AC 2010-1156: UNCOVERING AND REPAIRING ATOMIC BONDING MISCONCEPTIONS WITH MULTIMODAL ASSESSMENT OF STUDENT UNDERSTANDING IN AN INTRODUCTORY MATERIALS COURSE

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Uncovering Atomic Bonding Misconceptions with Multimodal Topic Module Assessments of Student Understanding in An Introductory Materials Course

Abstract

Though much work has been done in physical sciences on misconceptions, little work has been done on misconceptions in the context of structure-property-processing performance relationships in materials used in engineering design. The research question in this paper is, "How can misconceptions for engineering materials be most effectively identified in order to develop effective teaching and learning activities for repairing misconceptions?" For an introductory materials class with 38 students, misconceptions were uncovered, categorized and monitored over the span of a fifteen-week introductory materials science course. To do so, open-ended assessments requiring multiple modes of expressions (sketching and writing) of concepts for various content areas (atomic bonding, crystal structure, deformation, polymers, and electrical properties) were administered before and after each teaching module. A mixed methods (qualitative and quantitative) analysis of student responses on the multimodal assessment was carried out. Student misconceptions were further elicited and categorized using emergent themes coding. Some categories of misconceptions were consistent with literature. Others (such as a magnetic mechanism for bonding and atoms becoming either soft or brittle during deformation) were new and previously unreported. Results indicated that multimodal assessment gave a more effective and a more detailed indicator of student conceptions, misconceptions and conceptual change than a unimodal assessment would have. We propose that, for an introductory materials course, assessments using multimodal expressions of topical concepts will more effectively uncover and assess the nature of student misconceptions. This improved insight into student conceptual frameworks can lead to more effective misconception repair for structure-property relationships about engineering materials than would a traditional assessment. Details of results, analysis, conclusions and implications are presented and discussed in the full paper.

Introduction

Misconception research has been done primarily from a physical science perspective. Traditionally, engineering students learn prerequisite knowledge in physics and chemistry. As a result, student understanding is often limited to an understanding of phenomena rather than an ability to apply and use knowledge for engineering applications. For example, in a review of student bonding conceptions, Robinson[1] found that students believed that the only types of "real" bonds were covalent and ionic bonds. Continuing, he reported that chemistry students could not recognize metallic bonds as "proper" bonds. Because many chemistry courses aim to teach students to explain the natural world, emphasis is placed on covalent and ionic bonding. But in engineering, understanding of metal and polymer behavior is crucial for real-world applications and requires an understanding and working knowledge of metallic and van der Waals bonding.

Many engineering students complete their science prerequisites in courses structured for natural scientists with limited treatment of engineering content. Many engineering faculty assume that students entering their courses are well prepared with respect to materials design and selection. If we again consider atomic bonding for materials science courses, it can be seen that this is not the case. Following a natural science course, some students may have never heard of van der Waals bonding[2]. So when presented with concepts about the structure and properties of metals and polymers, students may have conceptual barriers to learning. The challenge for introductory engineering course instructors is to build on student understanding of scientific phenomena and help students shift their lens from one of natural science explanation to one of engineering design, investigation and innovation.

The goal of this research is aimed at answering the question, "How can misconceptions for engineering materials be most effectively identified in order to develop effective teaching and learning activities for repairing misconceptions?" To do so, multimodal assessments were developed and utilized. These multimodal assessments, both formative and summative, gave students opportunities to express ideas in multiples modes, or representations. Various modes were used including verbal, written, visual, mathematical, diagrammatic, and graphical modes. From these assessments, student misconceptions were documented. And just by engaging in multimodal expression of ideas, students were often able to repair these elicited misconceptions.

Background

Concepts and Misconceptions

In order to learn, students need to modify and/or create concepts with mental models in their conceptual framework. These concepts are mentally constructed groupings of objects, thoughts, events, pictures, or symbols that enable learners to organize knowledge by being able to associate additional objects, thoughts, events, pictures, or symbols as either fitting or not fitting the concept[3]. From a constructivist perspective, it is assumed that students come into the classroom with a variety of preformed concepts[4]. These preformed concepts, referred to as preconceptions, are created as learners experience, observe, and are taught about phenomena throughout daily life and in prior coursework[5]. Some of these preconceptions may be consistent with scientific, or normative, conceptions. However, others are non-normative. These non-normative preconceptions can act as barriers to student learning and prevent students from properly conceptualizing new information. When preconceptions hinder student learning or provoke incorrect explanations or predictions of scientific phenomena, they are often referred to as misconceptions[5].

Misconceptions Relevant to Materials Science

Atomic Bonding Misconceptions

In 1989, Peterson, Treagust and Garnett developed a test for identifying misconceptions of bonding and molecular structure called the Covalent Bonding and Structure Test. The test provided insight on student conceptions and aided in developing distractors for concept inventories of atomic bonding[6,7]. The misconceptions found included "equal sharing of an electron pair occurs in all covalent bonds", "the shape of molecules is due only to the repulsion between the bonding electron pairs", and " nitrogen atoms can share five electron pairs in bonding" [6].

Peterson and Treagust[7] found that, while student ideas about atomic bonding developed throughout advanced chemistry courses, often misconceptions did as well. For example, they found that 60% of 17-year-old students knew the correct position of the electron pair in a bond between hydrogen and fluorine. Yet only 55% of first year university students could identify the position of that pair. This work implied that students who held misconceptions about bond polarity tended to retain them. Barker[8] examined conceptual development of bonding topics over time, reported the changes in students' basic ideas about covalent bonds and molecular structure over a two-year period. It was found that 80% of 16-year-olds could distinguish between single and double covalent bonds in methane, ethane and water molecules in terms of the numbers of electrons involved. However, only 66% of that sample could so the same approximately fifteen months later. These studies showed that it was more likely for students to retain misconceptions than correct concepts. To further investigate the resilience of student bonding misconceptions, the Covalent Bonding and Structure test was used by Birk and Kurtz to look at the strength of the misconceptions within students' conceptual frameworks[9]. The test was given to six groups of people: high school chemistry students, first semester general chemistry students, second semester general chemistry students, advanced undergraduates, new graduate students, advanced graduate students and faculty. Results suggested that misconceptions were in fact resilient over time, with misconceptions existing in all groups[9].

In 2006, Ünal, Çalik, Ayas, and Coll[2], conducted an extensive survey of all research on bonding conceptions and understanding. They found much work had been done to probe student conceptions of covalent and ionic bonding. However, little had been conducted to explore student thinking about metallic or secondary bonding, specifically van der Waals bonding[2]. A summary of student bonding misconceptions as reported by Ünal et al. is shown in Table 1.

Table 1
Summary of Atomic Bonding Conceptions as Reported by Ünal et al.[2]

Bonding Type	Known Conceptions
Covalent Bonding	• electrons are shared
	• one atom donates an electron to another atom
	• bond between metals and nonmetals
	• bond polarity depends on quantity of valence electrons
	all electrons are shared equally
Ionic Bonding	• bonds result in creation of molecules
	• electrons are transferred
	• bond strength is determined by quantity of bonding electrons
	• bond cancels charge difference between ions
Metallic Bonding	• not real bonds
	• metallic bonding forms molecules
van der Waals Bonding	• no recorded conceptions

In 1998, two separate literature reviews were done in which student conceptions about the nature of bonding were examined. Boo[10] and Robinson[1] both found, independently, that students considered covalent and ionic bonding to be the "real" bonding types, while metallic was not[1,10]. In 2003, Coll and Treagust examined student conceptual understanding of metallic bonding[11]. Students were first asked to create a visual representation of metallic bonding and then to choose a visual depiction (provided on cards) most similar to their mental model of metallic bonding. It was found that secondary school students were most likely to choose a sea of electrons model while undergraduates and postgraduates preferred a space-filling model. While this did not reveal misconceptions, it did elicit preferred models for understanding metallic bonding. While work on metallic bonding conceptions is limited, even less has been documented on student conceptions of van der Waals bonding, as research in that area of student conceptions referenced mainly the confusion between intra and intermolecular forces[2].

Crystal Structures

Limited work has been done on crystal structure conceptions with respect to materials science and engineering concepts. In 2003, Krause et al.[13] surveyed students over time in introductory materials science courses. They found that many student misconceptions in this area were rooted in geometry and spatial visualization. When students were asked how many sides and edges existed on a cube, only 61-79% answered correctly prior to instruction and still only 81-88% answered correctly following instruction.

Deformation

Again, little work has been recorded on student understanding of material deformation in the context of materials science and engineering courses. Krause et al.[13] found that students had difficulty in their understanding of material deformation. Students were asked why a metal rod that was pulled through a tapered hole smaller than the diameter of the rod was to become stronger. Prior to instruction, 7-8% of students choose the correct answer, with 23-38% choosing the correct answer following instruction[13]. Most often, students incorrectly responded that strength in the metal was achieved as a result of bond compression[13].

Polymers

To this point, very limited work has been done regarding student understanding of polymers. Indirectly, there has been some work describing bonds involved in polymers (covalent and van der Waals bonding). However, misconceptions have not yet been documented about student understanding of polymer behavior, properties, or deformation mechanisms.

Electrical Properties

Misconceptions in the area of electrical properties are limited to conceptions about electricity and magnetism in the physical sciences. Little work has been reported on student conceptions about electrical properties *of materials* in the context of introductory materials engineering courses. In a study by Krause et al.[13] students were asked to explain why aluminum is a better conductor than glass. Prior to instruction 20-36% of students could correctly answer, with 51-76% able to do so following instruction. Students most often claimed that electrons moved faster in aluminum then in glass.

Methods

The primary purpose of this study was to utilize multimodal assessment to elicit student misconceptions in the areas of atomic bonding, crystal structure, deformation, polymers, and electrical properties. Additionally, student conceptual were measured for each of the determined content areas.

Participants

Participation in this study was voluntary, though assessment was discussed and primarily collected during the course of a regular class. Participants in this research were from a sample of 38 students enrolled in a 2009 semester of an introductory materials science and engineering course. Of the 40 students initially enrolled, only 38 were selected due to students withdrawing early from the course. Of the 38 students who remained enrolled in the course, all students were engineering majors with 13 (34.21%) chemical engineers, 9 (23.68%) mechanical and aerospace engineers, 8 (21.05%) industrial engineers, 7 (18.42%) materials science engineers, and 1 (2.63%) bioengineer. There were 9 (23.68%) females and 29 (76.32%) males.

Teaching Methods and Interventions

The introductory course in which the sample was drawn was a 15-week semester course required for most engineering majors meeting for seventy-five minutes two times per week. The course was taught by a professor with a Ph.D. in engineering and 28 years teaching experience. Throughout instruction students were asked to frequently express their mental models in multiple modes in addition to the multimodal assessment tool. Student expressions and explanations of thinking took place in different ways, or representations, including written, verbal, diagrammatical, mathematical, graphical and, kinesthetic. By having students explain their ideas in each of these modes at various times throughout the course of instruction, frequent multimodal expressions of ideas were consistent throughout the entire course.

Measures

Topical Module Assessments

To obtain specific information about student conceptions, open-,ended pre-and-post Topical Module Assessments were created. In order to develop the assessments, common misconceptions were reviewed from the literature, past research, the Materials Concept Inventory, and experiences from prior sections of the introductory materials science and engineering course. These assessments required students to respond to questions using multiple representations. These multiple representations, or modes of expression, included written descriptions, concept sketches, and diagrammatical representations. The Bonding Module Assessment incorporated concept sketching and written descriptions of bond types as well as identification of bond type and important properties of common household items. The Crystal Structures Module Assessment asked students to sketch locations of atomic on various planes of body centered and face centered cubic unit cells. The Deformation Module Assessment asked students to describe what occurred during deformation of different types of materials and accompany their description with a sketch. The Polymer Module Assessment asked students to describe and sketch the internal atomic structure and describe and sketch what occurs during deformation. The Electrical Properties Module Assessment asked students to predict changes in conductivity resulting from changes in the material and to support their answers with a sketch. The assessments were scored for conceptual understanding.

Quantitatively, on each question, each student had the opportunity to score a maximum of two points. Any answer that was correct was awarded two points, an answer that was partially correct but may have had some incorrect ideas was awarded one point, and an answer that was blank, completely incorrect, or non-relevant was not awarded any points. This rubric allowed for achieving a maximum nonzero score, different for each assessment, and a minimum score of 0. A paired samples *t*-test was conducted in order to assess significance in gains. This allowed for an understanding of the change in student conceptual frameworks and provided evidence to support quantitative conceptual change.

Qualitatively, each written response on each Topical Module Assessment was read and any misconceptions present were recorded. It was possible, and often occurred, that there were multiple misconceptions for each student's response to each question. After reading through and making note of student misconceptions, similar misconceptions were grouped into categories. These categories were developed through emergent themes from student misconceptions as displayed on each Topical Module Assessment. For example, many student misconceptions of crystal structure included addition or deletion of atoms in the unit cell. Not all misconceptions involved adding or removing the same atom, but because these were similar misconceptions, hinting at an emergent theme, they were grouped into one category referencing extra or missing atom(s). Each student conception was then assigned categories based on these emergent themes. This categorization process continued for each student response to each question on each Topical Module Assessment. The categorization based on the emergent themes yielded categories of misconceptions about atomic bonding, crystal structures, deformation, polymers, and electrical properties.

Results and Discussion

Student responses to each Topical Module Assessment were quantitatively analyzed to assess levels of conceptual change throughout the semester. The results of the *t*-tests are shown in Table 2. As seen, students exhibited statistically significant conceptual gains in all content areas. To check the ability of the Topical Module Assessments to measure conceptual gain, scores were compared to student gains on the Materials Concept Inventory (MCI), a previously reliable and validated assessment used to measure conceptual change in introductory materials science[14]. As seen in Table 2, the standardized effect sizes on the MCI were consistent with gains on the Topical Module Assessments. This confirms that the topical module assessments are capable of measuring conceptual change of materials science concepts.

Table 2
Summary of Topical Module Assessment Gains

Topical Assessment	Number of Students	Mean Differences (SD)	Standardized Effect Size, *d*
Bonding	38	3.63 (2.37)**	1.53
Crystal Structure	31	.95 (1.41)**	.67
Deformation	30	.68 (1.55)*	.44
Polymers	20	1.52 (1.60)**	.95
Electrical Properties	20	1.02 (1.89)*	.53
MCI – Control	27	3.89 (3.79)**	1.03

*$p < .05$, **$p < .01$.
Note: The mean differences were calculated by comparing scores before instruction to scores after instruction.

Qualitatively, each Topical Module Assessment was read and misconceptions were categorized through emergent themes coding. The categories of misconceptions found for each content area (bonding, crystal structures, deformation, polymers, and electrical properties) are discussed below and can be seen in Table 3.

Table 3 (continued on next page)
Categories and Student Misconceptions (Excluding Null Categories) from Pre and Post Assessments

Category	Misconceptions Present in Category
Bonding	
Incorrect Constituents Category	• Incorrect classification of elements involved in bond
Magnetic Attraction	• Caused by or create magnetic "reactions"
Crystal Structures	
Incorrect Configuration	• Atoms touching when should not; • Atoms not touching when should
Extra and/or Missing Atom(s)	• Extra atoms are in unit cell; • Atoms are missing from unit cell
Deformation	
Incorrect Bond Behavior	• Bonds weaken; Bonds damaged; • Confusing macroscopic stretching with microscopic stretching; • Bonds slipping
Incorrect Atom Behavior	• Atoms shift; • Atoms separate; • Atoms rub, • Create heat; • Atoms get closer to each other

Table 3 (continued)
Categories and Student Misconceptions (Excluding Null Categories) from Pre and Post Assessments

Category	Misconceptions Present in Category
Deformation (continued)	
Grain Boundaries Change	• Increased size; • New boundaries form; • Shifting along the boundary
Phase Change	• Phase change; • Phase transformation
Crystal Structure	• Forced from crystalline structure; • Crystal structure breaks
Polymers	
Polymer Chains Stretch	• Chains stretch; • Chains elongate; • Intermolecular bonds stretch;
Incorrect Bond or Atom Behavior	• Van der Waals are cross linked; • Van der Waals are flexible; • Covalent bonds are weak; • Atoms get softer; • Atoms become brittle; • Atoms snap; • Secondary bonds are strong
Electrical Properties	
Impurities and Conductivity	• Conductivity with addition of more higher conductivity metal; • Arsenic is not conductive; • Conductivity of As changes overall conductivity; • Group V elements decrease conductivity
Dislocation and Grain Boundary	• Dislocations form; • Grain boundaries reduce in size and reduces conductivity; • Impurities bend grains
Atomic Scale	• Atom size effects conductivity

Atomic Bonding Misconceptions

The Bonding Module Assessment asked students to describe four types of bonding at the atomic level. These types were covalent, ionic, metallic, and van der Waals bonding. The following categories of misconceptions were created and are listed below with specific examples:

Null Category

Many students, especially prior to instruction left blank responses or simply stated that they did not know. Some misconceptions categorized this way included "can't even make a good guess," "no idea", and "I remember this but…?" Prior to instruction, the frequency of null conceptions was much greater with many more blank and uncertain comments containing question marks. However, following instruction, fewer misconceptions were present in this category. This decrease in frequency suggests that students begin to assimilate bonding concepts into their existing conceptual framework.

When students incorrectly described the participants in a bond, it was placed in this category. A few examples are that covalent bonding is described as "a metal and nonmetal that bond together by sharing electrons" and ionic bonding occurs when "two metals that bond together by transferring electrons." Some students described that a covalent, ionic, and/or metallic bond occurs between a metal and a gas or a nonmetal and a gas by stating that ionic bonding is a "bond between a metal and a gas…" or covalent bonds are "bonds of metal or bonds of gasses." Student misunderstanding of elements that participate in various bonding types such as these were present only in the Bonding Module Assessment prior to instruction. This suggests that misconceptions in this category are not robust and can be relatively easily repaired.

Magnetic Attraction Category

An interesting, unique, and previously unreported misconception category emerged stating that bonds either created or were caused by a "magnetic reaction". Two misconceptions categorized this way included, a van der Waals bond is "a weak bond where atoms are magnetized" or an ionic bond occurs when "electrons are giving up magnetic attraction." Misconceptions in this category were only present on the assessment given prior to instruction, suggesting, again, that they are not robust and may be easily repaired.

Crystal Structures Misconceptions

The Crystal Structures Module Assessment required students to sketch atoms that were bisected by three planes ((1 0 0), (1 1 0), and (1 1 1) planes) for both a face centered cubic crystal structure (FCC) and a body centered cubic crystal structure (BCC). The following categories of misconceptions are reported below:

Incorrect Configuration Category

When drawing the either FCC or BCC crystal structures, some students sketched atoms to be configured such that they were touching neighboring atoms when they should not have been. In some cases, the opposite occurred, when students neglected to sketch neighboring atoms touching when they should have been. Specifically, for the FCC structure, many students drew atoms in the (1 1 1) plane that did not touch when they should have been touching. The frequency of this misconception was greater following instruction. Another misconception in this category was revealed from atoms sketched that were touching when they should not have been touching for the BCC in the (1 1 0) plane. This misconception was most apparent in assessment prior to instruction. Misconceptions of incorrect configurations of atoms on the (1 1 1) plane seem robust and difficult to repair. This may result from the required transfer between spatial ability and conceptual understanding of crystal structures.

Extra and/or Missing Atom(s) Category

Misconceptions were placed in this category if students sketched too few or too many atoms on any of the planes in their visual representation. If the sketch showed atoms in the correct locations and configurations but were missing atoms or added extra atoms the misconception would be put into the *Extra and/or Missing Atom(s)* category. The most prominent misconception in this category involved the addition of an extra atom directly in the middle of the (1 1 1) plane on the BCC drawing. However, this misconception was found more often prior to than following instruction. As a result, this misconception is probably not robust and may be easier to repair.

Deformation Misconceptions

The Deformation Module Assessment consisted of two questions regarding three different material objects including a paper clip, a polyethylene trash bag, and a glass beaker. The first question asked the students to describe the atomic level structure of the object while the second question asked them to describe what happens at the atomic level when the object is deformed. The following misconceptions have been categorized and listed with specific examples:

Null Category

Student misconceptions were placed in this category if responses were blank or were limited to question marks. There were few null misconceptions present both prior to and following instruction. This may be because students could relate the concepts to either every day experiences and/or prior knowledge and were able to create a conception.

Incorrect Bond Behavior Category

If students attributed atomic level deformation to occur due to a damaged, weakened, or incorrectly changed bonds, the misconception was placed in this category. When describing the paper clip deformation, one student responded "bonds get weaker" while another reported that "some bonds will be broken or weaken." Additional misconceptions placed in this category included phrases like bonds flex and bonds bend. Specifically, a student said "bonds flex elastically to a point, then tear" and another said "van der Waals bonds slipping" occurs at the atomic level of a trash bag during deformation. Other misconceptions reported that after a trash bag is deformed and stretched, new van der Waals bonds form. One response was that "van der Waals bonds break and reform in new places." Though some misconceptions in these categories were present following instruction, there were significantly more responses on the assessment given before instruction occurred. This suggests that students may have been misapplying prior knowledge however, were able to repair the misconception as a result of instruction.

Incorrect Atom Behavior Category

Similar to the previous category, misconceptions that referred to incorrect change in atom behavior were placed in this category. Words used to describe atom behavior throughout deformation such as "shift," and/or "separate" were considered misconceptions in this category. Additional misconceptions categorized this way were "the atoms are coming closer together" and "atoms rub together creating heat and breaking the particles up, melt the clip." The frequency of misconceptions in this category was greater prior to instruction. This suggests that students may have been trying to use macroscopic behavior to explain the behavior of atoms. Though these misconceptions may have resulted from this lack of transfer, results suggest that they were seemingly easy to repair.

Grain Boundaries Change Category

Some misconceptions reported that as a material deforms, grain boundaries are changed. Misconceptions such as these included "grain size increases," there is "movement along grain boundaries," and "new grain boundaries form." The previous misconceptions were only present on assessments following instruction. Other misconceptions were present only in the assessment prior to instruction such as some phases "grain boundaries for the bag increase…" and "the atoms become more closely bonded" during deformation of a trash bag.

Phase Change Category

Misconceptions attributing deformation to phase changes were placed into this category. Quite a few students responded that a phase change would occur as a glass beaker deforms. Some students said that during paper clip deformation a "phase change" or "phase transformation" would occur. The frequency of conceptions in this category was much greater prior to instruction. This suggests that misconceptions such as these are not robust.

Crystal Structure Category

In this category, student misconceptions that claimed that deformation resulted from changes occur from the crystal structure like atoms leaving the crystal structure. Some specific examples included, "the crystal structure stays intact, but breaks along the lines of cells" and "the atoms are forced apart from their crystalline organization." Misconceptions in this category were present primarily on the assessment prior to instruction, suggesting that these misconceptions may not be robust.

Polymer Misconceptions

The Polymer Module Assessment consisted of two questions for three different polymer objects. The three polymers were a rubber band, a plastic fork, and a polyethylene bag. The first question asked the students to describe the atomic level structure of the polymer, and the second question asked them to describe what happens at the atomic level when the object is stretched or bent. The following misconceptions have been categorized below.

Null Category

As before, student misconceptions were placed in this category if responses were blank or were limited to question marks. Some of these responses include blank responses, "I don't have a clue," and "I don't have the slightest idea." There were few null misconceptions present both prior to and following instruction. This may be because students could relate the concepts to either every day experiences and/or prior knowledge and were able to create a conception.

Polymer Chains Stretch Category

Misconceptions referencing incorrect stretching of polymer chains or bonds were placed in this category. It was common for many students to state that during the macroscopic stretching of the rubber band there is also microscopic stretching of the polymer chains. For example, a student said "stretching polymer chain" and another said "chains elongate." Misconceptions such as these were more apparent following instruction. Some believe that the bonds are physically stretching or bending. One said "intermolecular bonds stretched, covalent layers pulled further apart". These misconceptions were most often present following instruction. The change in frequencies of misconceptions in this category suggests that students were able to speak more technical about polymers following instruction, though there may have been some misconceptions created as a result. The additional misconceptions created may be substantive misconceptions, which could be difficult to repair.

Incorrect Bond or Atom Behavior Category

Misconceptions were placed in this category if there was mention of either non-normative bond or atomic behavior. These were grouped together because many times, the misconceptions were linked in student responses. This category includes misconceptions with any description of a bond that is false, specifically like "weak covalent bonds," "flexible van der Waals" or "cross linked van der Waals." One student responded the "atoms are becoming softer and more brittle" and another reported that atoms snap at the atomic level." The frequency of misconceptions in this category was greatest prior to instruction, which would usually suggest that they are not robust. However, it is concerning that these conceptions exist following instruction through the Atomic Bonding Module.

Electrical Properties Misconceptions

The Electrical Properties Module Assessment was comprised of three questions prompting students to do the following: describe the change in conductivity of a pure zinc object if a few percent copper is added, describe the change in conductivity of a pure silicon object if a few percent arsenic is added, and describe why an LED lights up when a voltage is added. The following categories of misconceptions have been created from student responses:

Null Category

As was done before, student misconceptions were placed in this category if responses were blank or were limited to question marks. There were few null misconceptions present both prior to and following instruction. This may be because this topical area was taught near the end of the semester, allowing students to at least form some conception or prediction for each scenario. Frequency of null misconceptions was consistent prior to and following instruction.

Impurities and Conductivity Category

Misconceptions were placed in this category if there was any incorrect idea about the effect of adding impurities to a metal on conductivity. Many of the students claimed that adding additional conductive element to a less conductive compound would result in an increase in the overall conductivity. One student wrote “the conductivity increases because the copper is very conductive” and another “it increases as copper is a good conductor.” Another student responded that Arsenic’s conductivity level changed the semiconductor’s overall conductivity claiming, “the conductivity decreases because of the impurity with less conductivity.” The frequency of misconceptions was greatest in this category prior to instruction, suggesting that misconceptions such as these are not robust.

Dislocations and Grain Boundary Category

Misconceptions were placed in this category if a change in conductivity was incorrectly attributed to either dislocation or grain boundary behavior. Some students said that dislocations were formed from the addition of copper which decreased the conductivity. A specific response was, “more grain boundary dislocations” cause a decrease in conductivity, “conductivity decreases because dislocations get in the way,” and “conductivity decreases due to barriers to the motion of dislocations.” Additional responses referenced a reduction in conductivity resulting from a reduction in grain boundaries. One student claimed, the conductivity “reduces more grain boundaries”. Misconceptions in this category were found in both the pre and post assessments; however, the frequency was greater prior to instruction. This may be a robust misconception.

Atomic Scale Category

Misconceptions were placed in this category is they referenced a change in conductivity as predicted by atomic size or a difference in sizes between the participation species. One student responded, “Because Zn and Cu are so close in size, and because they have a different # of e- [electrons], conductivity goes up”. Other students wrote, “conductivity goes down because As is much bigger and allows less free space for electrons to move,” “it becomes less conductive as the nonconductive As atoms begin to compound with the silicon,” “impurities cause bent grains,” and “when As is added, it becomes less conductive because it’s a group V” element. Misconceptions in this category were exclusive to assessments prior to instruction. This suggests that this misconception is not robust.

Summary and Conclusions

Student misconceptions were elicited through multimodal assessment tools in the areas of atomic bonding, crystal structure, deformation, polymers, and electrical properties. Each Topical Module Assessment was quantitatively assessed for conceptual change. Standardized effect sizes on each assessment were generally consistent standardized effect sizes from the MCI.

From these assessments, emergent themes coding revealed categories of misconceptions for each of the topical areas. Some of these categories, such as many of those for atomic bonding, were consistent with the literature. However, most misconceptions are new and previously unreported. New misconceptions include a magnetic mechanism for bonding, atoms snapping or bonds flexing and tearing as a result of deformation, and atoms becoming either soft or brittle when stressed. These misconceptions were elicited as a result of frequent multimodal probing through the pre and post Topical Module Assessments.

Traditional assessments and concept inventories have limitations when assessing student conceptual frameworks. Elicited conceptions are restricted to those that have been chosen to be distracters on tests. As a result, limited work on misconceptions has thus far appeared in the literature on many materials science concepts. This work initiates the creation of a taxonomy of misconceptions for introductory materials science and engineering concepts. With a complete understanding of misconceptions for these topics, appropriate interventions and pedagogies can be developed and implemented.

There are different normative models for topical content present in introductory materials science where one aims at creating and understanding a fundamental model of the natural world while the other strives to use that understanding in practice to relate atomic level structure to macroscopic properties. These differing goals result in differing methods of modeling, understanding, and teaching of concepts. The goal of introductory engineering courses is to shift engineering students from the lens of natural science to understand materials to the lens of an engineering normative model for using materials for design and innovation in new engineering products, systems, and processes. In order for this transition to occur, both faculty and students must be aware of the necessity to facilitate this transformation. By frequently utilizing multimodal expression of student mental models, like the multimodal Topical Module Assessments, this transition can be monitored and enhanced.

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