these topics. In order to address these difficulties, we are in the process of designing and field testing 45 minute in-class active learning group-work lessons, similar in structure and style to lessons shown to be effective in physics education research efforts.

Introduction

An understanding of the definitions of basic mechanical properties is fundamental to understanding materials science. A number of researchers have investigated student understanding of some mechanical properties such as students' beliefs about strong materials[3] and students' understanding of strengthening mechanisms behind coldworking[4]. In this paper, we add to the existing research on student difficulties with mechanical properites. We study in detail a few concepts including student confusion between mechanical stress and force, and student confusion between stiffness and strength.

All of the data presented here was collected after students received direct instruction and homework on these topics. The lecturer for the class was an experienced teacher who was aware that students have difficulties with these topics and took steps in class to address these difficulties with slides aimed specifically at the definitions for stress, elasticity, yield strength, and stress strain plots as well as clicker questions and live demos.

Participants and Methods

The participants in this study were enrolled in the introductory materials science engineering course at The Ohio State University, a required core course for many of the engineering major programs. The students ranged from 2nd to 5th year students and about 10% of the students intended on becoming materials science engineering majors.

Data was collected over a period of 4 quarters, with approximately 160 students per quarter, and was collected in three ways. First, midterm and final exam data was collected. The exams were in multiple choice format and some of the items for one quarter (about 10-20%) were designed by us in collaboration with the instructor. These items were aimed at testing specific student difficulties with the course material. Second, for two of the four quarters, volunteer students were recruited for testing and interviews. These students received a small amount of extra credit and the opportunity to volunteer was offered to all students in the class. Approximately 25% of students volunteered in these quarters. The volunteers participated in a one-hour session in which they were interviewed for part of the session and tested in the remaining portion with multiple-choice or free response questions. For the interview portion of the session, students were in a separate room. Some of the interviews were video and audio recorded. About 60% of the students were interviewed individually, the rest were interviewed in groups of 2 or 3.

The third method of collecting data integrated student participation more directly into the course. In addition to the standard homework, students were also given a “flexible homework” assignment with credit for participation as part of the course grade. The flexible homework assignment consisted of participation in a one-hour session in our research lab where students would complete some combination of testing and interviewing. Several times during the quarter, we would randomly select a recitation section, and ask students to sign up for flexible homework. Typically, about 95% of students participated in the flexible homework. Those students who did not wish to come to an interview/test session were given the opportunity to complete a one-hour homework assignment instead. During the flexible homework session, students were told to answer the questions as best they could, even if they have not yet seen the material. For the testing portion of the session students sat at individual stations in a quiet room. The test items were in either multiple-choice, free-response, or a multiple-choice-with-explanation format. Students completed the material at their own pace. Afterwards we would informally ask students whether they had any questions and/or to explain their answers. We observed during these sessions that students made a good faith effort to answer the questions to the best of their ability.

Difficulties Distinguishing Between Force and Stress.

Many students have difficulty applying the fundamental concept of stress to the definition of yield strength. For example, Figure 1 presents a very straightforward question comparing the yield strengths of two (otherwise identical) samples of metal with different cross sections. This question was administered to 117 students after they received instruction and homework on this topic. Remarkably, only 23% of students correctly answered this question. The majority of students, 67%, chose the rod with the larger diameter as having the larger yield strength.

Based on student interviews and comments made during recitation group work, we found that students often associate yield strength with force rather than stress. In fact, students often used the terms force and stress interchangeably and inconsistently. For example, a typical student's definition for strength is:

S1: "Strength is the ability to take a force without permanent deformation."

S2: "Strength is how much a material can be loaded without failure."

It is interesting to note that a small but persistent number of students (10%) chose the thinner rod as being stronger. These students often respond that the smaller rod would experience a greater stress because its area is smaller. They recall that they need to consider the area when moving between force and stress, but they are confused about how to use this information and over simplify the problem by not considering the change in force for the two rods. A typical student response was:

S3: "$\sigma y = F/A$. Since (the) crosssectional area of A is greater than (the) crosssectional area of B. $\sigma yA < \sigma yB$."

Students' difficulty with this fundamental definition of strength may cause difficulties with understanding related topics as well. An example of this is given in the next section on student difficulties with understanding the effects of changing the shape of a metal through coldworking.

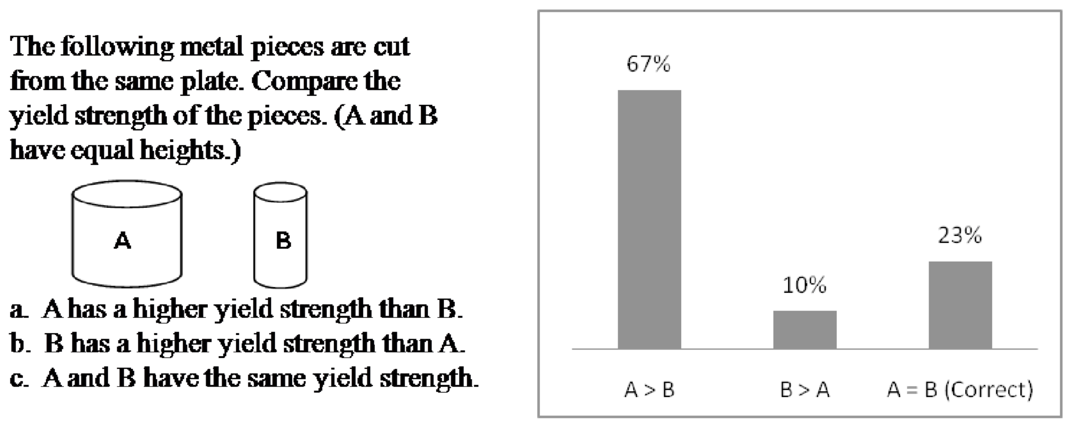

Figure 1: Response percentages, to the indicated question, assessing students' beliefs of yield strength's dependence on area. N = 117

Difficulties with Cold Working Effects on Yield Strength

We asked 68 students to answer the free response coldworking question in Figure 2. This question is somewhat similar to an item on the Materials Concept Inventory[4], which is a multiple choice item giving choices explaining why a cold drawn wire increases in strength. In contrast, the question in Figure 2 is more broad and open-ended, asking the student to predict the change in strength and provide an explanation.

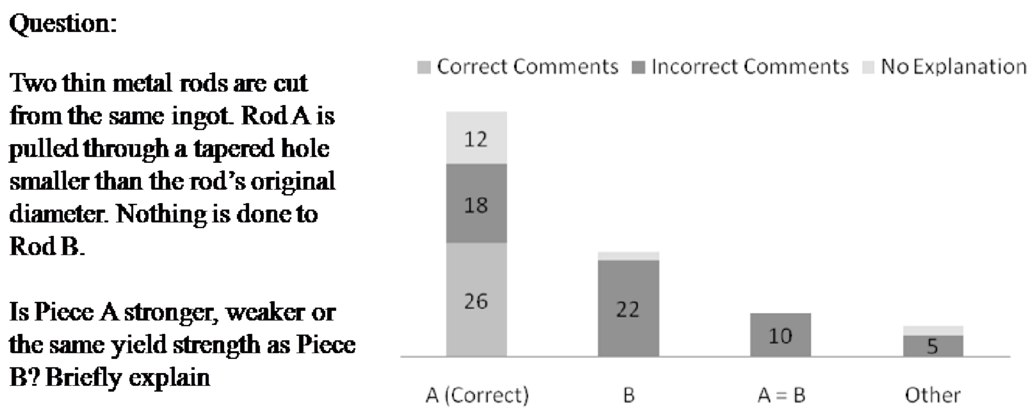

Figure 2: Students' Response Percentages for the Effect of Cold Working on Yield Strength. N = 68.

There are several interesting results from student responses. First, only 56% of the students correctly predicted that the yield strength of a cold-drawn metal increases. Furthermore, as seen from the breakdown of students' responses in Figure 2, only half of the students who correctly indicated which rod was stronger (26% of all students) also gave correct reasons for their choice. An additional 12% of students chose the correct answer, but when asked for an explanation, these students did not offer any reason for why this strengthens the metal. They only, somewhat redundantly, stated that, "Piece A is stronger than B due to the cold working done on the metal." While these students might have been able to provide a correct explanation for the mechanism by which coldworking strengthens a material, it is not clear from their response whether they understood this, and these students were labeled as 'no explanation'. (All quotes in this paper are direct quotes from students either via interview data or written responses. The only changes made were grammar and spelling changes.)

Second, 10% of the students responded that coldworking a piece of metal does not change the strength of the material. Of these 7 students who responded that A = B in strength, 6 students provided explanations similar the response, "They are the same material. They have the same composition and remain unaffected microscopically after deformation."

Third, 22% of students responded that B was stronger. Of these 15 students, 9 students, 13%, explained their answer writing things like, "[A] has a smaller diameter, therefore smaller cross sectional area, and will be weaker." This is reminiscent of the student responses about strength and cross sectional area reported on in the previous section. See Table 1 for a more complete breakdown of students' responses and explanations.

Table 1: Typical Student Explanations and Choices for the Question in Figure 2. N= 68

Choice and Explanation Category	A Typical Student Response	Percentage of Students	Number of Students
Chose A and Labeled as No Explanation	"A is stronger since it is cold worked."	12%	8
Chose A = B	"They are the same material. They have the same composition and remain unaffected microscopically after deformation."	9%	6
Chose B	"[A] has a smaller diameter, therefore smaller cross-sectional area, and will be weaker."	13%	9
Chose A and labeled as Incorrect	"The area got smaller so it is stronger."	6%	4
	"The atoms are closer together. Things are more compact."	6%	4

Many of these student difficulties with this question appear to stem from basic misconceptions with fundamental concepts in materials science. For example, the misconception that yield strength is dependent on the size of the rod and the misconception that yield strength is only dependent on material composition accounts for 19% and 9% of incorrect choices respectively.

Difficulties Differentiating Stiffness from Strength

Although not as prevalent, another difficulty students have with fundamental concepts in material science is that students often confuse strength with stiffness and vice versa. There seems to be two related but slightly different causes for this confusion.

First, student response patterns suggest that many students believe that a stiff material will have a high yield strength, and conversely, a material with a high yield strength will be stiff. Evidence of the confusion between stiffness and strength is provided by results from the two multiple choice questions in Figure 3. For the first question in Figure 3, in which Metal A has a higher yield strength than metal B, 27% of students, answer choices a and c combined, responded that it was true that, "Metal A will have less strain at a given stress than metal B." In addition, students' responses to the second question imply that a roughly equal number of students believe if a material is stiffer than it must be stronger. This can be seen by 21% of students responding that, "A stiff material requires a large stress to cause permanent deformation," when they were asked question II, "Which of the following is true of mechanical behavior?" (See Figure 3 for data on these two questions.)

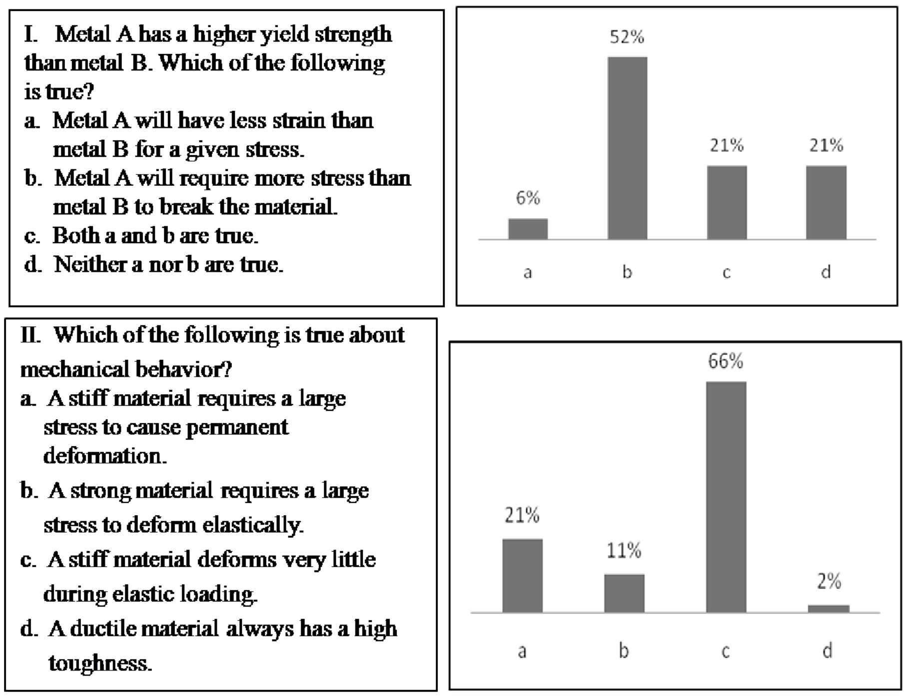

Figure 3: Response percentages, to the question to the left, showing students' confusion between the definitions of stiffness and strength. (N=89 for I and N = 160 for II.)

A second reason for why students tend to confuse strength and stiffness is that the students simply do not know the technical, materials science definitions for these terms, or at least they are not aware that these terms, which are common in everyday language, need to be used carefully and with technical precision. For example, twenty three students were asked to freely respond to the question, "What is the difference between strength and elasticity?" All students responded to this question by giving respective definitions for strength and elasticity. There were several interesting patterns of responses.

Three out of the 23 students, 13%, referenced strain in their definitions for strength. Typical student responses were:

S4: "Strength is the combination of elasticity and ductility."

An additional 3 students wrote ambiguous statements that confused concepts of strength and elasticity such as:

S5: "Strength is how resistant a material is to elastic deformation."

Also, students tend to use the common, everyday meanings for the terms. For example, there is some evidence that students view the term "elasticity" as synonymous with "stretchability" and/or elastic deformation, rather than associating elasticity with Young's modulus. 30% of students responded to the question, "What is the difference between strength and elasticity?" with typical responses such as:

S6: "Elasticity is how much something is able to deform before becoming plastically deformed."

And, an additional 17% responded:

S7: "Elasticity is the materials ability to return to what it was prior to the load being applied."

We found that this confusion between stiffness (or elasticity) and strength only occurs in a small (though significant) number of students. Nonetheless, in order for students to gain a basic understanding of materials science, they must first have a basic conceptual understanding of mechanical properties such as yield strength and elasticity. At minimum, approximately a quarter of the student population does not understand this very fundamental and essential concept, even after instruction.

Difficulties Finding Young's Modulus from a Stress-Strain Plot

We report, in this section, on students' difficulties correctly comparing the Young's modulus for two stress strain curves. When asked to compare the Young's modulus of two materials represented by two stress-strain curves, we found that students often chose the wrong curve. Student errors could be due to two reasons. They could be the result of the difficulties that students often have with graphs in general, or they could be the result of students' difficulties with the definition of the modulus of elasticity.

A multiple choice quiz was given to 48 students taking the introductory material science course. This quiz consisted of a sequence of stress-strain plots with two different curves drawn on each plot. For each plot, students were asked which of the two curves had the higher modulus of elasticity, yield strength, tensile strength, ductility, and toughness. (See Figure 4 for the four graphs and a breakdown of students' responses.) While students had difficulties with most of these properties, only the students' responses for the modulus of elasticity are discussed here.

We analyzed the data in two ways. First, as seen in Figure 4, we present the response percentages for each question. Second, in order to get an idea of the extent to which students are answering consistently, we categorized students into one of 4 categories, as shown in Table 2. Each category corresponds to a consistent method - across the four questions - of choosing an answer. For example, a student who consistently chose the stress-strain curve with the higher peak (i.e. high tensile strength) would be placed in the “Higher Peak” category. Each student is place in a particular category if he/she answered in a manner consistent with that category at least three out of four times. This allowed students to be grouped into their main, or most often used, reasoning method even if they did not always use that method. When students’ responses are analyzed in this manner, we see that only 65% of students correctly answered these questions using slope. Also, all of the incorrect students answered based on one of three incorrect categories: over all height of the graph, 15%, greater elastic strain, 13%, or greater overall strain, 6%.

The incorrect answers that students chose can be loosely separated into two main areas of mistakes. Students either use the overall height of the graph to guide their responses or students use the strain. The 15% of students who use the height of the graph to guide their answers might be confusing the Young’s modulus and stiffness with the yield or tensile strength of the material, or they might believe that stiffness and strength are necessarily related so that it is ok to use the tensile strength to assess the stiffness. In addition, students may simply be using an easily found and salient feature of the graph because they are struggling with how to use the graph itself. (Student difficulties with height of a graph and slope of a graph is a fairly well researched topic[2].) While students may be struggling with the graph itself, students’ written responses to other questions reveal confusion between elasticity and strength. This would suggest that many of these students were not misreading the graph but were answering consistently with a belief that they should look at height, or stress, to find Young’s modulus. Unfortunately, we have not yet had a chance to assess students for direct interview or testing data which would corroborate that students who use height on the stress-strain plots are doing so because they are thinking about strength. Thus, at this time, we can only report that this stress-strain data is consistent with confusion between strength and stiffness seen in other areas.

Table 2:Response Patterns Seen Across the Four Questions. N=48

The question was: Which metal has a higher modulus of elasticity?
Circle one A, B, or A = B. Students are placed in a model by answering at least three of the four questions consistently with the model’s response pattern.

Model Name: description of feature used	Response Pattern	Percentage Percentage	Number of Students
Correct: Higher slope	A, A, B, B	65%	31
Length: Higher percent elongation	B, A = B, A, A	6%	4
Stretch: Lower slope or greater strain	B, B, A, A	13%	6
Height: Higher peak	A, B, A, A = B	15%	7

Students who used the strain of the graph to guide their answers might be simply mistaking greater Modulus as being the lower slope material. This would explain the 13% of students who picked a greater elastic strain, which on our graphs is always a lower slope. However, as mentioned in the previous section, they may also be making a more important conceptual error in mistaking

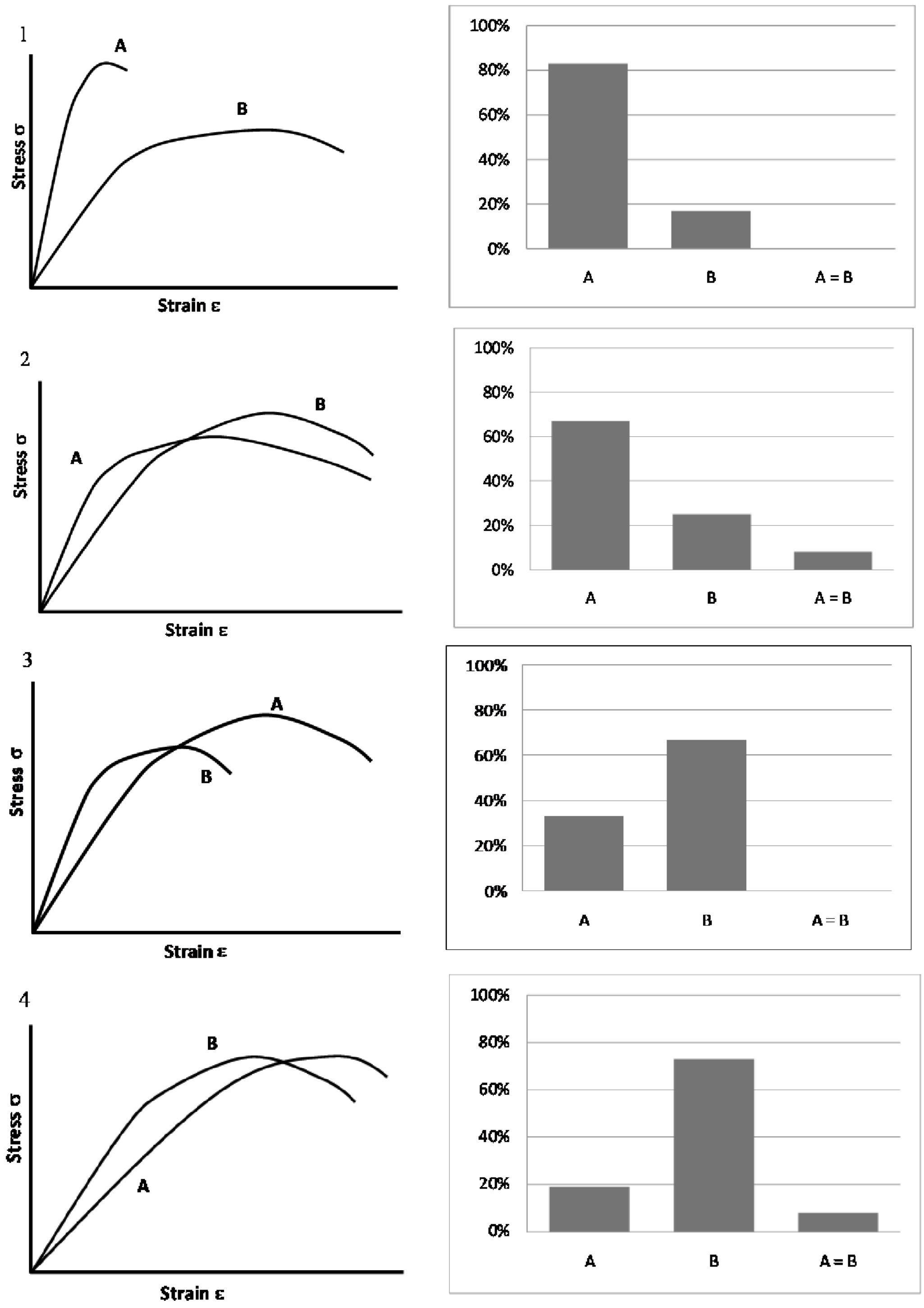

Figure 4: Response Percentages. The question was, “Which metal has a higher modulus of elasticity. A, B or A = B?” Each graph corresponds to the stress-strain plot to its left. N=48

greater modulus for the material with a greater stretching ability (i.e. greater strain). The common use of the term elasticity refers to the property of a material which can be visibly stretched and return to its original shape. This use of the term agrees with a material scientist's use of the term when talking about elastic deformation. However, when elasticity is used to refer to Young's modulus strain or amount of stretch alone is not sufficient. Based on multiple choice questions with free response explanations of the choices, it is clear that many students, conservatively at least 17% but maybe as many as 50% of students, confuse elastic deformation with elasticity/stiffness.

The use of stress-strain plots is an easy way to quiz students on their understanding of modulus of elasticity, yield strength, tensile strength, ductility, and toughness, but we believe they are also a convenient teaching tool. In a recitation class environment, we presented students with a worksheet of 7 different plots and had them work in small groups to compare the mechanical properties of various pairs of stress-strain curves, such as shown in Figure 4. This exercise appeared to significantly facilitate student understanding of stress-strain plots and their understanding of the definitions and differences between various mechanical properties such as yield strength, ductility, and elasticity (as defined by Young's Modulus). The students were, for the most part, engaged in this activity and students seemed to see its value for the course. This could be seen by the students' level of dialog in the groups, questions to the TA, and completion of the worksheets which were not for a grade.

In addition to the plots, students were required to assess the correctness of a set of written hypothetical students' statements about different mechanical properties. These hypothetical statements represented several misconceptions that students often have, such as, "A stiffer material is stronger." While students were fairly good at the graph questions by this point in the recitation, they often had difficulty with these questions. Students struggled with analyzing the written descriptions of graph features, and they had difficulty categorizing what was not useful, or true, in finding each property although they knew what was useful. For example, most of them understood that yield strength could be found from the stress where the graph changed from linear to nonlinear, but they would still struggle with a question like, "The yield strength is given by the stress needed to break the material. True or False?" This suggests that giving students the plots by themselves does not necessarily transfer to an overall understanding of the mechanical properties. While this is not particularly surprising, it is important to keep in mind when planning instruction, test questions, and so on for a course.

Conclusion and Summary of Findings

We reported here on student difficulties in understanding the mechanical properties of metals and on pilot instructional materials designed to help students overcome these difficulties. While we are not the first researchers to report students' difficulties in understanding mechanical properties, our research adds to the exisitng literature on students' conceptual difficulties in this area. First, students have difficulty answering a simple question asking if a rod of equal length but greater diameter will have the greater yield strength. Surprisingly, 77% of students answer this simple conceptual question incorrectly. This same difficulty, correctly applying the concept of stress rather than force, can be seen in students incorrect answers much later in the quarter such as 13% of students choosing an unworked rod as being stronger because, "A [the worked rod] has a smaller diameter, therefore smaller cross-sectional area, and will be weaker." Second, students have difficulty understanding and explaining coldworking. We presented students with a question which was very similar to the question on the Materials Concept Inventory about drawing a rod through a hole. However, we found that when given an open ended question 25% of students chose the unworked rod as being stronger. We believe that this is important for instructors to consider when interpreting students' responses to the Materials Concept Inventory question and that a complimentary question which allows for students to choose the unworked rod or both rods as being of equal strength would give instructors a more complete understanding of where their students are struggling with coldworking. Third, students have difficulty differentiating the mechanical properties of stiffness and strength often choosing, incorrectly, responses which imply a stiff material must be strong or vice versa a strong material must be stiff. While this problem occurs in a small fraction of students, about 20%, it appears in several areas including stress-strain plots, written multiple choice, and free response questions. Also, it is representative of the basic difficulties students have with the simple definitions of mechanical properties especially when such definitions are counter to common uses for terms. The last difficulty discussed here is difficulties finding the Young's modulus from a stress strain plot. 35% of students consistently use something other than slope to find the modulus. The most common incorrect features used are the overall height of the graph or a lower slope/greater elastic strain each accounting for about 15% of students. We have used such stress-strain plots in informal recitation sessions, and we are optimistic about their usefulness as a teaching tool to aid students in learning to differentiate between the different mechanical properties and their precise definitions and meanings.

Future Research

The next phase in this study is to construct a set of worksheets designed to be completed in groups of 3 or 4 students during 45 minute recitations for the introductory materials science course. These worksheets will be aimed at addressing the conceptual difficulties we have presented here as well as other areas of student difficulty and problem solving skills. This style of interactive group work has been found to be effective in teaching students difficult physics topics[1], and the goal is to determine whether such activities can produce similar benefits for introductory materials science classes.

Acknowledgements

This work has been supported in part by the Center for Emergent Materials at the Ohio State University, an NSF MRSEC (Award Number DMR-0820414).

References

1. Heller, P., Keith, R., and Anderson, S. (1992). “Teaching Problem solving through cooperative grouping. Part 1: Group vs individual problem solving.” Am. J. Phys., 60: 627-36.

2. McDermott, L.C., Rosenquist, M.L., and van Zee, E.H. (1987). “Students difficulties in connecting graphs and physics: Examples from kinematics.” Am. J. Phys., 55: 503-13.

3. Kitto, K.L., (2007). “Analyzing What Students Write about Materials - Another Strategy for Developing Conceptual Knowledge in a Materials Engineering Course.” ASEE/IEEE Frontiers in Education Conference, S2G-14-8.

4. Krause, S., Decker, J.C., Niska, J., Alford, T., and Griffin, R., “Identifying Student Misconceptions in Introductory Materials Engineering Classes”, A.S.E.E. Annual Conference, 2003.