AC 2008-2026: AN INTERVENTION USING CONCEPT SKETCHING FOR ADDRESSING DISLOCATION-RELATED MISCONCEPTIONS IN INTRODUCTORY MATERIALS CLASSES

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An Intervention Using Concept Sketching for Addressing Dislocation-Related Misconceptions In Introductory Materials Science and Engineering Classes

Abstract

In materials science and engineering (MSE) a major goal of the discipline is to effectively teach learners from other engineering disciplines about engineering a material's macroscale properties based on the knowledge and understanding of its atomic-scale structure. This goal is a significant intellectual challenge because learners must develop a conceptual framework to understand and solve materials-related problems in their own discipline. There are significant difficulties in addressing materials-related problems in a discipline because robust misconceptions are used by students attempting to understand and correlate the concrete "macroworld" of everyday objects, properties, and phenomena to the abstract "atomic and micro-scale world" of atoms, molecules and microstructure, which are types of features of a material that actually control its properties. These misconceptions, which are scientifically-inaccurate interpretations about materials, can neither explain nor predict materials' phenomena or properties. In this study, different teaching methods were used to address the question, "What is the effect of pedagogy on student conceptual understanding of deformation and thermal processing and associated property changes of metals in an introductory materials class?" For classes in 2002, 2003, and 2007, content delivered by lectures, pair-based discussions, and team-based concept sketching, respectively, were compared in teaching the effect of deformation or annealing on a metal's properties by invoking the atomic-level structural feature of dislocations to understand macroscopic-level property changes in strength, ductility, and fracture toughness. The effect of the pedagogy was assessed from responses to dislocation-related questions on the Materials Concept Inventory (MCI). Results showed that a team-based concept sketching pedagogy was most effective in achieving conceptual change of faulty mental models about deformation-related misconceptions. This indicates that concept sketching may be an effective pedagogy both for revealing misconceptions and achieving conceptual change about other physical phenomena in materials engineering, as well as diverse physical phenomena in other engineering disciplines.

Introduction

Dislocations are a major structural feature of crystalline metals that play a significant role in their structure-processing-properties-performance relationships. The knowledge and understanding of the nature and behavior of dislocations is fundamental to understanding the relationships between features of a metal at the atomic and microscale level and at the macroscale level properties such as ductility, strength, and fracture energy. Since most incoming students in a materials class have little or no knowledge of dislocations, considerable time is spent teaching about dislocations and their role in processing and property change. In materials science and engineering (MSE) a major goal of the discipline is to effectively teach learners from other disciplines the relationship between a material's macroscale properties and its atomic-scale structure. But, this is a challenge because, in MSE, there is difficulty in learners constructing a useful conceptual framework which effectively links the concrete "macroworld" of everyday properties and phenomena to the abstract "atomic and microscale world" of atoms, molecules and microstructure, which are types of features of a material that actually control its properties.

The behavior of materials is often counterintuitive and, when "novice" learners use everyday experience to create the *mental models* that comprise their conceptual framework[1], they may result in misconceptions. These are an individual's scientifically-inaccurate interpretations of the world that can neither explain nor predict phenomena nor properties. A typical example of a faulty mental model resulting in a misconception is "the malleable copper atom"[2]. Thus, it is important to use effective teaching and learning strategies to foster student learning in MSE in order to address students' "commonsense", but incorrect, mental models about materials, such as "the malleable copper atom."

The understanding of the science of learning is described in *How People Learn*: *Brain, Mind, Experience, and School*[3], which highlights some of the most important findings in the field. One finding, which is about how experts and novices learn and transfer knowledge to new contexts, suggests that, to develop competence, students must develop deep content understanding and need to learn to organize their facts and ideas into a conceptual framework that facilitates retrieval and transfer to new applications. A second is that research on performance of experts and on metacognition indicates that learners can develop their own expertise by defining learning goals and monitoring their progress. A third finding is that students bring their own experience to the classroom as prior knowledge about how the world works. This prior knowledge consists of mental models and associated conceptions (which may or may not be correct) which they have developed from a variety of sources. Such sources might include; earlier classes, textbooks, personal observation, television, and the internet[4]. These prior conceptions may persist during instruction and, if they are incorrect, or applied incorrectly, can act as barriers to learning. The faulty mental models of incorrect prior conceptions are often referred to as misconceptions. The faulty mental models and associated misconceptions are robust and difficult to displace with scientifically correct mental models. However, effective pedagogy can displace faulty mental models and associated misconceptions by stimulating cognitive processes that achieve conceptual change and alter students' conceptual frameworks. In MSE, an important topical area is dislocations and the related phenomena in metals. Misconceptions can be assessed by dislocation-related questions on the Materials Concept Inventory (MCI) [5], which often show only limited gains in understanding in pre-post MCI testing[6]. In this study dislocation-related misconceptions associated with deformation or annealing of metals were assessed with specific questions on the MCI in order to address the research question of, "What is the effect of pedagogy on student understanding of dislocation-related phenomena and behavior in an introductory materials class?"

Background

Mental Models and Conceptual Change

Constructivism espouses the belief that students learn most effectively by constructing their own knowledge and refers to learning as conceptual change[7, 8]. *How People Learn* discusses how cognitive processes act to achieve conceptual change, which occurs through modification of a student's conceptual framework. The 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 individual[10]. Useful mental models allow us to understand, explain, and predict behavior of systems and phenomena, whereas faulty mental models, which lead to misconceptions, cannot. After revealing and characterizing students' misconceptions, teaching strategies may be devised and tested in order to develop the most effective means of displacing the misconceptions. For example, one effective approach has been shown to be through inquiry learning activities that employ processes such as "cognitive dissonance" which use discrepant events, and by "analogical reasoning" which uses concrete, real-world analogies to bridge to individual understanding of abstract concepts.

As an individual communicates his/her mental models through some form of external representation they are creating their *expressed models.* These models might take the form of verbal or written descriptions, equations, sketches, diagrams, physical models, computer models or other forms of representation[1]. Thus, *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 used as indicators to reveal misconceptions and then to track conceptual change as measured by techniques such as the concept inventories, interviews, concept sketches, journaling etc. In this project verbal models are used in pair-discussion and concept sketching was sometimes used with team activities, while the assessment used was multiple-choice questions on the MCI to measure pre-post conceptual change.

Mental Models and Barriers to Conceptual Change – Robust Misconceptions

Conceptual change is sometimes difficult and may be impeded by robust misconceptions resistant to change because of students' arguments, contradictions, and obstinacy[11, 12]. Thus, the general strategies of assimilation or accommodation have been used to promote conceptual change[13], but for an individual to want to adopt a new concept, it should also be intelligible, plausible, and fruitful[14, 15]. The general strategy of assimilation is to build on and modify existing mental models and associated concepts of a conceptual framework. In contrast is accommodation, in which change occurs by major revision or replacement of an existing misconception and associated mental model[16]. One way to do this is with "cognitive dissonance", which occurs when a misconception cannot logically explain new theory, information, or data, nor can it predict phenomena in a reliable way[17]. These general strategies have been implemented in specific ways in classroom inquiry activities that include: pair discussions[18]; writing activities and group collaboration[19]; laboratory experiments, group work and vee diagrams[20]; and computer-aided learning[21].

While some aspects of conceptual knowledge about characteristics of materials at the atomic-scale are developed in chemistry and physics courses, other important atomic-scale structural features of materials related to macroscale phenomena and properties are not presented. To understand the conceptual framework and associated mental models that explain and predict macroscale properties of materials, new content on atomic-scale structure is introduced in MSE classes. In one sense, the difficulty in developing a fundamental understanding of a material's behavior is an issue of scale. This is because a material's properties are often counterintuitive since they are observed and measured at the macroscale, but can only be explained at the atomic and microscale level. This length scale difference is five to ten orders of magnitude smaller than the scale at which we view properties and phenomena in our lives. As such, informal, "commonsense" mental models[22, 23] are developed in the mind of a "novice learner" which can be scientifically flawed and need to be revised or replaced by mental models aligned with the scientifically-accepted concepts of *consensus models*.

In MSE courses major atomic and microscale features of materials are incorporated in mental models as a basis for conceptual understanding of macroscale properties and include atomic bonding, crystal structure (or amorphous lack of structure), defects (both static and dynamic-diffusion), and microstructure (including grains, grain boundaries, grain size, shape, orientation and distribution and also phase size, shape, orientation, and distribution). Atomic-scale features are significantly affected by material composition and processing treatment (thermal, mechanical, electrical, magnetic, etc.) and are used to design and engineer materials to achieve desired properties and performance for given applications. The atomic and microscale features described above strongly affect a material's mechanical properties and need to be incorporated into an individual's mental models and conceptual framework of MSE in order to predict relationships between atomic-scale structure and macroscale properties. For other functional properties, such as electrical, thermal, and optical properties, a material's electronic band structure must also be incorporated into an individual's conceptual framework to explain and predict macroscale properties. Examples will now be presented of faulty mental models and misconceptions that cause incorrect atomic-scale structure / macroscale property relationships.

There are many types of macroscale-property / atomic-scale-structure misconceptions that exist. One is misattribution of macroscopic properties to atomic scale features. For example, copper metal is not malleable because "individual copper atoms are malleable"[2]. Another example related to thermal processing is in explaining why taking a hard, strong copper wire from a hardware store and holding at 600°C for 15 makes the copper a softer, weaker material. Although the answer is reduction of dislocation density and recrystallization, a few of the misconceptions proposed by students include; "atomic bonds are weakened" or "atomic bonds are stretched"[23]. Another set of misconceptions about phases of materials was revealed from the question, "In what phases can nickel exist?" Responses included: “I have never heard of Ni gas”, “I have never seen Ni gas”, and “I have only seen Ni as a solid”[23]. The faulty mental models that gave rise to these and other misconceptions originated from various sources individuals use to create "commonsense", novice-learner models that can neither explain nor predict macroscale materials behavior. Some sources include; personal observation, television, textbooks, internet, teachers, and prior classes[4]. To modify a person's conceptual framework of macroscale-property/ atomic-scale-structure relationships, faulty *mental models* must be revised or replaced by conceptual change to a scientifically-accepted model.

How Well Do Engineering Students Learn Materials Science and Engineering?

It was found that students from various disciplines taking introductory MSE courses had typical pre-post conceptual gains for a MCI test[24, 25] of that was typically limited to 7-15% when content is delivered by lecture-based courses. Responses on MCI questions indicated misconceptions were pervasive[25, 26], and often related to students' application of inappropriate analogies of macroscale phenomena of everyday life to explain properties of materials really controlled by its atomic-scale structure. In contrast, Hake's[27] survey of 6000 students in physics courses showed that, using an effective teaching strategy, such as "student engagement", can lead to conceptual gains of 40% or more as measured by the Force Concept Inventory[28]. This requires mental model modification for conceptual change that promotes a reconstruction of students' flawed conceptual frameworks and can be achieved with effective learning using strategies that can employ a variety of techniques and methods. To succeed in achieving effective learning, faculty in MSE and other engineering disciplines need to understand *how their students learn* in order to develop effective teaching strategies for improving student knowledge, skills, and motivation. To accomplish this, it is first necessary to characterize students' prior knowledge and misconceptions, and the nature of mental models that comprise their conceptual frameworks. One way is with pre-post tests with the MCI[7] which has been used at Arizona State and at some other institutions[24, 29] with Douglas[30] demonstrating that the MCI is a valid instrument but needed improved reliability. Such assessment can be used to determine what pedagogies most effectively promote conceptual change.

Procedures, Results and Discussion

Different pedagogies were used to teach the introductory materials classes in MSE in three different semesters during the fall terms of 2002, 2003, and 2007. The introductory materials engineering courses were taught by the authors in those years, but since department faculty are rotated in and out of the six sections per year, an interval occurred between 2003 and 2007. Also, modified curricula for all disciplines in the Fulton school of Engineering were first implemented in the fall 2006 term. In 2002 the course content was delivered using classroom lectures alone. In 2003 student-pair based classroom discussions supplemented lectures. In 2007 team-based discussions and, occasionally, concept sketching[31-34] was used to supplement lectures. In the 2007 course concept sketching was used for the topic of metal deformation but not for the topic of annealing of work hardened material. On the MCI there was one question that reflected each of the two topics. The questions and results for each of the two topics are presented below

There are many types of macroscale-property/atomic-scale-structure material misconceptions that exist. One is the inappropriate attribution of a macroscale property to an atomic-scale feature. For example if a softer, lower strength, annealed metal is cold worked by die drawing, extrusion or cold rolling, dislocation multiplication and pinning occurs which will increase strength. The reasons are not related to the misconceptions suggested by students, such as densification, bond compression, or bond strengthening. This type of question, as well as the pre-post scores for such a question from the MCI, are shown below.

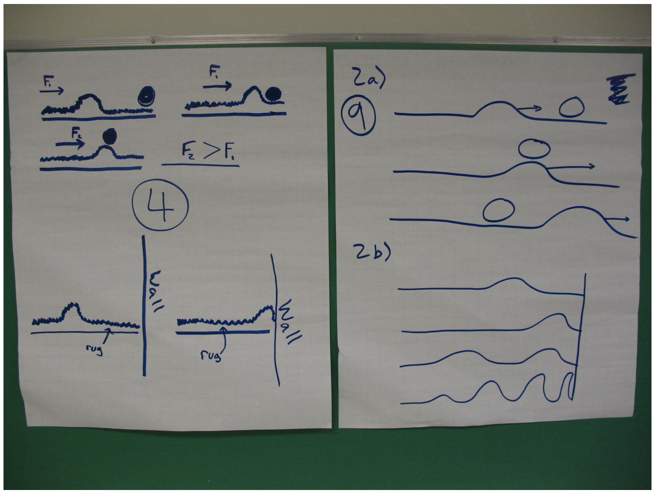
If a rod of metal is pulled through a tapered hole smaller than the diameter of the rod, the strength of the metal in the rod increases. This is because:_______

a) the density has increased
b) there are more atomic level defects present
c) there are less atomic level defects present
d) the bonds have been strengthened
e) the bonds have been compressed

	Pretest	Posttest	Gain
Fall 2002, n = 51	8%	18%	11%
Fall 2003, n = 48	4%	58%	56%
Fall 2007, n = 32	20%	81%	76%

For the years 2002, 2003, and 2007, gains for the MCI deformation question were 11%, 56%, and 76%. Student and team based discussions significantly increased gains for this question from 11% to 56% comparing 2002 to 2003 and from 11% to 76% comparing 2002 to 2007. The pretest score in 2007 was moderately higher than 2002 or 2003 (20% versus 8% and 4%, respectively), which could be due to broad curriculum revisions for all disciplinary programs that was implemented in fall 2006.

The results are quite reasonable in comparison with findings about the Force Concept Inventory where traditional, lecture-based teaching produced gains around 20% (low range) whereas interactive engagement (IE) produced gains of 30% - 60% (medium range)[27,35]. Thus, for fall 2002 with lecture-based teaching, the gain was in the low range of 11% which is even slightly lower than the FCI traditional teaching value of 20%[27]. When teaching with pair-discussions in fall 2003 the gain increased to 56% which is in the middle range and is in agreement with FCI gains with various IE methods with gains of 30%-60%[27]. However, the greatest gain of 76% was found for 2007 when concept sketching was used which would fall in the high gain range (>60%). In the concept sketching activity the teams of 3-4 students used large sheets of sticky-back poster paper to discuss and then sketch an image of their interpretation of the "ripple-in-the rug" model of edge dislocation motion. Using that model they were requested to sketch a dislocation pile up at a grain boundary and also a dislocation interacting within a single grain of metal. Examples of the sketches are shown in figures 1a and 1b below. In the team based environment students' mental models were corrected through negotiation during discussion and then sketched, or expressed, as the manifestation of the mental model that was common to all team members. This engagement and concept discussion effectively displaced student misconceptions resulting in 76% of the students selecting the correct choice on the exit MCI question.



Figures 1a and 1b. Two student teams' conceptual sketches of the "ripple in the rug" model of a dislocation showing the effect of a precipitate and a grain boundary impeding dislocation motion.

Another set of macroscale-property/atomic-scale-structure material misconceptions was shown for the situation in which a cold worked metal was annealed at an elevated temperature for a moderate time. For example, when a hard, strong piece of heavy gauge copper wire from a hardware store is held at 600°C for 15 minutes and cooled it becomes softer and weaker. It is not due to the misconceptions suggested by students, such as bond weakening, density lowering or, increased space in the crystal lattice. Rather it is annealing out of dislocations and recrystallization of the deformed copper grains. The original question, as well as the pre-post scores for such a question from the MCI, are shown below.

After a piece of copper wire from a hardware store is heated it becomes softer because:_______

a) the bonds have been weakened
b) it has fewer atomic level defects
c) it has more atomic level defects
d) the density is lower
e) there is more space inside the crystal lattice

	Pretest	Posttest	Gain
Fall 2002, n = 51	2%	16%	14%
Fall 2003, n = 48	4%	53%	51%
Fall 2007, n = 32	0%	48%	48%

For the three years 2002, 2003, and 2007, the gains for the MCI annealing question were 14%, 51%, 48%. It can be seen that student and team based discussion significantly increased gains for annealing question, but there was little difference between the scores for the 2003 and the 2007. This result was unlike the highest score found for the deformation question in 2007 course, which was attributed to the concept sketching activity. Thus, it appears that the lack of including a concept sketching activity for the mechanism of annealing a cold worked metal inhibited further conceptual gain on dislocation related phenomena. Although student and team based discussions improved conceptual knowledge gain over lecture based learning, the lack of students having an opportunity to clarify their mental model of annealing may have prevented further understanding of the annealing mechanism that softened the metal.

For the years 2002, 2003, and 2007, gains for the MCI annealing question were 11%, 56%, and 76%. Student and team based discussions significantly increased gains for this question from 16% to 51% and 48% in comparing 2002 to 2003 and 2007, respectively. As with the deformation question, the results are quite reasonable in comparison with findings about the Force Concept Inventory as previously discussed[27, 35]. Thus, for fall 2002 with lecture-based teaching, the gain was in the low range of 16% which is similar to the FCI traditional teaching value of 20%[27]. When teaching with pair-discussions in fall 2003 and fall 2007 the gains increased to 53% and 48%, both values of which are in the middle range and in agreement with FCI gains with various IE methods with gains of 30%-60%[27]. However, unlike, the deformation question, which further increased the gain, concept sketching was not used with annealing and the gain was similar for 2003 and 2007 with gains of 51% and 48% respectively. This limited data indicates that discussion and concept sketching to express students' mental model may be more effective than pair discussion or team discussion alone.

Final Discussion and Conclusions

It is seen for these limited results, that student conceptual understanding of macroscale properties / atomic and microscale structure in the key topical area for metals of dislocation-related phenomena and properties that, traditional, lecture-based teaching results in a low gain of student conceptual understanding as assessed by a deformation and an annealing question on the MCI. When students are taught with interactive engagement, in this case with pair discussions, conceptual gain about dislocation related phenomena increases significantly to a medium conceptual gain for both deformation and annealing questions on the MCI. However, when concept sketching was used to supplement pair discussions in student engagement a high gain was found for the MCI deformation question, whereas the MCI annealing question still showed a medium gain when concept sketching was not used. Thus, concept sketching as another method for engaging students appears to enhance student learning even more than pair discussions. Negotiated team-based discussion and mental model expression through concept sketching hold good potential for improving pedagogy in introductory materials engineering courses. These results indicate that concept sketching may facilitate repair of students' conceptual frameworks through the displacement of robust misconceptions. Students initially invoke concepts related to atomic bonding as the basis to interpret property changes of metals in deformation or annealing. However, after using interactive engagement teaching about dislocations and associated phenomena and properties in deformation and annealing, a significant fraction invoke the correct concept to explain the property changes. There is a shift in conceptual understanding from atomic bonding related changes to dislocation based property change as a result of processing by deformation or annealing. It would certainly be useful to characterize students' initial understanding through concept sketching and then later compare the results of concept sketching after covering dislocation related topics. Understanding students' misconceptions in materials engineering courses is in the early stages, but concept sketching may prove to be a useful tool for both revealing misconceptions as well as supplementing pedagogy to displace robust misconceptions.

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Bibliography

1. Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models in science education, in Gilbert, J. K., & Boulter, C. J. (Eds.), *Developing models in science education*. Dordrecht, Netherlands, Kluwer Academic Publishers.
2. Ben-Zvi, R., Eylon, B., & Silverstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education*, *63*, 64–66.

3. Donovan, M. S., Bransford, J. D. & Pellegrino, J. W. (Eds.) (1999). *How People Learn: Bridging research and Practice.* National Academy Press, Washington, DC.
4. Kikas, E. (2004). Teachers' conceptions and misconceptions concerning natural phenomena. *Journal of Research in Science Teaching, 41(5)* 432-448.
5. Krause, S., Decker, J., Niska, J., & Alford, T. (2002). A Materials Concept Inventory for introductory materials engineering courses, *National Educators Workshop Update 2002*, 17, 1-8.
6. Krause, S., Decker, J. C., & Griffin, R. (2003). Using a Materials Concept Inventory to assess conceptual gain in introductory materials engineering courses. *2003 Frontiers in Education Conference Proceedings,* Savannah, GA.
7. Vygotsky, L. (1962) *Thought and Language,* T. E. Hanfmann & G. Vaka (Eds.), Cambridge, MA: MIT Press.
8. Von Glaserfield, E. (1987). *The Construction of Knowledge: Contributions of Conceptual Semantics* (Seaside, CA: Intersystems Publications, Inc.).
9. Norman, D. (1983) Some observations on mental models. In *Mental Models,* D. Gentner and A. Stevens (Eds.), Hillsdale, NJ, Erlbaum.
10. Gilbert, J. (1995) The role of models and modeling in some narratives in science learning. *1995 Annual Meeting of the American Educational Research Association*, San Francisco, CA.
11. Niaz, M. (2005). How to facilitate students' conceptual understanding of chemistry? – A historical and philosophy of science perspective. *Chemical Education International, 6(1),* 1-5.
12. Vosniadou, S. and Brewer, W. F. (1992) Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*, 535-585.
13. Dykstra, D. I., Boyle, C. F., & Monarch, I. A. (1992). Studying conceptual change in learning physics. *Science Education*, *76(6)*, 615-652.
14. Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*(2), 211-227.
15. Hewson, P. W. (1996). Teaching for conceptual change. In *Improving teaching and learning in science and mathematics*. D. F. Treagust, R. Duit, & B. J. Fraser (Eds.), New York, NY: Teachers College Press, Columbia University.
16. Lakoff, G. (1993). The contemporary theory of metaphor. *Metaphor and thought* 2nd ed., In A. Ortony (Ed.), New York, NY, Cambridge University Press.
17. Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science education. *Review of Educational Res.*, *63*, 1–49.
18. Kobayashi, Y. (1994). Conceptual acquisition and change through social interaction. *Human Development*, *37*, 233-241.
19. Fellows, N. (1994). A window into thinking: using student writing to understand conceptual change in science learning. *Journal of Research in Science Teaching*, *31*, 985-1001.
20. Ebenezer, J. V., & Gaskell, P. J. (1995). Relational conceptual change in solution chemistry. *Science Education*, *79*, 1-17.
21. Biemans, H. J. A., & Simons, P. R.-J. (1995). Computer-assisted instruction and conceptual change. *1995 Annual Meeting of the American Educational Research Assoc.*, San Francisco, CA.
21. Nieswandt, M. (2001). Problems and possibilities for learning in an introductory chemistry course from the perspective of conceptual change. *Science Education*, *85,*158-179.
22. Talanquer, V. (2006). Commonsense chemistry: a model for understanding students' alternative conceptions. *Journal of Chemical Education, 83(5)* 811-816.
23. Krause, S. Tasooji, A., & Griffin, R. (2004). Origins of misconceptions in a Materials Concept Inventory from student focus groups. *2004 ASEE Annual Conference and Exposition Proceedings,* Salt Lake City, UT.

24. Jordan, W., Cardenas, H, and O' Neal, C. B. (2005). Using a Materials Concept Inventory to Assess an Introductory Materials Class: Potential and Problems. *2005 ASEE Annual Conference and Exposition Proceedings,* Portland, OR.

25. Krause, S., Decker, J., Niska, J., & Alford, T., & Griffin, R. (2003). Identifying student misconceptions in introductory materials engineering courses. *2003 ASEE Annual Conference Proceedings,* 732-740

26. Krause, S., and Tasooji, A., (2007). Diagnosing Students' Misconceptions on Solubility and Saturation for Understanding of Phase Diagrams, *2007 American Society for Engineering Education Annual Conference Proceedings,* Honolulu, HI.

27. Hake, R.R. (1998). Interactive-engagement versus traditional methods: A six-thousand survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66(1)*, 64-74.

28. Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, *30(3)*, 141-151.

29. Gleixner, S. H., Douglas, E., & Graeve, O. (2006) Project-based introductory to materials engineering modules on biomaterials, solid oxide fuel cells, non-volatile memory, and fiber reinforced plastics. *2006 ASEE Annual Conference and Exposition Proceedings,* Chicago, IL.

30. Douglas, E. (2007) Effects of sex and ethnicity on performance on the Materials Concept Inventory. *2007 ASEE Annual Conference and Exposition Proceedings,* Honolulu, Hawaii. on CD.

31. Song, S., and Agogino, A.M., (2004) An analysis of designers' sketching activities in new product design teams, *Proceedings*, *2004 ASME Design Theory and Methodology Conference*, American Society of Mechanical Engineers, Salt Lake City, Utah.

32. Schutze, M., Sachse, P., and Romer, A., (2003) Support value of sketching in the design process. *Research in Engineering Design*, Vol. 14, 89–97.

33. Lowe, R., (1993). Constructing a mental representation from an abstract technical diagram. *Learning and Instruction*, v. 3, 157-179.

34. Johnson, Julia K. and Reynolds, Stephen J., (2005). Concept sketches – using student-and instructor-generated annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, v.52, 85-95.

35. Pearce H. T. & P. le Roux. 2000. "The Force Concept Inventory: its meaning for teaching physics," in *Proceedings of the 2nd Southern African Conference on Engineering Education*, Vanderbylpark, South Africa, 219-224.