

AC 2007-413: DIAGNOSING STUDENTS' MISCONCEPTIONS ON SOLUBILITY AND SATURATION FOR UNDERSTANDING OF PHASE DIAGRAMS

Stephen Krause, Arizona State University

Stephen J. Krause is Professor and Associate Director of the School of Materials in the Fulton School of Engineering at Arizona State University. He teaches courses in general materials engineering, polymer science, characterization of materials, and materials selection and design. He conducts research in innovative education in engineering, including a Materials Concept Inventory, and also in adapting design, engineering and technology concepts to K-12 education. He is currently working on an NSF sponsored MSP developing courses for high school teachers connecting math, science and engineering.

Amaneh Tasooji, Arizona State University

Amaneh Tasooji is an Associate Research Professor in the School of Materials at ASU and has been teaching and developing new content for materials science and engineering classes and laboratories. She has developed new content and contextual teaching methods from here experience as a researcher and a manager at Honeywell Inc. She is currently working to develop new assessments to to reveal and address student misconceptions in introductory materials engineering classes.

Diagnosing Students' Misconceptions on Solubility and Saturation for Understanding of Phase Diagrams

Abstract

Students in introductory chemistry classes often harbor or develop misconceptions about solubility concepts of solutions that inhibit their ability to understand of the nature of solution behavior. Subsequently, when these prior misconceptions are carried over into introductory materials engineering classes, they also inhibit students' ability to understand the liquid and solid solution concepts necessary to effectively understand and use phase diagrams. The end result is that students may never fully comprehend and appreciate the relationships between phase diagrams, materials' microstructures and associated correlations to materials' properties. This research, which is associated with misconceptions revealed from a Materials Concept Inventory (MCI), has investigated students' understanding of concepts of solubility and saturation that are associated with liquid and solid solution behavior necessary to understand phase diagrams. Student knowledge of solution behavior was studied with two-tiered questions. For the first tier-question students chose a schematic diagram that represented the solution characteristics that portrays their mental model about some aspect of solution behavior. In the second-tier response students then described the reason for their choice of a given diagram for the first-tier question.

Misconceptions about liquid-solid solution behavior in chemistry classes have been moderately well studied. Those related to the concepts of solubility and unsaturated, saturated, and supersaturated solutions are also pertinent to the study of solid solution behavior. In fact, the prevalence and persistence of solution-related misconceptions is demonstrated by the fact that changes of student understanding on a solution-concept related item on a previously administered MCI only moved from 39% to 67% correct on pre and post class administration of the MCI. For example, in a salt-saturated water solution, with water-saturated salt resting at the bottom of a beaker, students often believed that putting a small additional amount of salt in the beaker would increase the concentration of salt in the solution. One student said, "adding salt to an already saturated salty solvent will increase concentration slowly." The most common misconception in this research was that a supersaturated solution contained both liquid and solid phases instead of a solution with solute concentration above equilibrium. The diagnosis of this and other misconceptions represents identification of faulty mental models of the physical behavior of solutes and solvents and creates the possibility of devising interventions to address the misconceptions. Thus, the misconceptions about solution behavior carried over from chemistry classes need to be first diagnosed and then addressed in introductory materials engineering classes in order to more fully understand and use phase diagrams. Additional details on the nature of the misconceptions and suggestions about possible interventions to address them are discussed.

Introduction

The science of learning is moving forward rapidly, as described in *How People Learn: Brain, Mind, Experience, and School*¹, which summarizes and highlights some of the most important findings in the field of cognition of teaching and learning. One important finding about how experts and novices learn and transfer knowledge to new contexts suggests that, to develop

competence, students must have deep content understanding and that their facts and ideas need to be organized in a conceptual framework that facilitates retrieval and transfer to new applications. This would include transferring the conceptual knowledge of liquid-solid solution behavior in chemistry classes to liquid-solid and solid-solid solution behavior in phase diagrams in materials engineering classes. Another finding is that students bring their own experience to the classroom as prior knowledge about how the world works. This prior knowledge consists of prior conceptions (which may or may not be correct), which may persist during instruction and act as barriers to learning. In order to achieve content understanding, prior conceptions, which are incorrect, and can be referred to as misconceptions, need to be modified or displaced through cognitive processes that act to achieve conceptual change. This can occur through modification of a student's mental models that comprise their conceptual framework.

In order to determine if students are using appropriate, *scientifically-accepted concepts* to solve problems, there must be well-designed and well-tested assessment tools that can measure conceptual knowledge. The physics community has been using a well-regarded tool known as the Force Concept Inventory (FCI) created by Hestenes et al.^{2,3}, and tested broadly by Hake⁴ for students in high school and college physics classes. The FCI questionnaire utilizes a series of multiple-choice questions, frequently based on qualitative, concept-oriented problems on a particular topic. It measures deep understanding and conceptual knowledge of a topic rather than shallow knowledge associated with memorization of facts or routine algorithmic equation solving ability. Using an approach similar to the development of the FCI, a Materials Concept Inventory (MCI) was developed and tested on introductory materials engineering classes at Arizona State University (ASU) and Texas A & M University (TAMU)^{5,6}. It has also been used at a few other universities with good preliminary results in characterizing conceptual knowledge change in MSE^{7,8}. The FCI is regarded as a well-accepted yardstick for measuring student conceptual understanding in Newtonian physics. As such, the change in the FCI pre-post results of a class is considered a measure of the effectiveness of different teaching methods on the performance of students in that class. As a result, the FCI has acted as a catalyst to foster changes in teaching methodology and stimulated debate on best teaching practices.

One of the more difficult topics in introductory materials engineering classes is that of phase diagrams. For example, on a question on a previously given MCI about solutions, students moved from 39% correct to 67% correct on pre and post tests⁶. This demonstrated that students initially understood solution concepts poorly and did not improve as much as desired for understanding concepts related to phase diagrams. Without an effective conceptual understanding of these solution concepts, students may never fully understand and appreciate the relationships between phase diagrams, materials' microstructures and associated correlations to materials' properties. Unfortunately, students in introductory chemistry classes can harbor or develop misconceptions about solubility and solutions that inhibit their understanding of the nature of solution behavior. Subsequently, these scientifically invalid concepts can be carried over into introductory materials engineering classes as incorrect prior conceptions (or misconceptions). As such, they can inhibit students' ability to understand the liquid and solid solution concepts necessary for effectively knowing about and using phase diagrams.

The goal of the work in this research has been to measure student conceptual knowledge about solution behavior, diagnose the nature of faulty mental models that students' may hold, and

measure the conceptual change achieved through active learning and the resultant ability to apply the concepts to solid-solid solution behavior necessary to understand and use phase diagrams.

Background

Mental Models and Conceptual Development

A conceptual framework is comprised of *mental models*, which are transformed representations of real-world systems or phenomena called *modeled target systems or phenomena*⁹. As such, *mental models* are defined as simplified, conceptual representations that are personalized interpretations of *modeled target systems or phenomena* in the world around us. Thus, the transformed *modeled target systems or phenomena* become the *mental models* which become more visible or comprehensible to the individual¹⁰. Useful *mental models* allow one to understand, explain, and predict behavior of systems and phenomena, whereas faulty *mental models*, which lead to misconceptions, cannot. An individual communicates his/her *mental models* with some form of external representation which are *expressed models*. They might be verbal or written descriptions, equations, sketches, diagrams, physical models, computer models or other forms of representation¹¹. Thus, the *expressed models* reveal students' "ways of thinking" when elicited by appropriate questions or activities. In fact, when students use a *mental model* in their conceptual framework and express it in various forms, they are, in effect, explaining their ideas or "modeling a concept". These *expressed mental models*, or modeled concepts, can be utilized as indicators that track conceptual change when measured by techniques such as concept inventories, interviews, drawn schematics, journaling etc. A student is considered to have achieved appropriate concept understanding when her/his *expressed models* align with those that have been agreed upon by scientists or groups of learners, and are referred to as *consensus models* or *scientifically-accepted models* or *concepts*¹⁰. A characteristic of deep conceptual knowledge and effective mental models is the ability to be able to transfer the use of the concept to new contexts in different situations.

Transfer of Conceptual Knowledge to New Contexts

A major goal of the mathematics and science courses taken by engineering students is to provide a conceptual foundation of knowledge and processes that can be applied to engineering content and applications. This requires the student learner to have the ability to take the conceptual knowledge of a subject from the context of science learning and transfer it to the context of engineering design and problem solving. When learners have the ability to accomplish this, the book, *How People Learn*¹, describes them as having, or developing, *deep conceptual knowledge*. This is also characteristic of an individual who is becoming, or has become, an "expert" in an area of conceptual knowledge. This is in contrast to the *shallow conceptual knowledge* of a "novice" who lacks the ability to transfer his/her knowledge to new and different contexts other than the one in which the knowledge was acquired¹. This ability to transfer knowledge is also an indicator that effective conceptual change has occurred and has stabilized¹.

In this study on the nature of solubility and solutions, the hope has been that such conceptual knowledge had developed in high school and college chemistry courses could transfer to the study of phase diagrams in materials engineering courses. Thus, the mental models linked to the

conceptual knowledge of the interaction of liquid-solid solutions could be extended to liquid-solid and solid-solid solutions found in phase diagrams. As such, concept questions have been devised to examine student understanding of these concepts, reveal student misconceptions, and test the ability to transfer the conceptual knowledge of the context learned in chemistry courses to the different context of phase diagrams in a materials engineering course.

Misconceptions about Solution Behavior in Chemistry Courses

Students' understanding (and their misconceptions) related to solutions in chemistry has been studied for more than two decades¹². Numerous aspects of knowledge about the nature of solutions have been examined including: dissolution¹³, melting point depression and freezing point elevation¹⁴, and solubility^{14, 15}. The studies that are most pertinent to understanding of solution concepts related to phase diagrams are those that related to solubility, including the meaning of the terms unsaturated, saturated, and supersaturated^{14, 15}.

Mulford and Robinson¹⁵ queried students about how solution concentration changed when water evaporated from a beaker of water with sugar sitting at the bottom. This was done with a two-tiered multiple choice set of questions. In the first-tier question students chose what, if any, change in concentration occurred. In the second-tier question the students were given four choices as to the reason why they selected the answer in the first-tier question. In the first tier question only 32% (34% post) specified that the solution concentration stays the same as the water evaporates while 64% (61% post) believed concentration increased and 3% (4% post) thought it decreased. In the second tier question, 40% (48% post) stated that there was the same amount of salt in less water while 30% (18% post) specified that the salt didn't evaporate and remained in solution while only 25% (26% post) stated that more saturated salt forms at the bottom of the beaker. Although the reason for the responses was not discussed, it might be inferred that there was a misconception that the meaning of supersaturation is that there is excess solid present as a separate phase in the beaker.

Another study by Pinarbasi and Canpolat¹⁴ examined students understanding of the terms unsaturated, saturated and supersaturated. Three schematic diagrams of beakers with water were shown to students from which students had to match the appropriate word with the diagram. The unsaturated solution had a low density of dots (sugar molecules dissolved in water) in the beaker (C). The saturated solution had a higher density of dots and also had a small mound of saturated sugar sitting at the bottom of the beaker (B). The supersaturated solution had the highest density of dots but there was no sugar sitting on the bottom of the beaker (A). A significant majority, 78%, incorrectly chose beaker B as being supersaturated. The primary reason that was given was that there was excess solute (undissolved sugar) sitting in the beaker. This result is similar to the previous one, with both studies having a large fraction of students holding misconceptions.

At ASU a similar question was posed on a previously administered MCI as follows. When three tablespoons of salt are mixed into a glass of water and stirred, about a teaspoon of water-saturated salt remains on the bottom. If a small percentage of salt is slowly added to the glass while stirring the solution, the concentration of the salt in the solution will: a) increase; b) stay the same; c) decrease. Similar to the previously cited studies, 61% of the students selected the wrong answer, which was that the concentration increases. The reason was probably the same, a

misconception about the definition of the term supersaturation. The results of this study provide an answer to nature of this and other misconceptions.

Development of Liquid-Solid Solution and Solid-Solid Solution Concept Questions

The development of the concept questions about solubility and solutions for this study followed the general principles and guidelines described by Hestenes¹ for the FCI that were also utilized in the development of the MCI. These will be briefly reviewed here. When developing a given question, it should only have a single correct response since multiple correct responses make analysis of results difficult. The questions and responses should be basic, simple and as short as possible, since this shortens test-taking time and helps reduce ambiguity. The questions should use everyday lay terminology, and not use terminology specific to a course since this allows more effective pre-test and post-test evaluation of results. When appropriate, the use of diagrams, schematics, and graphs helps shorten questions, simplify responses, and reduce time.

In this work second-tier “explanation” questions were used to examine the underlying reason and conceptual basis for selection of an answer in the multiple-choice, first-tier question. Such information can be used to diagnose faulty mental models with the potential for designing better interventions in order to alter or replace incorrect mental models and achieve conceptual change. The pretest was given before instruction on phase diagrams and consisted of two two-tiered questions that had characteristics similar to those found in the literature of chemistry misconceptions related to solutions^{14, 15}. The post-test was given after instruction on phase diagrams and had two questions from the pretest plus an additional question that tested similar concepts in the different context of phase diagrams. The three questions will now be described.

The first question is shown below and examined student understanding and definition of the concepts of liquid solid solutions which are unsaturated, saturated and supersaturated.

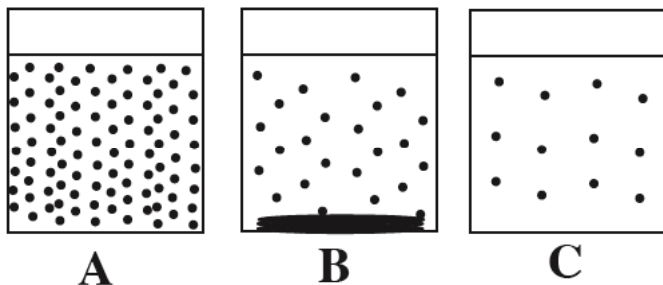
I. There are different concentrations of sugar solutions in beakers A, B, and C. One of the solutions is *saturated*. Another of the solutions is *unsaturated*. A third solution is *supersaturated*. (Increasing concentrations are illustrated by the increasing density of the dots in the diagrams. The dots represent the dissolved sugar molecules. The undissolved sugar in beaker B is shown as a darkened area at the bottom of the beaker.) (*Correct answers are in bold*)

In the questions below, please *circle the correct answer* and then *give an explanation*.

I.1. **Solution A** is (saturated, unsaturated, **supersaturated**). PLEASE EXPLAIN!

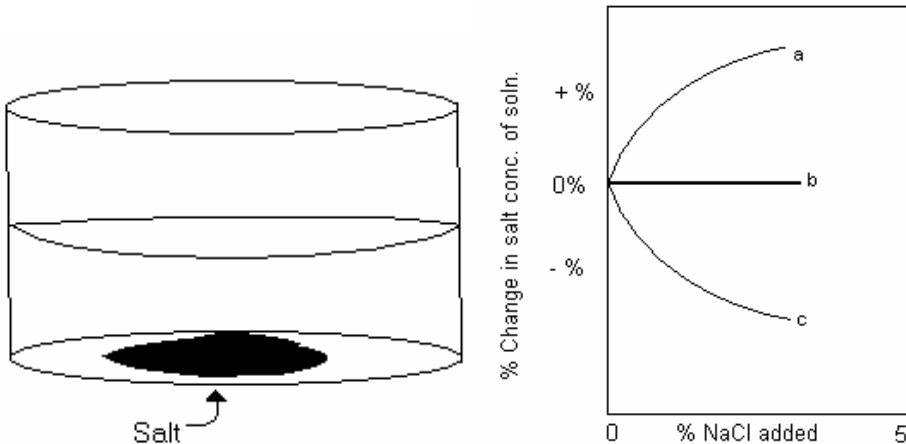
I.2. **Solution B** is (**saturated**, unsaturated, supersaturated).PLEASE EXPLAIN!

I.3. **Solution C** is (saturated, **unsaturated**, supersaturated).PLEASE EXPLAIN!



The second question shown below is from the MCI and utilizes the previously tested definitions and concepts of liquid-solid solutions as well as the effect of a perturbation (addition of a small additional amount of solute) on a saturated solution.

II. When three tablespoons of salt are mixed into a glass of water and stirred, about a teaspoon of water-saturated salt remains on the bottom. If a small % of salt is slowly added to the glass while stirring the solution, the change in concentration of the salt in the solution is given by curve: (Circle a or b or c) PLEASE EXPLAIN. (*Correct answer is in bold*)



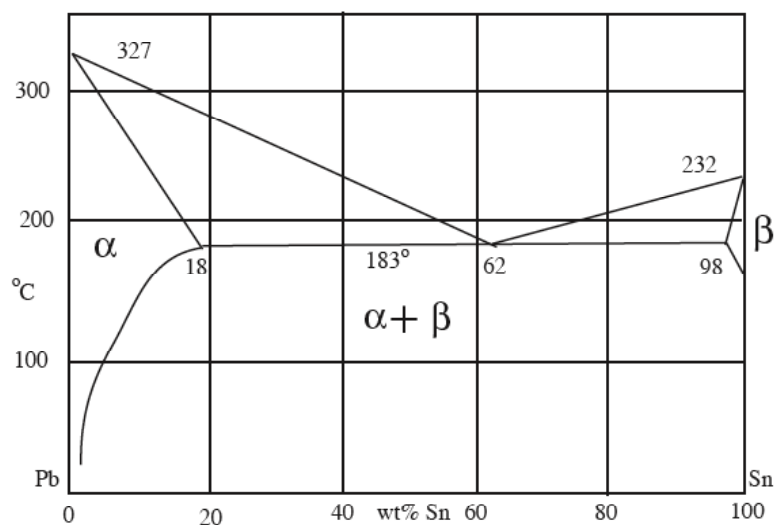
The third question, which was included *after* phase diagram instruction, examined the ability of students to transfer the conceptual knowledge they had learned from liquid-solid solutions to areas of the phase diagram concerned with solid-solid solutions. An additional concept was added, which was the non-equilibrium process of rapidly quenching a single-phase solid to a temperature below its solubility limit to create a single-phase, supersaturated solid solution. This is, of course, a key concept in processing of many metals to achieve a desired microstructure and associated properties.

III. From the Pb-Sn phase diagram below, circle the answer for questions about a 90Sb-10Sn alloy. (*Correct answers are in bold*)

III.1. For a 90Sb-10Sn alloy at 170°C , the α phase is (*unsaturated, saturated, supersaturated*) with Sn atoms. PLEASE EXPLAIN

III.2. For a 90Sb-10Sn alloy which has been slow cooled from 170°C to 50°C and held at that temperature, then the α phase is (*unsaturated, saturated, supersaturated*) with Sn atoms. PLEASE EXPLAIN

III.3. For a 90Sb-10Sn alloy which has been rapidly quenched from 170°C to 50°C and held at that temperature, then the α phase is (*unsaturated, saturated, supersaturated*) with Sn atoms. PLEASE EXPLAIN



Methods

The participants were 40 students enrolled in a broadly subscribed introductory materials science and engineering class. The class was composed of 1 freshman, 11 sophomores, 14 juniors, and 14 seniors. The disciplines in which the students were enrolled were 1 in architecture, 3 in bioengineering, 4 in chemical engineering, 1 in civil engineering, 4 in industrial engineering, 4 in materials engineering, and 23 in mechanical engineering.

The solution concepts pretest was administered in the fifth week of a 15-week semester and was given before the topic of phase diagrams was discussed. The solution concepts test consisted of the first two questions described above. The students were given twenty minutes to respond to the questions and turned in the results anonymously. The posttest was administered in the seventh week of the semester and was given after the topic of phase diagrams had been completed. The test consisted of the first two questions on the pretest, as well as a third question on various aspects of the nature of solubility in phase diagrams. As before, the students were given twenty minutes to respond to the questions and turned in the result anonymously.

Results and Discussion

The results for Question I (3 schematic diagrams on saturation) on the pretest will be presented and discussed here with correct answers indicated with *italics*. Part 1 of Question I (solution A - supersaturated) had 38% of the class choose the correct answer of *supersaturated* while 3% chose unsaturated and 57% chose saturated. On Part 2 of Question I (solution B - saturated) 30% chose the correct answer of *saturated* while 11% chose unsaturated and 59% chose supersaturated. Finally, on Part 3 of Question I (solution C - unsaturated) 86% chose the correct answer of *unsaturated* while 14% chose saturated and 0% chose unsaturated. Part 2 of this question revealed that the 70% of the students did not understand the definition of the word saturation. One misconception believed by 11% of the students was that the solution was "unsaturated" because there was "undissolved" sugar at the bottom of the beaker ("there is still a lot of sugar that is not mixed"). This also indicates that they may not have understood the

concept of limited solubility. The other misconception held by 59% of the students was that the term "supersaturation" meant that there was excess solid in the beaker ("there is so much sugar it cannot mix with the water"). Again, this shows that students did not understand the concept of solubility limit. Thus, overall, students held misconceptions for Part 2, which included both unsaturated solution and supersaturated solutions, both of which are related to misconceptions that are misunderstandings of the definition of saturation and the associated concept of solubility limit.

The level of performance for part 2 of Question I, 70% incorrect, is quite similar to that observed in the Pinarbasi and Canpolat¹⁴ chemistry class previously discussed, where 78% were found to be incorrect. The situation is similar for the two studies because there is saturated solute sitting on the bottom of the beaker. As stated by Pinarbasi and Canpolat¹⁴ from interviews, students assumed that supersaturated meant that there was excess solute (undissolved sugar) sitting in the beaker. This also corresponds to the same misconception held by the majority of students in the materials engineering class, as demonstrated by the excess sugar in the bottom of schematic container "B". It is clear that the students brought a prior misconception with them into the materials engineering class. Most materials engineering instructors, including myself, have assumed that their students have a solid understanding of the nature of solutions and of the meaning of the terms unsaturated, saturated, and supersaturated, but this is not true. In some sense this could be considered an instructor held misconception about student prior knowledge.

The results for Question II (effect of solute addition on saturated solution concentration) in the pretest were that 41% of the class selected the incorrect answer (increasing solution concentration) of "a". One student said, "If you already have saturated salts on the bottom, and if you add more, you will continue to add more concentration of salt". The correct answer (constant concentration) of "b" was selected by 49%. 10% of the class selected the incorrect answer "c" (decreasing concentration). The most frequent written responses indicated that students believed that the term "concentration" referred to the amount of salt that had been added to the water overall, not the amount that had actually dissolved into the water. Question II asks what is "the change in concentration of the salt in the solution?" Either the students misunderstood the definition of concentration or, possibly, the wording in the question needs to be clarified by changing to "the change in concentration of the salt *which has been dissolved into* the solution".

The level of performance of 51% incorrect is similar to level of 67% incorrect that was observed by Mulford and Robinson¹⁵ in their chemistry class. Although the question was slightly different, it still utilized the same principle for solving the problem. In that problem there was excess sugar in a water-based solution, and the problem was to determine how the solution concentration changed when half of the solution evaporated. The misconception of increasing solution concentration when solid material sits at the bottom of the beaker seems to be another aspect of the previous misconception of the meaning of saturation. That is, if students do not know what the characteristics of a saturated solution are, then the perception that solution concentration increases with water evaporation or, with solute addition, may be another related misconception. This again shows that the misconceptions held by the majority of students who came to the materials engineering class held a similar prior misconception that was not effectively addressed in prior chemistry classes at other institutions.

On the posttest the results for Question I was a surprising 100% of the class selected the correct set of three answers: 1) supersaturated; 2) saturated; and 3) unsaturated. The change from the pretest to the posttest for the three parts was 38%, 30%, and 82% correct on parts 1, 2, and 3 to 100% correct on all three parts. This demonstrates that, for this problem, the instruction on phase diagrams was very effective in addressing student misconceptions on the concept of solubility and the meanings of unsaturated, saturated, and supersaturated. The instruction included team-based active learning activities and discussion of the concept questions given on the pretest. These posttest results could not be compared to those of the chemistry class of Pinarbasi and Canpolat¹⁴ since, curiously, this concept was not addressed in instruction.

The results for Question II on the posttest were that 92% of the class selected the correct answer "b" while 8% chose incorrect answer "a" and none selected the incorrect answer "c". Thus, the change from the pretest to the posttest was from 49% to 92% incorrect. This demonstrates again that, for this problem, the instruction on phase diagrams was effective in addressing the student misconception that solution concentration changes if salt is added. Again, these posttest results could not be compared to those of the chemistry class of Mulford and Robinson¹⁵ since this concept was not addressed in their instruction.

The results for Question III (Pb-Sn phase diagram), given only on the posttest after instruction, had scores of 75%, 92%, and 81% correct on parts 1, 2, and 3. This performance very good, but not excellent, indicating that the students had partial, but not complete transfer of understanding of the concepts of unsaturated, saturated, and supersaturated solid-solid solution behavior found in the phase diagram used. For the first part of Question III (single phase region) 75% of the class chose the correct answer of *unsaturated*, 14% students chose saturated, 8% chose supersaturated, and 3% did not respond. For the second part of Question III (two phase region) 92% chose the correct answer of *saturated*, 11% chose unsaturated, 11% chose supersaturated, and 6% did not respond. For the third part of Question III (quenched from single phase region) 81% chose the correct answer of *supersaturated*, 2% chose unsaturated, 17% chose saturated, and 8% did not respond. The responses on the three parts of Question III as 75%, 92%, and 81% correct are moderately good scores that reflect good, but not complete understanding of the concepts of unsaturated, saturated, and supersaturated on the phase diagram. The scores were lower than for posttest Questions I and II, which indicates that there was not full conceptual transfer from the solution understanding in chemistry classes, supplemented by instruction in the materials engineering class, to the new context of phase diagrams. Additional probing, possibly with interviews or focus groups, will be necessary to better understand student thinking to develop more effective teaching on the subject of phase diagrams.

Summary and Conclusions

This paper has shown that students bring from introductory chemistry classes faulty mental models and associated misconceptions about solubility concepts of solutions that inhibit their understanding of the nature of solution behavior. Subsequently, these misconceptions can be carried over into introductory materials engineering classes and can inhibit students' ability to understand the liquid and solid solution concepts that are necessary to effectively understand and use phase diagrams. The end result is that students may never fully understand and appreciate the relationships between phase diagrams, materials' microstructures and associated correlations to

materials' properties. This research investigated students' mental models of their understanding of concepts of solubility and saturation processes associated with liquid and solid solution behavior and showed that the prior conceptions and associated faulty mental models can be addressed during active-learning, team-based instruction to achieve conceptual change to understand solution concepts in liquid-solid solutions. The two-tiered questions portrayed the students' mental models about some aspects of solution behavior, but the mental models and conceptual understanding did not transfer completely to solid solution behavior necessary to understand thermal treatment in phase diagrams.

The prevalence and persistence of solution-related misconceptions is demonstrated by the fact that student understanding on solution concepts displayed the same characteristic misconceptions found in research on misconceptions about solutions found in chemistry classes. The diagnosis of these misconceptions represents identification of faulty mental models of the physical behavior of solutes and solvents and creates the possibility of devising interventions to address the misconceptions. Thus, the faulty mental models and associated misconceptions about solution behavior carried over from chemistry classes need to be first diagnosed and addressed in introductory materials engineering classes in order to understand both liquid-solid and solid-solid phase behavior and the use of phase diagrams. This is especially important in the interpretation of the effect of thermal treatment on phase behavior and the correlation of the resultant microstructure to materials' properties.

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