Engineering Students' Comprehension of Phase Diagram Concepts: an International Sample

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Abstract

Materials science is an essential discipline for students in the mechanical and metallurgical engineering programs because many of them find jobs in industries where materials are relevant, such as electronics, aerospace, and automobile. Phase diagrams have proven to be a topic in materials science in which students demonstrate alternate conceptions. An essential first step in constructing a pedagogical approach to teaching phase diagrams in a specific program is to assess the students' conceptions.

There has been significant interest in improving the teaching of materials science in general and phase diagrams in particular in two top universities, one in Mexico and the other in Canada. In both universities, there are successful mechanical engineering programs in which materials science is part of the curricula. In this research, we implemented a project aimed to improve the students' conceptions of crucial concepts in materials science.

In this work, as a first step, we used an instrument inspired by items from the Materials Science Concept Evaluation (MSCE) to assess students' understanding of concepts related to phase diagrams. In addition to multiple-choice questions, we asked for their reasoning to deepen our understanding of their conceptions. We added open-ended items with corresponding spaces for their reasoning. We administered that instrument to undergraduate engineering students from these two universities after the phase diagram topics were covered. With the analysis of the multiple-choice and open-ended questions combined with a qualitative method to categorize the students' approach to each item, we present in this paper the students' conceptions and difficulties they had with this topic. We concluded that students in both countries had difficulties with the identification of phase fractions, the compositions of both alloys and individual phases, and solid solubility in binary phase diagrams.

Keywords: Materials research education, phase diagrams, STEM, educational innovation, higher education

Introduction

The study of how students understand concepts in science and engineering is relevant for researchers and educators to be able to modify and design teaching strategies or curricula to improve students' learning. Tools for evaluating conceptual understanding have been extensively developed and tested in fields like physics, where questionnaires such as the Force Concept Inventory (FCI) [1] and the Conceptual Survey of Electricity and Magnetism (CSEM) [2] have been created to assess student comprehension in introductory physics courses. Employing these kinds of surveys is not only useful to quantify "correct answers" but also to delve into student mistakes qualitatively to identify and categorize alternate conceptions.

In the case of materials science, there are two efforts to develop these kinds of concept evaluation surveys, namely, the Materials Concept Inventory (MCI), introduced by Krause, et al. [3], and the Materials Science Conceptual Evaluation (MSCE), designed by Rosenblatt & Heckler [4]. The MCI assesses student learning on the topics of atomic structure and bonding, band structure, crystal geometry, defects, microstructure, phase diagrams, and the macroscopic properties of materials in the families of metals, polymers, ceramics, and semiconductors. Krause et al. [5] identified alternate conceptions both before and after instruction in areas such as geometry in crystallography, phase diagrams, and material properties. Notably, the MSCE was designed to complement the MCI; it examines the topics of atomic structure, mechanical properties, defects, diffusion, phase diagrams, failure, and the processing of metals. Furthermore, the authors categorized four general areas of student learning difficulties: a) student confusion of similar concepts, b) student difficulties with reasoning about concepts with more than one variable, c) student use of inappropriate models or analogies, and d) student difficulties with typical graphs and diagrams used in materials science [6]. Because both instruments were designed to assess a wide range of topics in materials science, they identify a variety of alternate conceptions that are not limited to one single area of materials science.

In fields like physics, research has not stopped at just the FCI or CSEM; specific student difficulties within the areas of interest have been studied carefully. For instance, the alternate conceptions of students taking electricity and magnetism courses about electrical fields illustrated through the use of line diagrams have been studied [7]. Similarly, research has explored students' understanding of more specific topics within materials science. Heckler & Rosenblatt [8] examined the difficulties students had in conceptualizing atomic bonds and their relationship to macroscopic mechanical properties of metals. The same authors [9] reported students' difficulties in identifying and differentiating mechanical properties such as yield strength and stiffness. Conceptions regarding crystal structure have also been reported using a multiple-choice Crystal Spatial Visualization Survey (CSVS) assessment tool [10]. The CSVS was also used to measure the learning gain of students after instruction assisted by computer-based visualizations [11].

Phase diagrams, the area of focus for this work, are highlighted by the authors of the MCI and the MSCE as a topic of difficulty for students. Krause et al. [3] stated the importance of grasping the concepts of phase diagrams to understand the origin of microstructure in materials and their eventual relationships with processing and properties. They identified student confusion in concepts like solubility and solubility limits. Heckler & Rosenblatt [6], on the other hand, found that students conflate similar concepts like a mass fraction of phases and their composition when interpreting a binary phase diagram. Furthermore, Demetry [12] extensively explored student understanding of the use of the lever rule in phase diagrams and the effect that teaching strategies have on their comprehension. Although some work has been found in the literature, the current paper aims to expand on identifying and categorizing the difficulties students have in the specific topic of phase diagrams.

Finally, it is not uncommon to find research on conceptual understanding being performed on students with diverse national origins. Sağlam & Millar [13], for instance, studied the alternate conceptions that high school students in Turkey and England had about electromagnetism. Although the authors state that making a comparison of the students' understanding in the two countries was not one of their objectives, they were able to explore the extent to which patterns in answers were similar between the students of both nationalities. While research in conceptual understanding in materials science has been done comparing students' results from different universities (such as the work done by Krause et al. for the FCI [3]), there is a gap in the literature about the conceptual understanding of student populations in different countries. This research tries to fill that gap and look at whether differences and similarities between countries exist.

Methodology

Participants in this study were undergraduate mechanical engineering students enrolled in an introductory materials engineering course in a top private Mexican university and a top public Canadian university. Students typically take the course in the second or third year of their mechanical engineering degrees as a mandatory requirement in both universities. It is managed and taught by the Materials Engineering department at the Canadian university and by the Mechanical Engineering department at the Mexican university. The language of instruction at the Canadian university is English. The language of instruction for the course at the Mexican university was also English, although different classes in the subject are taught in both Spanish or English. The courses in both universities are instructed traditionally through lectures and have not integrated any active learning techniques in their pedagogy.

We designed a short questionnaire, combining multiple-choice and open-ended questions, and the students were asked to explain their responses in every case, regardless of whether it was an open or closed question. We included four questions in this instrument; we adapted the first from Question #20 in the MSCE [4]. Questions number 2 to 4 were inspired by the MSCE but were independently designed for this questionnaire. Implementation of the test at both universities was similar: The students in both Introductory Materials engineering courses were presented with the instrument and allowed 15 minutes to respond at the end of a regular lecture, with the permission of the course instructor. In both cases, we evaluated the student conceptions of phase diagrams near the end of the semester, when that topic is covered. Although no course credits or extra credits were assigned to this activity, both the assistants implementing the instrument and the course instructors encouraged students to answer to the best of their ability. The surveys were subsequently digitalized, analyzed qualitatively, categorized, and reported in this work.

As this is a work in progress, preliminary results are shown from student responses acquired in the Fall 2019 term, in which 21 students were surveyed in Mexico and 12 in Canada, for a total of 33 students. More data will be collected from students in the upcoming terms as part of the same project.

Results and discussion

Question description

The questions on the instrument were based on the Cu-Ag binary phase diagram shown in Figure 1. Some selected points within the diagram were highlighted for their use further in the questionnaire, and a few aids were included, such as dotted lines and composition values.

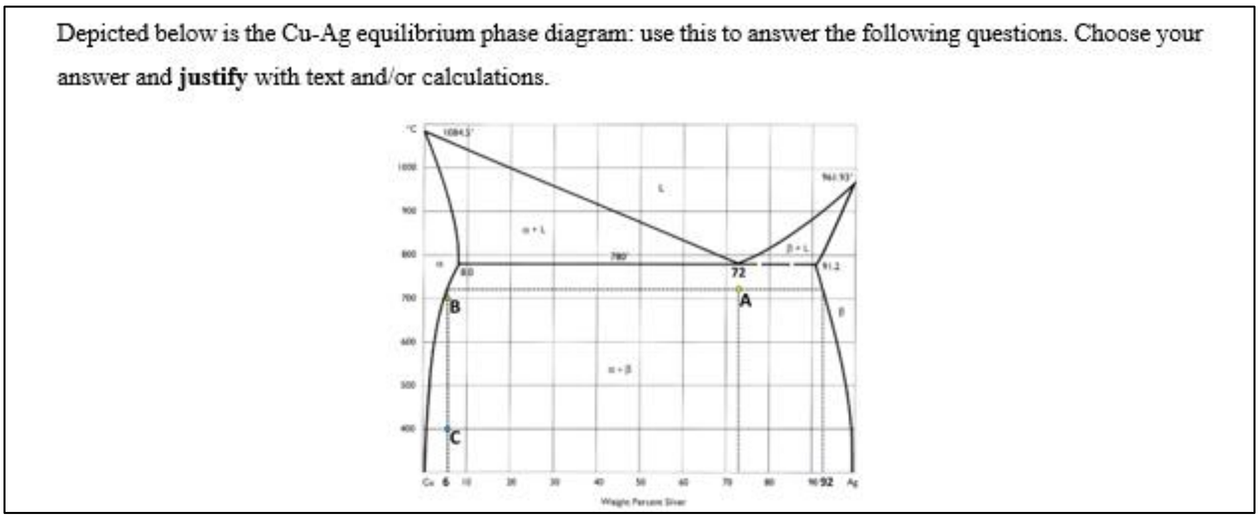

Figure 1. Cu-Ag equilibrium phase diagram used as a reference for the entirety of the instrument, as presented to the students.

Table 1 presents the full text and possible answers, where applicable, of the questions presented to students through the test. Question #1 aimed to identify how familiar students are with the use of phase diagrams to calculate an alloy's phase fraction using the lever rule. They could misidentify the fraction of the α phase as the eutectic Ag composition (72%), as the solid solubility composition of the α phase of that alloy (6%), or as the β phase fraction of the alloy (77%). Appropriate use of the lever rule should yield a 23% content of the α phase. As a follow-up, Question #2 sought to identify whether students recognize that an alloy at that composition and temperature is a two-phase α + β alloy and that the rest of the alloy is comprised of a second solid solution phase and not only Ag atoms. No mention of the eutectic composition or microstructure was strictly required or expected.

Table 1. Questions included in the instrument presented to students along with their multiple-choice answers, when applicable. The requests for reasoning are shown in bold type.

<table>
<tr><th>#</th><th colspan="12">Question</th></tr>
<tr><td rowspan="2">1</td><td colspan="12">At point A, what fraction of the alloy is α phase? Choose your answer and justify with text and/or calculations.</td></tr>
<tr><td colspan="3">a) 77%</td><td colspan="3">b) 23%</td><td colspan="3">c) 72%</td><td colspan="3">d) 6%</td></tr>
<tr><td rowspan="2">2</td><td colspan="12">What makes up the rest of the alloy at point A? Please choose and clearly explain your answer.</td></tr>
<tr><td colspan="4">a) Only β phase</td><td colspan="4">b) Only Ag atoms</td><td colspan="4">c) Both Ag and Cu atoms</td></tr>
<tr><td>3</td><td colspan="12">Which 6% Ag alloy contains a higher amount of α phase, B or C? Please explain your answer.</td></tr>
<tr><td>4</td><td colspan="12">What is the difference, if any, between the composition of the α phase in the alloys at points B and C? Please explain your answer.</td></tr>
</table>

In Question #3, students should correctly identify that alloy B will show a higher amount of α phase than alloy C, either from relating it to the lever rule or just to the proximity to the solvus line. Furthermore, Question #4 intends to inquire whether the students can identify the temperature dependence of the solid solubility of the α phase, because the α phase is a solid solution of Cu and Ag atoms, and the α phase in alloy B will have a higher concentration of Ag than the alloy C.

Results by question

In question #1, students were asked to choose one out of four options and then provide an explanation behind their choice. After reviewing the students' answers, we found four general reasonings that corresponded to each of the options. In Figure 2, we observe that the most selected answer (42% of students) was b) 23%, which was the correct answer. Here, most students correctly employed the lever rule to determine the α fraction of the alloy, either quantitatively through calculations, or qualitatively, by describing the proper use of the lever rule.

24% of students selected option c) 72%. These students chose the composition of the alloy, which in this case, is the eutectic composition. A typical response when selecting this option was "the point is a distance of 72 on the axis." This demonstrates the fact that these students confuse the concepts of phase fraction and composition, which previously has been identified as an alternate conception in the study of phase diagrams.

Meanwhile, an equal fraction of surveyed students selected option d) 6%. A frequent response of students in this category was that "there is 6% α in the alloy." This type of response indicates that students confuse phase fraction not only with composition but with solid solubility. They may not fully comprehend that the α phase is a two-element phase and that the axis composition percentage corresponds only to an elemental compositional amount.

Finally, a small fraction of students (9%) selected a) 77%. All of these were students who applied the lever rule, either qualitatively or quantitatively, but mistook the corresponding fraction to the opposite phase. Notably, 30% of the students did not explain their answers.

For question 1, a larger proportion of students in the Mexican institution responded correctly than those in the Canadian institution. The students who incorrectly responded in the Canadian institution answered in equal proportions options c) and d). The small number of students answering each option makes it difficult to conclude whether there are significant differences; however, what is clear is that students in both institutions have similar difficulties.

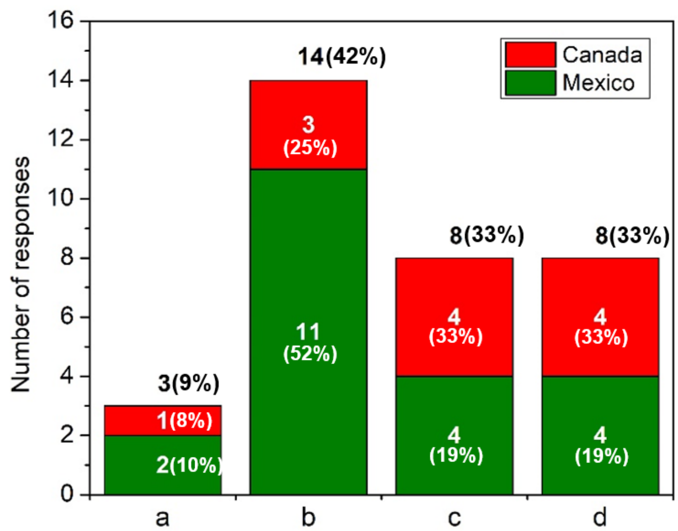

Figure 2. Summary of results from Question #1.

Figure 3 displays a breakdown of student responses from the multiple-choice options on question #2. The wording of these options allowed students to choose that the rest of the alloy contained either a) Only β phase or c) Both Ag and Cu atoms since β includes both types of atoms. Three general lines of thought were identified from the students' answers. Notably, around 30% of the students overall did not provide an explanation to back up their answers.

The least selected option (only 6% of students) was b) Only Ag atoms. Students who selected this option also referred to the 72% silver content of the alloy, indicating their confusion between phase fraction and composition. The second most popular selection (27% of students) was a) Only β phase. The majority of students that chose a) responded along the lines of, "The alloy is found on an α+β region, so if the first part was made of α, the rest must be β." This suggests an understanding that this is a two-phase alloy, where each one makes up a fraction of the total alloy. The most selected option (67% of students) was c) Both Ag and Cu atoms. Similar to those who chose a), some of the students who selected c) also indicated that the alloy was in a two-phase region. However, another typical response from students was that the rest of this alloy corresponded not to the β phase directly, but to a "mixture of solids that have Ag and Cu." This vague answering makes it unclear to sort whether students identified the remainder phase fraction as being formed by both types of atoms, or if the whole alloy is just a mixture of Ag and Cu atoms, disregarding its integration in distinct phases.

The proportion of Mexican and Canadian students who selected the different options in question 2 is similar. In the case of students in the Canadian institution, no student chose option b) Only Ag atoms. However, 10% of students in the Mexican institution selected that option. As seen in the student responses to question 1, the students in both countries faced similar difficulties.

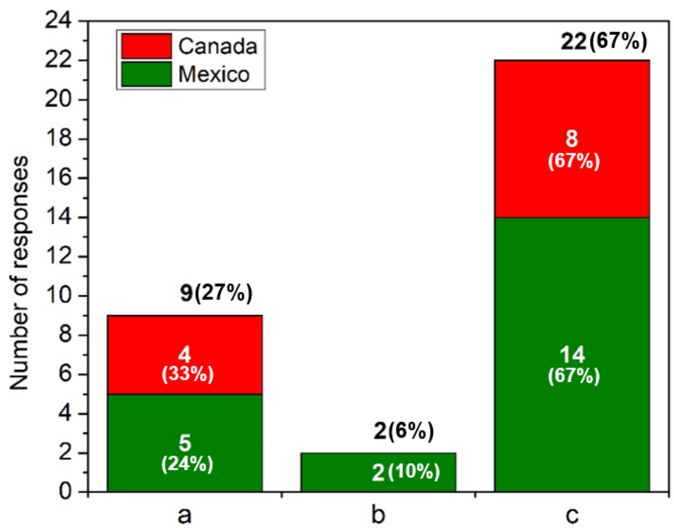

Figure 3. Summary of results from Question #2.

In question #3, students were asked to state which alloy with the same elemental composition, whether the one at point B or the one at point C, had the highest fraction of α phase. Nearly 20% of the students who selected a multiple-choice answer did not back it with an explanation.

The first category of responses corresponds to those who answered that the fractions were equal for both alloys (9% of students). This answer is a clear case of students confusing the concept of phase fraction with composition, as they attributed that both lying on the same point on the percentage-of-Ag-composition axis should have the same amount of α phase.

The most popular choice (64% of students) was the correct answer, where B has a higher fraction of α phase than C. Many students supported this claim by stating, "B is closer to α phase than C," or a similar qualitative or quantitative interpretation of the lever rule. These responses suggest that students understand how to interpret qualitatively that an alloy "closer" on a horizontal line to a phase has a higher fraction of that phase.

In another category of answers, students related the temperature to the phase fraction of the alloy. In some cases, they selected the correct answer. They explained that "B is at a higher temperature," which may indicate they relate the concept of phase fraction with the alloy's temperature as an "intuitive" form of interpreting the lever rule. A small fraction of students, however, selected C "because C is at a lower temperature," contradicting this approach.

A last category of answers corresponds to a previously undescribed alternate conception. Student responses similar to, "The length of the horizontal line that goes across the α region and crosses point B is larger than the one that crosses point C" show that students select B because the solid solubility of Ag in α at that temperature is higher than that of C. This shows the students' confusion regarding the concepts of solid solubility, phase fraction, and both phase and alloy composition. Although the α phase in alloy B will indeed be more abundant in Ag than the α phase in alloy C, this is not because the phase fraction will be different due to the relative proximities to the solvus line, as calculated by the lever rule.

Answers to question 3 do not show any differences when comparing the students in the Mexican and Canadian institutions. The same fraction of students answered the question correctly, and similar percentages responded with incorrect answers.

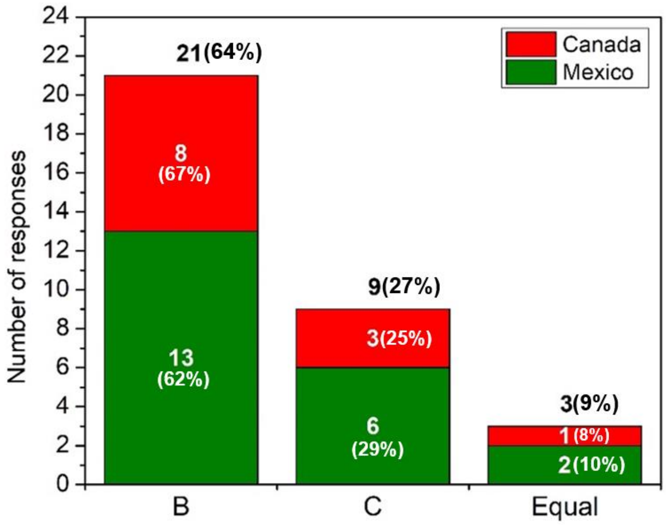

Figure 4. Summary of results from Question #3.

Finally, question #4 directly asked students to comment on the differences in composition between the α phases present in alloys B and C. Only 6% of the surveyed students provided the correct response, which is that α has a higher Ag content in alloy B compared to C. However, there were alternate conceptions in this question that fell into three categories: there is no difference; there are differences in composition, and there are differences in phase fraction.

39% of the surveyed students stated that there was no difference or that they had the same "percentage content," referring to the alloy's composition. These students attributed the composition of the alloy to the composition of a single-phase and, thus, declared that no difference existed between B and C. On the other hand, 12% of the students argued that alloys B and C had different compositions with more Cu or more Ag atoms, not only confusing alloy and phase compositions but also failing to identify that both alloys have the same elemental composition. Finally, 42% of the students stated that the difference was the quantity of the phases in B and C. Because the question required describing *differences* in composition, this case shows the conflation of phase fraction and composition concepts. Some students only qualitatively described that a difference existed, and some said one phase was more prevalent in one alloy than the other.

Conclusion

A questionnaire was administered to undergraduate mechanical engineering students in introductory materials engineering courses in a Mexican and a Canadian university to study students' alternate conceptions of the topic of phase diagrams. The instrument consisted of four questions (two multiple-choice and two open-ended questions) regarding a Cu-Ag equilibrium phase diagram. The test was administered in similar ways in both institutions.

After analyzing the answers, we grouped the difficulties that students were having into three major categories: a) identification of phase fractions, either qualitatively or quantitatively by use of the lever rule; b) compositions of both alloys and individual phases, and c) solid solubility in binary phase diagrams. In the latter, confusion reigned in the concept of solid-solution phases being formed by two types of atoms, and the existence of two-phase regions. It is common that students confuse the concepts of phase fraction and composition and also confuse phase fraction with solid solubility. These two difficulties have previously been identified as alternate conceptions in the study of phase diagrams.

In question 3, we found a previously undescribed alternate conception in which students relate the length of the horizontal line from 0% Ag to the solvus line to the fraction of α phase at different temperatures. This misconception exhibits the students' confusion about the concepts of solid solubility, phase fraction, and both phase and alloy composition.

We found that students from the Mexican institution have similar difficulties to those of students in the Canadian institution. However, because this is a work in progress, the quantitative analysis is preliminary. As the pool of surveyed students increases in both institutions, we will have a more extensive analysis of the identified alternate conceptions based on more data for comparison of the students in the two countries. Furthermore, the preliminary round of implementations suggested to us minor modifications that can be made to the questionnaire to improve the expected quality of the student responses, thereby yielding useful information about their alternate conceptions in phase diagrams.

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