Student Difficulties with Basic Concepts in Introductory Materials Science Engineering

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Abstract - **We report on findings of a project to identify specific student difficulties in a university-level introductory materials science course for engineers. This is the first part of a larger project to design and assess evidence-based curricular materials for this course. Through interviews, testing, and classroom observation of over 1000 students, we examined in detail student understanding of basic topics in materials science including topics such as atomic structure, mechanical properties, defects, diffusion, phase diagrams, failure, and the processing of metals. We identified four general areas in which students have difficulties: Student confusion of similar concepts, student difficulties with reasoning about concepts with more than one variable, student use of inappropriate models or analogies, and student difficulties with common graphs and diagrams used in materials science. We provide a number of specific examples of each category, focusing on the materials science of metals. While these student difficulties are interesting in their own right, a careful examination of these difficulties can also provide useful information for the design of instructional materials.**

Index Terms – Concepts, Diagrams, Graphs, Materials Science, Misconceptions.

INTRODUCTION

Basic concepts in material science and engineering are fundamental to a number of areas in engineering. In this paper, we report on some of the findings of a project to identify specific student difficulties in a university-level introductory materials science course for engineers. This is the first part of a larger project to design and assess evidence-based curricular materials for this course. The second part, which includes the implementation of curricular materials based on our findings of student understanding, is reported in another paper in these conference proceedings [1]. Therefore our goal in this paper is to identify and characterize some of the student difficulties in several content topics in materials science in order to gain insight into student understanding of this important area, and to provide a starting point for the design of instruction to improve student learning in this area. This basic strategy is similar to other successful efforts in physics education research and other areas [2], [3].

Several previous studies have identified and described a number of student difficulties with concepts in introductory materials science [4]-[6], including some of our own recent efforts [7], [8]. A "Materials Concept Inventory" has been developed to assess conceptual understanding in materials science [4]. In this study we report on a wide range of additional student difficulties with basic materials science concepts and characterize in more detail some of the student difficulties found in earlier studies. The content topics investigated are directly addressed in a common introductory materials science and engineering course, and are covered in a commonly used text by Callister [9].

We have organized our findings into four areas: Student confusion of similar concepts, student difficulties with reasoning about concepts with more than one variable, student use of inappropriate models or analogies, and student difficulties with common graphs and diagrams used in materials science. We will provide examples of each area in the context of several content topics, such as properties of materials, and we will focus on concepts applied to metals. We will begin by first describing the participants and methods of obtaining data.

PARTICIPANTS AND METHODS

The participants in this study were enrolled in the introductory materials science course for engineers, which is a required core course for many of the engineering major programs at Ohio State University, a large public research university. The students ranged from 2nd to 5th-year engineering students. About 10-15% of the students intended on becoming materials science engineering majors, and about 35% of the students were mechanical engineering majors, the most common major in the course.

Data was collected over a period of 7 quarters, for a total of approximately 1000 participants. The data was collected in four ways. First, we conducted individual or group interviews on over 200 students. These interviews consisted of asking a wide range of open ended and multiple choice questions, such as those presented in this paper. Several dozen interviews were videotaped, and the rest were recorded via interview notes. The interviews were used to first explore areas of difficulty, then to focus on specific difficulties identified in the initial interviews and free response tests. Most interviews were conducted individually, but some were given in groups of 3 or 4.

The second method of data collection was via free response and multiple choice tests. In addition to the standard homework, students were 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 where students completed some combination of testing and interviewing. Throughout the quarter, students were randomly selected to participate in the flexible homework. Typically, about 95% of students participated in the flexible homework. The tests items were in either multiple-choice, free-response, or a multiple-choice-with-explanation format. Students completed the material at their own pace at individual stations in a quiet room. 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.

The third method for collecting data was via observations in recitations, which were conducted in small group format. The authors participated in some of these sessions. This method was used to further verify and/or clarify student difficulties found via interviews and tests.

Finally, the forth method for collecting data was via the official exams administered as part of the course. The exams were in multiple choice format, and some of the items (about 10-20%) were designed by us in collaboration with the instructor. This method helped to assure that student answering was not simply an artifact of the testing context, i.e., whether performance would dramatically improve for high–stakes testing contexts. We found no large differences in answer patterns on exams compared to the other methods of collecting data.

Most tests and interviews were at least one week *after* the relevant instruction, however some were administered before relevant instruction. The data reported here is all post instruction.

Most of the difficulties reported here were first found in interviews. We subsequently devised questions to demonstrate the relative frequency of these difficulties in the student population. Thus incorrect answers to the questions should not be viewed as uninteresting artifacts of the particular questions, but rather indicative of student difficulties with understanding the materials science concepts underlying the questions, or possibly, as in the case with questions in graph or diagram format, some of the difficulty arises from the format itself.

STUDENT CONFLATION OF SIMILAR CONCEPTS AND TERMS

Students commonly conflated similar terms and concepts in the materials science topics studied. Interestingly, after finding initial evidence of confusion, we found that following further conversation many students *could* distinguish between the two concepts in question, such as force and stress. Therefore in some cases, rather than finding that students *could not* make the distinction between the concepts in question, we found instead that students often simply *did not* distinguish between them. For example, after brief conversation, students would often easily grasp (or recall) the distinction between stress and force. While these are precise terms in the domain of engineering, students nonetheless often appeared to equate the concepts, or they often used the terms interchangeably.

In some cases, it appeared that the confusion of terms was partially due to common language usage. For example, when referring to a property of a material in everyday language, *stiff* is often synonymous with *strong* or *tough*. However, these terms are not synonymous in materials science and have precise and critically different meanings.

Therefore, there appears to be two issues associated with student incorrect usage or application (interpreted as confusion) of similar terms and concepts. First, the students must *learn the distinction* between the concepts in question. This may or may not be difficult depending on for example whether the differences are subtle or whether both concepts are complicated. Second, it may be the case that in everyday experience the two concepts or terms in question are habitually used interchangeably, and even if a distinction is understood by the students, they may not recognize the need to distinguish between the concepts or terms. This second issue then involves the student learning that the *distinction is important* in some circumstances, especially in matters concerning material science.

I. Conflation of Mechanical Properties

Consistent with previous work [10], including our own [8], we found that even after instruction students often equate mechanical properties, use them interchangeably, or at very least think the properties are necessarily correlated. Perhaps the most prevalent and fundamentally important confusion is between the concepts of material strength and elasticity, and even if the students do understand the difference, they often believe the properties must be correlated. That is, they believe a stiff material must be strong and vice versa. This is highlighted by the questions in Figure 1A and 1B. The first question concerns a conceptual definition of modulus of elasticity. Only one-third of the students answered correctly, with most students confusing the concept of yield strength with elasticity. This question requires a careful reading of the answer choices and is somewhat subtle, yet interviews revealed that student understood the options and chose purposefully.

The second question (Figure 1B) is somewhat more straightforward, yet only 13% of the students answered correctly. Approximately 40% of students believed that the material with a higher yield strength will also have a higher tensile strength, which is not unreasonable, and over 40% (the majority) of students answered that the material with a higher yield strength, also has a higher tensile strength and higher modulus of elasticity.

Finally, was also somewhat common for students to believe that there is a strict anti-correlation between yield strength and ductility, namely that a highly ductile material has low strength, as shown in Figure 1C.

What is the Young's modulus of elasticity or 'stiffness' of a material?

(33%) a. A measure of a material's resistance to elastic strain when under stress.
(19%) b. A measure of a material's ability to return to its original shape after a load is applied.
(11%) c. A measure of a material's ability to stretch or deform without breaking.
(37%) d. A measure of a material's ability to withstand an applied stress without permanently deforming.

Two pieces of metal, A and B, are the same size and shape but Metal A has a greater yield strength than Metal B. Which of the following statements is true?

(13%) a. Metal A will permanently deform at a greater stress than Metal B
(2%) b. Metal A will have a greater tensile strength than Metal B
(2%) c. Metal A will have a greater young's modulus of elasticity than Metal B
(40%) d. Both a & b
(44%) e. a, b, & c are all true

Which of the following is the best statement describing the relationship between ductility and yield strength?

(10%) a. A metal with greater yield strength is more ductile
(29%) b. A metal with a greater yield strength is less ductile
(10%) c. A metal with greater yield strength tends to be more ductile
(40%) d. A metal with greater yield strength tends to be less ductile
(10%) e. Ductility has no relation to yield strength

FIGURES 1A (TOP), 1B (MIDDLE) AND 1C (BOTTOM) MATERIAL PROPERTIES QUESTIONS AND STUDENT RESPONSE PERCENTAGES. (N= 63). STD. ERR. OF VALUES IS ≈ 6%.

II. Conflation of Energy and Force in atomic bonds

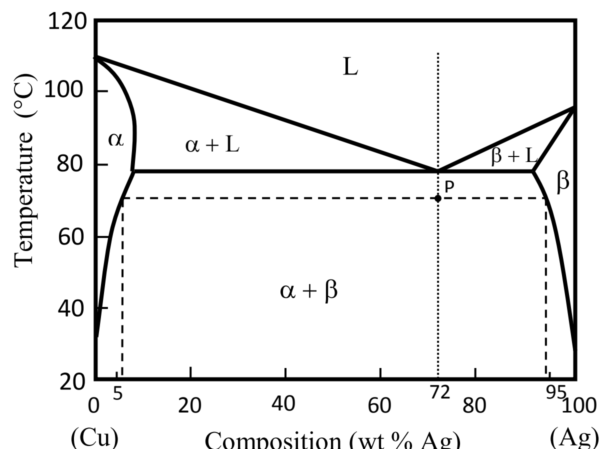
Student often confused the concepts of force and energy when referring to the strength of atomic bonds. Atomic bonds are often described by instructors as being either "strong" or "weak". Unfortunately this can be misleading or confusing to the student because sometimes the word "strong" refers to the force of the bond and sometimes it refers to the bond energy. Like many misconceptions, the use of a common word can lead to difficulties in understanding the proper scientific concept. In everyday usage, "strength" usually refers to force, whereas normally when an expert speaks of a strong atomic bond, it is meant in terms of a large binding energy.

In general we observed that it was common for students to use the terms *force* or *energy* when discussing the origins of macroscopic properties such as elasticity, strength and melting temperature, with little regard for the scientific accuracy of their own usage of the words. The failure to distinguish between energy and force in atomic bonds may be contributing to student difficulty in understanding how the properties of atomic bonds are related to macroscopic properties such as strength and elasticity.

II. Conflation of Composition and Phase Fraction

When considering binary alloys, students often confused the concept of composition and phase fraction. This is especially the case for binary eutectic alloys. Typically, there are three quantities of interest: the mass fraction of the phases, the composition of the phases and the average composition of the material, and the differences among these quantities are frequently confused. For example, in binary eutectic alloys, we found that post instruction, about 25% of students incorrectly believed that the α phase was composed of 100% of one of the metals in the alloy and the β phase was 100% of the other metal.

Interestingly, many students who incorrectly believed in "pure phases" still successfully performed lever rule calculations (cf. [11]), which inherently assume that the composition of phases is mixed. In short, many students do not fully understand the nature of the α and β phases, namely that they are comprised of a mixture of elements, and the composition may change depending on factors such as temperature.



At point P in the phase diagram above, what fraction of the alloy is α ?

(48%) a. 6%
(28%) b. 26%
(10%) c. 28%
(14%) d. 72%
(0%) e. 94%

FIGURE 2
PHASE DIAGRAM QUESTION AND STUDENT RESPONSE PERCENTAGES. (N= 107). STD. ERR. OF VALUES IS ≈ 4%.

Student responses to questions about phase diagrams demonstrate another important area in which the confusion of composition and phase fraction is evident. Figure 2 provides an example of a question about a binary eutectic diagram. In this case, most students provided an answer about composition when the question was about phase fraction. Certainly, one must also consider that students have difficulty simply with understanding phase diagrams themselves, which are complicated and unfamiliar to students. However, it appears that the misunderstanding or neglect for the difference between the concepts of composition and phase fraction contributes to the difficulty.

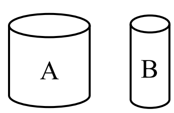
STUDENT DIFFICULTIES WITH REASONING ABOUT MULTI-VARIABLE CONCEPTS

When answering questions about a concept or particular quantity, students often only considered that concept to depend on only one variable, even if the concept was in fact a function of more than one variable. This student difficulty with reasoning about multi-variable concepts could be seen as a special case of student confusion of two related concepts. That is, students may conflate two related concepts because they fail to recognize that one of the concepts depends on yet another factor. For example, students may conflate force and energy of atomic bonds because they fail to recognize that binding energy is derived from the *work* needed to separate atoms, which is a function of both force *and* displacement. Below are more examples.

II. Conflation of Force and Stress

As mentioned earlier, we found in tests, interviews, and in the classroom that many students use the terms *force* and *stress* interchangeably. We also found that when questioned further, most students did recognize the formal difference between the two concepts. Nonetheless, they often failed to recognize that the two terms must be used carefully. This could be interpreted as a difficulty with the multivariable concept of stress, which is the ratio of force to cross sectional area. We propose that many students simply ignore the *area* variable and consequently equate stress with force. One place where this is manifest is in the common incorrect reasoning with questions involving yield strength, force and stress. In particular, students usually associate yield strength with force rather than stress. A dramatic example of this is demonstrated by student post instruction responses to the question in Figure 3. In this simple question, the majority of students believed that yield strength depended on cross sectional area, or put another way, that yield strength was defined in terms of force rather than force per unit area.

The following metal pieces are cut from the same plate. Compare the yield strength of the pieces. (A and B are equal in height)



(60%) a. A has a higher yield strength than B
(8%) b. B has a higher yield strength than A
(32%) c. A and B have the same yield strength

FIGURE 3
FORCE VS. STRESS QUESTION, AND STUDENT RESPONSE PERCENTAGES. (N= 114). STD. ERR. OF VALUES IS ≈ 4%.

II. Conflation of Mass Density with Atomic Separation

We found that an overwhelming majority of students assumed that high mass density necessarily implied small atomic separation. In this case, students ignored the fact that mass density depends on *both* atomic separation and atomic mass. When pressed in interviews, most students quickly recognized that atomic mass is a factor. However the neglect of atomic mass when considering mass density was quite pervasive, as shown in the results of Figure 4.

This assumption that mass density necessarily determines atomic separation may seem like a minor and innocuous oversight. Students may have simply interpreted (implicitly or explicitly) that "density" means "number density" rather than the more commonly assumed "mass density" (even if "mass" is explicitly stated). Furthermore, the focus on number density might be expected, since the lessons on crystal structure focus on numbers of atoms, for example when calculating the atomic packing factor, rather that the mass of the atoms. However, the failure to think carefully about density may lead to errors in solving multi-step problems involving density. Furthermore, there is evidence that it is a symptom of a much deeper misunderstanding of microscopic and macroscopic properties, as will be discussed in the next section.

Material A has a greater (average) atomic separation than Material B. Which of the following must also be true given this information? (You may choose more than one.)

(72%) a. Material B has a greater mass density
(75%) b. Material B has a great atomic bond strength
(44%) c. Material B has a greater yield strength
(40%) d. Material B has a greater melting temperature.

FIGURE 4
QUESTION REGARDING ATOMIC SEPARATION, AND STUDENT RESPONSE PERCENTAGES. (N= 67). STD. ERR. OF VALUES IS ≈ 6%.

STUDENT USE OF INAPPROPRIATE MODELS OR ANALOGIES

Many students used physical models or analogies that were not suitable for the given situation. It is interesting to note that the examples here are all related to physical models at the atomic or microscopic scale, and students either used these atomic level models to make inferences about macroscopic properties, or they used observations about macroscopic properties to make inferences about atomic level models. Several examples are discussed below.

I. Stretched Atomic Bonds

A significant number of students believe that atomic bonds can be permanently stretched, much like the phenomenon of a permanently stretched spring. Evidence of the stretched-bond model is shown in Figure 5, and was verified in numerous interviews. Students were asked post instruction to compare the atomic separation in a metal before and after plastic deformation, and 71% of them indicated that the bonds would be stretched after plastic deformation. Note

A metal is permanently elongated by a load, then the load is removed. Which of the following is true?

(29%) a. Atoms will be rearranged compared to before the elongation.
(11%) b. The atomic bonds will be stretched compared to before the elongation.
(60%) c. Both a) and b) will occur.

FIGURE 5
PLASTIC DEFORMATION QUESTION, AND STUDENT RESPONSE PERCENTAGES. (N= 64). STD. ERR. OF VALUES IS ≈ 6%.

that this idea of stretched bonds is similar to the results found previously regarding a question in the Materials Concept Inventory, in which many students answered (pre-instruction) that when a wire is drawn through a tapered hole, the bonds have been compressed [4].

This incorrect model of plastic deformation reveals that students do not understand the process plastic deformation at a microscopic level, and this may in turn contribute to difficulties in understanding how yield strength is determined by the propagation of dislocations, rather than the permanent stretching of atomic bonds.

II. Incorrect Cause of Thermal Expansion

The mechanism underlying thermal expansion was not covered in the course studied. Therefore the data we obtained for this topic was considered as pre-instruction. Perhaps as to be expected, no students provided an adequate explanation of the cause for thermal expansion of a metal. Nonetheless, many students were very confident in their explanations. There were two common explanations. The most prevalent explanation (about 50% of students) involved the idea that in a heated metal, the atoms move with a greater amplitude, therefore they "needed more room to move", and this results in expansion. Most students thought this was an obvious and self-evident explanation. No students mentioned the need for an asymmetric potential to ensure a change in average position with increasing amplitude of oscillations. One positive side to this finding is that students understand that higher temperatures are associated with higher amplitude oscillations. Yet, they do not see the need to explain the cause beyond the analogy that the atoms "need more room to move".

The second common explanation (about 40% of students) involved the idea that the atomic bond itself was changed by the increase temperature. Specifically, some students believe that when the metal is heated, the atomic bonds "weakened", much like metal itself becoming softer or weakening when heated. This in turn allows for the atoms to move farther apart, resulting in expansion.

III. The Relation between Density and Other Properties

We found that an overwhelming majority of students believe that a number of material properties are causally related to, and thus predicted by, the density of a material. For example, most students believe that high mass density implies high melting temperature and high yield strength. In interviews, tests, and in classroom interactions we found this to be a pervasive belief that was difficult to change.

The logic of the argument typically consisted of a number of steps, each usually involving an incorrect assumption. Figure 6 provides an outline, and Figure 4 provides an example of typical student responses to a question relating some of the relevant ideas. First, as mentioned earlier, most students assume that relatively high mass density implies relatively small average atomic separation. Second, most students also believe that relatively small average atomic separation necessarily implies relatively large atomic bond strength. Finally, most students believe (correctly) that high atomic bond strength necessarily implies high melting temperature and (incorrectly) that high atomic bond strength necessarily implies high yield strength.

Therefore, the idea that high density implies high melting temperature and high yield strength is compelling to students because there is a natural and plausible (yet incorrect) mechanism: stronger atomic bonding due to smaller atomic separation. Some student responses also revealed other natural reasons for these incorrect beliefs [7], namely that students assume that denser materials have more matter, requiring a higher melting temperature (a confusion of temperature with thermal energy), and in everyday life, denser materials tend to be stronger than less dense materials.

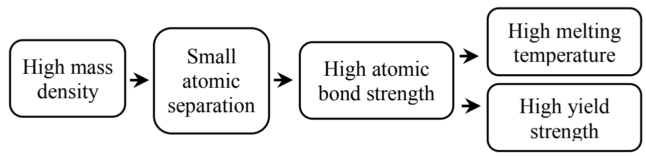
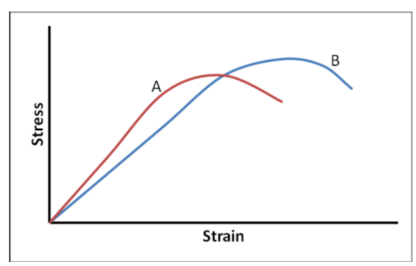


FIGURE 6
COMMON INCORRECT LINE OF REASONING ABOUT THE RELATION BETWEEN DENSITY, MELTING TEMPERATURE, AND YIELD STRENGTH. NOTE THAT ALL BUT ONE OF THE STEPS IS INCORRECT.

STUDENT DIFFICULTIES WITH GRAPHS AND DIAGRAMS

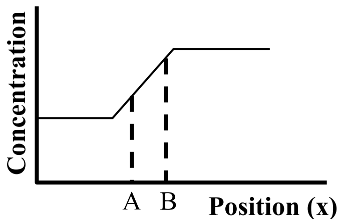
Student commonly had difficulty answering basic questions related to graphs and diagrams typically used in materials science and engineering. For relatively simple diagrams, such as stress-strain plots and concentration vs. position plots students displayed slope-height confusion, similar to well known student difficulties with kinematics graphs in physics [12]. For example, Figure 7 presents results from a simple question comparing modulus of elasticity of two materials represented in two stress-strain curves. Over half of the students chose the curve that had the higher maximum value, rather than the curve with the steepest linear slope. This explanation that "higher position on graphs means more" was commonly found in interviews.



Consider the stress-strain curves of two metals above. Which metal has a higher modulus of elasticity?
(46%) a. A has a higher modulus.
(54%) b. B has a higher modulus
(0%) c. The modulus of A is equal to that of B

FIGURE 7
STRESS-STRAIN GRAPH QUESTION, AND STUDENT RESPONSE PERCENTAGES. (N= 116). STD. ERR. OF VALUES IS ≈ 6%.

Interestingly, some students also thought that since the higher curve also had higher elongation until breaking, this was also seen as evidence of higher elasticity. This example highlights the fact, as discussed earlier, that many students conflate concepts such as ductility, strength and elasticity, and this difficultly is manifest in the reading of graphs.



The figure above shows the concentration of Aluminum as a function of position. How does the diffusion flux of Aluminum at point A compare to that at point B?
(8%) a. A > B
(29%) b. A < B
(63%) c. A = B

In the figure in the previous question, in which direction is there a net diffusion of the material at point A?
(51%) a. To the right (+ x direction)
(36%) b. To the left (- x direction)
(7%) c. The concentration profile is in steady state, so the net diffusion is zero.
(7%) d. There is no direction to the diffusion.

FIGURE 8A (ABOVE), 8B (BELOW)
DIFFUSION GRAPH QUESTIONS, AND STUDENT RESPONSE PERCENTAGES. (N= 62). STD. ERR. OF VALUES IS ≈ 6%.

Students also tended to base answers on height rather than slope for concentration vs. position graphs and questions about diffusion, as seen in Figure 8A. Additionally, from the answers to Figure 8B, it is clear that the students do not understand the meaning of the graph, or the relation between diffusion and concentration profiles.

Perhaps as to be expected, students also had great difficulty with novel, unfamiliar graphs and diagrams, such as phase diagrams and isothermal transformation diagrams. Figure 2 provides an example. Interviews revealed that the difficulty was two-fold. First, the students did not grasp the underlying concepts represented in these diagrams. Second, the students were unfamiliar and unpracticed in reading the diagrams and understanding the “rules” of the diagram.

CONCLUSION

We have identified and described a number of prevalent student difficulties relevant to an introductory university level materials science and engineering course. These difficulties were identified post–instruction, and in that sense were persistent. The difficulties identified tended to involve very basic concepts and skills. While the difficulties were quite specific, we placed them into general categories: conflation of similar concepts, reasoning about multivariable concepts, use of inappropriate models, and difficulties with diagrams and graphs.

The identified difficulties were typically not explicitly addressed in the traditional course or the text. Furthermore these difficulties were rarely if ever directly assessed in the traditional exams. Therefore these findings may be useful in the design of instructional materials to help students overcome these difficulties and gain a better understanding of materials science. In a companion project [1]. we apply these findings to develop and implement curriculum.

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