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Incorporating Research Experiences into an Introductory Materials Science Course*

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This study investigated whether the inclusion of a student-centered research component in an introductory materials science course resulted in a larger knowledge gain relative to traditional pedagogies. The redesigned course was taught in five different sections, over three academic years, at one of the largest public university, namely Texas A&M. Gains in conceptual understanding were quantified by comparing pre- and post-course completion Materials Concept Inventory (MCI) scores. Pre- and post- Pittsburgh Engineering Attitudes Scale—Revised (PEAS-R) was used to measure the impact of redesign course on student attitudes towards engineering. Additionally, a post hoc survey was conducted to collect students' opinions on research experiences at the end of semester. Students in the redesigned class demonstrated higher knowledge gain on the MCI relative to traditional lectures, consistent with previous studies that examined the effect of in-class active learning pedagogies. The post hoc survey showed a positive response of the students' with regards to improvements in their critical thinking, quality of learning, oral, written, and communication skills.

Keywords: course-wide research project; Student active learning; Engineering education; Materials science and engineering

1. Introduction

1.1 Importance of materials science education

The role of materials as technology enablers has become increasingly prominent in recent years. In fact, of the fourteen Grand Challenges for Engineering posed by the National Academy of Engineering, at least half require the design and/or development of new materials [1–4]. Hence, introductory materials science courses are considered essential components of a typical engineering student's curriculum, independent of their engineering major. As an example, 11 of 17 different undergraduate engineering programs at Texas A&M University require students to take an introductory materials science course in order to meet their curriculum requirements. Unfortunately, materials science courses are considered difficult by many students [5] as they are usually perceived as consisting of a random collection of facts that lacks an evident organizing framework or scaffold. Introductory materials science courses thus mirror introductory physics courses [6], although in contrast to physics, the multidisciplinary nature of materials science makes it impossible to reduce the field to only a couple essential fundamental principles, beyond the very general connection between processing, structure, properties and performance [7]. Content-based approaches to teaching materials science make it difficult for students to organize concepts and ideas into cognitive structures that enable them to apply the content to real-word problems with a high level of expertise [8]. Moreover, the evolution of the field itself has resulted in a considerable expansion in course content [7], compounding the problem in students' perception of the degree of difficulty of the subject.

1.2 Pedagogical background

Many studies have suggested that learning can be enhanced when instructors incorporate student-centered, interactive approaches [9–12]. Moreover, such pedagogical strategies have the potential to positively affect the further development of the students well beyond their university years [13]. On the other hand, lecture-based approaches are less effective at achieving learning outcomes than teaching approaches that engage students actively [14–15]. Unfortunately, introductory STEM courses are still delivered in a traditional manner across many institutions in the US and elsewhere. This is problematic as failing to engage students in an interactive manner in their first years of undergraduate engineering education not only affects their academic achievement but can also affect their entire university experience, and can impact retention in STEM-related majors [16].

Considerable attention has thus been paid to evidence-based improvements in pedagogical approaches to engineering education, particularly those involving different degrees of active learning [17–18]. Over the past decade and a half, multiple

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student-active learning pedagogies have been deployed and evaluated [12, 18]. These approaches have been shown to improve conceptual understanding [19] and allow students to develop more diverse strategies to understand the concepts and integrate the acquired knowledge, especially in the case of cooperative learning [12, 20]. Regarding large enrollment courses—increasingly common—Beicher, Saul, Allain, Deardorff, and Abbott [10] have shown that active/cooperative approaches can help students attain higher levels of conceptual understanding and improved attitudes as well as higher success rates, particularly for underrepresented groups, relative to traditional approaches. Specific research on materials science courses has shown that active learning improves conceptual understanding in great part because this approach helps overcome prior and persistent misconceptions [16].

While there are many different approaches to active learning, in this paper we focus on inquiry (research)-based pedagogies, which have been shown to result in remarkable improvements in overall educational experience. Hunter, Laursen, and Seymour [21], have shown that undergraduate research experiences in which faculty and students work collaboratively contributed to significant gains related to the professional socialization into the sciences while Russell, Hancock, and McCullough [22] found that participation in undergraduate research resulted in increases in understanding, confidence, and awareness.

1.3 The present study

We have recently redesigned a subset of sections of introductory materials science course (MEEN 222) at Texas A&M University by including student-active pedagogies and cooperative learning theories. As an integral part of the core engineering curriculum, the instructive objective of this course is to enable students to identify the relationships between materials properties and their structures at the electronic, atomic, microscopic and macroscopic levels. At Texas A&M University, this course has been taught in a traditional way - like at many other universities - through lectures with minimal active student involvement. The redesign consists of undergraduate research projects proposed and implemented by student teams under the supervision of the instructors, and completed outside of lectures, which are still taught following traditional methods. Given the new approach, the key question is *whether the students in the redesigned class showed a greater improvement in their conceptual understanding in materials science than the students in the traditional lecture-only class.* In addition, we were also interested in the students' attitudinal change towards the field of engineering. For the purposes of this paper, the learning aspects of focus are conceptual understanding along with scientific reasoning. Conceptual understanding of the subject was assessed through the Materials Concept Inventory (MCI) [16] while the students' attitudes were assessed using the Pittsburgh Engineering Attitudes Scale—Revised (PEAS-R) [23].

1.4 Description of undergraduate research project

In the redesigned materials science classes, the research project was conducted on a team basis. All student teams were required to prepare a final product according to the timeline in Table 1.

1.5 Research questions

Our study attempted to address the following questions. First, did incorporation of a research project result in a deepened understanding of the basic concepts of this introductory materials science course? We operationalized this question by conducting the pre- and post-Materials Concept Inventory (MCI) in both redesigned and traditional lecture-based classes. [16]. Second, did the student-centered learning experience on research projects, motivate students and result in more positive attitudes towards their chosen field of study? We operationalized this question by conducting the pre- and post- Pittsburgh Engineering Attitudes Scale—Revised (PEAS-R) in a redesigned class section. Third, what were student perceptions regarding the incorporated research project? Did they enjoy their research experiences? Did they agree that the research experiences enhanced their critical thinking, quality of learning, oral, written, and communication skills? A *post hoc* survey was created to focus on students' perspectives of the benefit of undergraduate research experience.

2. Methodology

2.1 Participants

This study started in Fall 2010 and ran for three consecutive years. During the research period, a total of 408 undergraduate students registered in the introductory materials science class sections involved in this study. Among them, 298 students in the redesigned class and 51 students in the tradition lecture-only class consented to participate in the study and completed both pre- and post-MCI. Table 2 shows the distribution of the participants' years of undergraduate study and majors by the type of class (traditional vs. redesigned). Overall, both classes showed similar distributions in the years of undergraduate study. The majority of the students were sophomores in both traditional

Table 1. Timeline and Descriptions of the Course-wide Research Project

Timeline	Major Activities	Details
First Class	**1. Making groups**	• The instructor randomly assigned 4–5 students into a group.
	2. Selecting an experimental demonstration	• Groups selected an experimental demonstration that illustrates relevant course content (e.g., characteristics of any material, material property, material process, or any concept) without instructor guideline. • The instructor suggested only possible sources from which the students could derive their ideas.
Week 1–2	**3. Submitting a research proposal**	• Each group was required to submit a two-page formal written research proposal that contained a rationale for the experiment and a description of the experimental procedure.
	4. Instructor's feedback	• The instructor evaluated each proposal to ensure that the scope of work was appropriate, met laboratory safety regulations, and could be addressed with laboratory resources to which students would have access. If necessary, a team might be asked to revise their proposal.
Week 3–13	**5. Group meeting & progress reports**	• Bi-weekly group meetings and progress reports were required to ensure continuous sustained effort on the project.
	6. Performing experimental work	• Students could use existing equipment in dedicated teaching laboratories or in a laboratory that was established specifically for the course as a part of this project.
	7. Instructor's guide for the research project	• During this process, the instructor provided logistical help in performing experiments and interpretation of results.
Week 14	**8. Oral presentation**	• Each group presented their experimental findings and were also encouraged to perform in-class demonstrations of their experiments.
	9. Written report	• A written report on the experiment was required to include the theoretical basis and brief description of linkages between the experiments and content taught in class.
	10. Evaluation	• Every oral presentation was evaluated by peers using concrete evaluation criteria as well as by the instructor and two invited professors. All contributed to the final project grade. • Each group member was graded individually, based on the evaluation of her/his overall contribution to the project by other group members.

(52.9%) and redesigned (52.5%) classes, and juniors followed closely (33.3% and 35.7%, respectively). The distribution of the majors varied slightly between the two groups while the rank-order was the same.

This course typically has had 4 to 5 sections taught by different lecturers. Students registered for the section of their choice independently. At the moment of their registration they were aware of the instructor's identity and class time but did not know whether the section was traditional or was redesigned. There was no control for the possibility that students could have gotten information about specific teaching styles of the section's instructor by communicating with students previously enrolled in the course.

Table 2. Participants' Information (%)

	Traditional	Redesigned
Years of Undergraduate Study		
Freshmen	2.0	1.4
Sophomore	52.9	52.5
Junior	33.3	35.7
Senior	11.8	10.4
Major		
Mechanical Engineering	49.0	56.3
Industrial Engineering	39.2	30.8
Others	11.8	12.9

2.2 Measurement Instruments

2.2.1 Materials Concept Inventory (MCI)

The Materials Concept Inventory (MCI) was developed to test misconceptions about materials structure, processing, and properties [24]. The MCI was modeled after the *Force Concept Inventory* by Hestenes, Wells, and Swackhamer [25]. The MCI consists of thirty multiple-choice questions which are scored correct or incorrect. These questions focused on six conceptual areas: (1) how microstructure affects properties of ductile and brittle materials; (2) how structure and properties of material change due to defects associated with permanent deformation; (3) how bonding electronic structure affects electronic, thermal, and optical properties; (4) what geometry features are related to atomic arrangements; (5) how bond type and strength affects properties of metals, polymers, and ceramics; and (6) how macroscopic rule-of-mixtures cannot be used to predict atomic-structure-based properties.

The MCI has been found to be able to detect "prior misconceptions", and "spontaneous misconceptions", and has been used to measure the conceptual knowledge gain in introductory materials science courses [16, 24]. The MCI developer administered it to a limited number of classes ranging in size from 16 to 90 students in 2002 at Arizona State University and Texas A&M University. The results revealed that most traditional lecture-based class showed conceptual knowledge gains between 15–20%, while an active learning section showed higher percentage of knowledge gain up to 38% [16, 24].

The psychometrics of the MCI test was analyzed with a sample of 303 undergraduate engineering students who enrolled in a materials engineering course [26]. Results showed that MCI had adequate reliability (Cronbach's $\alpha = 0.75$) and strong discriminatory power (Ferguson's $\delta = 0.96$). Post-MCI scores were significantly correlated with the final grade ($r = 0.50$, $p < 0.001$). Despite its many positive qualities, the MCI is not a perfect test to measure teaching effectiveness. Many scholars, including the MCI developers, have reported potential issues and encouraged further refinement [16, 26–27]. However, the MCI is still, to the best of the present authors' knowledge, the only instrument directly designed for measuring teaching effectiveness in materials science courses, and allows for comparison with previous investigations of teaching effectiveness.

2.2.2 Pittsburgh Engineering Attitudes Scale—Revised (PEAS-R)

The Pittsburgh Engineering Attitudes Scale—Revised (PEAS-R) was derived from the original version of the scale created at University of Pittsburgh [28]. PEAS-R has 28 items, and which assess seven different domains of attitude: (1) general impressions, (2) financial influences, (3) societal contributions, (4) social prestige, (5) enjoyment of math and science, (6) engineering as exact science, and (7) parental pressure [29]. The psychometric properties of the PEAS-R were found to be sound in terms of internal consistency reliability and structural validity with 980 engineering students [29]. The Crobach's alpha reliability coefficients of the seven domains ranged from 0.70 to 0.90. The factor structure of the seven domains under the 28 questions was supported by the results of confirmatory factor analysis [29]. We administered the PEAS-R before and after the teaching the introductory materials science course for one redesigned class section in the later year of this study

2.2.3 The locally constructed research survey

To measure the student's attitude towards the course-wide research project, we constructed an online *post hoc* Research Survey, which included 13 questions. We revised the research survey once to better satisfy our research purpose. In the first version, the first nine questions were five-likert rating scales (1 = strongly disagree; 5 = strongly agree), directly asking if students agree on statements like "research project helped me discover and develop significant connections among my program (major) core subjects" and the last 4 questions were open essay questions. Based on the student's first and second year's responses, three of the four essay questions were then changed to multiple-choice questions in the following year. This change facilitated the quantification of students' opinion. This survey was focused on whether or not the students agree that research project helps them to improve their ability in any aspects, or what specific aspects of improvement students agree that they had gained from research projects.

3. Results

3.1 Typical projects

In three years, more than 40 student-led projects were completed. Each project contributed to 10% to 15% of the final grade across semesters and sections. Different topics were covered by those projects, ranging from physical materials phenomena, through processing and application of different materials, to solving concrete technical problems. Students reported their research results and conclusions in research reports and presented them in the class. As examples, we provide two selected, but typical project presentations in Appendices A and B.

3.2 Improvement in conceptual knowledge gain

3.2.1 Comparisons between the traditional and redesigned classes

Table 3 shows the mean, M, and standard deviation, SD, of pre- and post-MCI scores of the redesigned and traditional classes, as well as the score increase, $\Delta M = (M_{post} - M_{pre})$, and conceptual gain, defined as $g = (M_{post} - M_{pre})/(30 - M_{pre})$, where 30 is the total number of questions on the MCI [19]. These data are compared against a control section with the traditional lecture-only method. The students in the redesigned class scored lower on the pre-MCI ($M = 11.4$; $SD = 3.3$) than those who enrolled in the traditional class ($M = 12.3$; $SD = 3.7$). However, the student in the redesigned class achieved higher post-MCI scores ($M = 14.6$; $SD = 4.0$) than those in the traditional class ($M = 13.6$; $SD = 4.0$). Thus, the average gain of MCI score is

Table 3. Descriptive Statistics of the Pre- and Post-MCI Scores

	Redesigned Class (N = 298)		**Traditional Class (N = 51)**	
	Pre-MCI	**Post-MCI**	**Pre-MCI**	**Post-MCI**
M	11.4	14.6	12.3	13.6
SD	3.3	4.0	3.7	4.0
ΔM		3.2		1.3
g		17.2%		7.5%

Note. M = mean score; SD = standard deviation; ΔM = raw score increase; g = conceptual gain.

greater in the redesigned sections (3.0 ± 0.9 within a 95% confidence interval) than in the traditional section (1.3 ± 0.9 within a 95% confidence interval). Furthermore, the average gain in redesigned section ($g_{redesigned}$ = 17.2%) also exceeds that of traditional lecture based section ($g_{control}$ = 7.5%).

We conducted a multiple regression analysis to formally test the difference in the post-MCI scores between the redesigned and traditional class while controlling for the pre-MCI scores. Overall, 33.3% of the variance of the post-MCI scores was explained by both the pre-MCI scores and type of classes (redesigned vs. traditional). Students who scored one point higher on the pre-MCI scored 0.68 higher on the post-MCI ($\beta = 0.57$, $t = 13.01$, $p = 0.000$). For students with the same pre-MCI scores, overall, the redesigned class group had 1.58 higher post-MCI scores than the traditional class group ($\beta = 0.14$, $t = 3.14$, $p = 0.002$).

Interestingly, the highest gains (g, ΔM) were found in B's Spring 2011 section in which a relatively small number of students (N = 39) enrolled in the class (Fig. 1). In contrast, among the redesigned sections, the lowest gains were found in the largest two redesigned class sections (N = 77, 102), potentially suggesting a class-size dependence on instructional effectiveness. However, while the class size of the traditional section was considered average (N = 51), both the percent gain, g, and the raw MCI score increase was lower than all of the redesigned sections.

The redesigned class had been taught in five sections by two instructors while the traditional class was taught by one instructor (Fig. 1). Instructor A taught three redesigned class sections while instructor B taught two redesigned sections. Instructor C taught the traditional section. Because the redesigned class and the traditional lecture-based class were taught by different lecturers, the results could reflect not only confounded effect of teaching methods, but also teacher differences. However, our observation data support that the lecturer of the traditional class did not have major traits that could significantly lower the teaching outcomes. The results support the hypothesis that students participating in course-wide research projects on average had higher concept knowledge gain and misconceptions than those attending traditional lecture class.

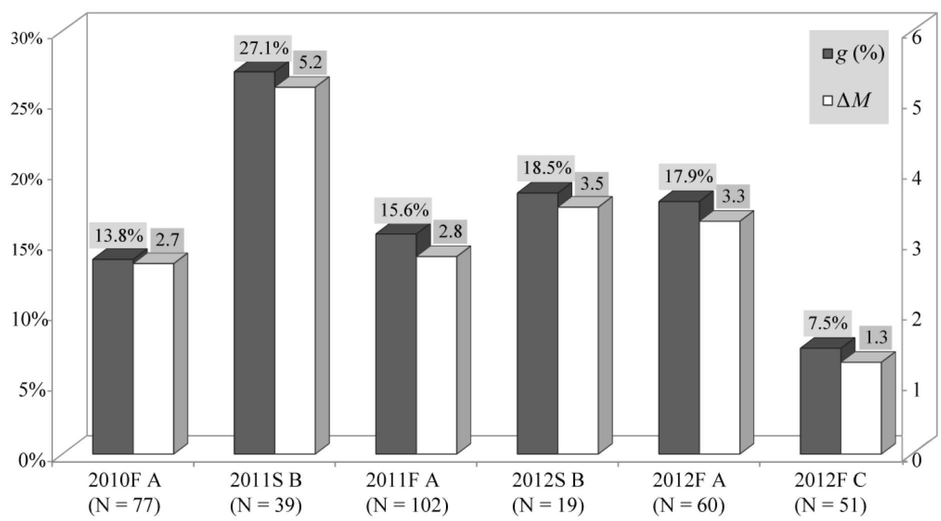

Fig. 1. Conceptual gain, g, and raw score increase, ΔM, across the redesigned class sections and in the traditional, control (2012F C) section. Instructor (A, B, C) and class size (N) are both indicated for each section.

3.2.2 Comparisons with previous studies on instructional effectiveness

Knowledge gain calculated from the MCI has been reported in previous engineering education literature in the context of understanding overall instructional effectiveness (Fig. 2). Comparing our data set against these previously reported data allows for inclusion of a broader baseline, and for a direct comparison between the approaches adopted in this study and other active learning instructional techniques. Despite these benefits, it is important to note that directly comparing results calculated from the MCI must be done cautiously, as the score on this test is sensitive to a number of factors, including curriculum content, which are likely to vary from institution to institution [27].

Krause, Decker, and Griffin found that students who took the traditional lecture-based material science classes typically showed g = 15% to 20%, while one particular active learning section had g = 38% [16]. However, detailed statistics are not provided for this data in the literature. While the average gain reported in the redesigned sections in this study lied within the 15% to 20% band of Krause, Decker, and Griffin [16], certain high-performing sections exceed this threshold (e.g., 2011S B, g = 27.1%). Furthermore, the lecture-based control in this study fell significantly below this threshold (g = 7.5%). This discrepancy may be partially explained by the strong alignment between curriculum content and MCI questions expected at the institutions where the MCI was originally developed.

In comparison, the redesigned sections reported in this study consistently outperformed traditional lecture-based instruction at Texas A&M and other institutions, as well as certain sections which incorporated active-teaching pedagogies. Jordan, Cardenas, and O'Neal [27] reported that 210 students in a traditionally taught section achieved only g = 10.3%. Yang [31] reported only g = 10.9% for a small section (N = 16) taught using a hybrid guided-inquiry/lecture-based instructional technique. In a larger study, compiling the results of sections taught using traditional lecture-based techniques or the process oriented guided inquiry learning (POGIL) technique in a variety of institutional settings, Douglas, Raymond, Waters, Hughes, Koro-Ljungberg, and Miller [31] reported (g = 16.4%, N = 226) for traditional lecture-based sections, and (g = 21.8%, N = 225) for POGIL-based sections. While Douglas, Raymond, Waters, Hughes, Koro-Ljungberg, and Miller [31] reported a moderately larger conceptual increase for POGIL-based sections ($g_{redesigned}$ = 21.8%) than that reported in this study ($g_{redesigned}$ = 17.2%), it is instructive to consider that the baseline measured in this study ($g_{control}$ = 7.5%) was significantly smaller than the baseline of the Douglas study ($g_{control}$ = 16.4%). Thus, the *increase* in instructional effectiveness demonstrated by incorporating a new instructional element ($\Delta g = g_{redesigned} - g_{control}$) was approximately a factor of 2 greater in this study (Δg = 9.7%) than in the Douglas study (g = 5.4%). In summary, comparison with previously reported literature results demonstrated that redesigned sec-

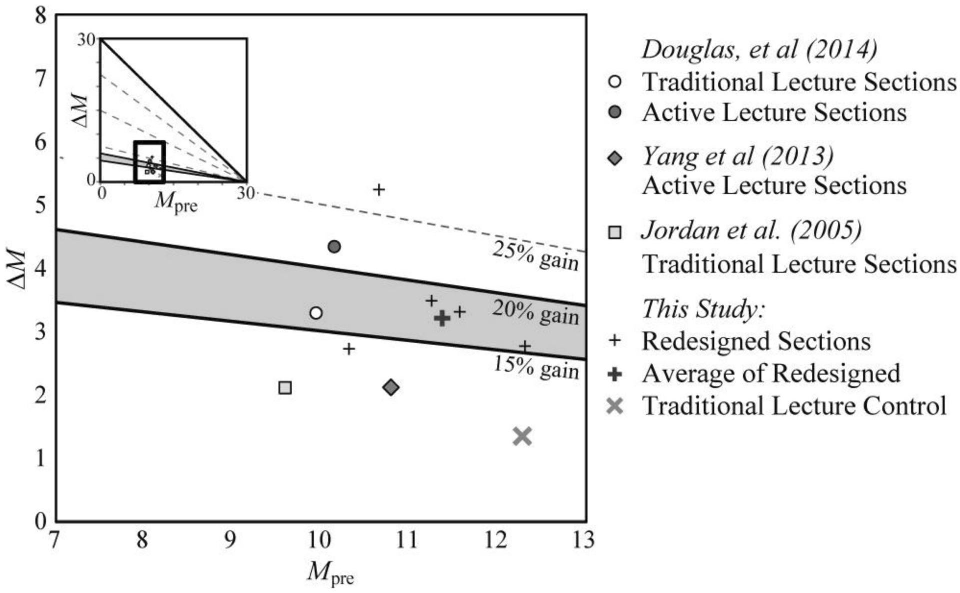

Fig. 2. Increase in score, ΔM, as a function of initial score, M_{pre} as reported in previous studies, and as determined in this study, following the approach of (Hake, 1998). Shaded region illustrates the typical 15% to 20% gain region, as reported by Krause, Decker, and Griffin (2003).

tions reported in this study consistently outperformed traditional lecture-based instruction at other institutions, and that the increase in instructional effectiveness by introducing this new pedagogical element was comparable to or greater than that offered by including other active-learning instructional elements.

3.3 Change of attitude and motivation

In the first two research years (i.e., 2010–2011 and 2011–2012 academic years) when PEAS-R was delivered as an optional test, leading to a low response rate (< 40%) and lack of statistically significant differences between the pre- and post-MCI scores on any of the seven subscales that could support a change of motivation and attitude towards Engineering. Subsequently, we incentivized student participation by providing bonus credit to students who completed both of the pre and post-PEAS-R in Fall 2012, leading to a 78% response rate. Table 4 shows the PEAS-R's seven subscales' reliability (Cronbach's α) on the pre- and post-PEAS-Rs. The subscales of "financial influences", "engineering as exact science", "societal contributions", "enjoyment of math and science" and "parental pressure" were relatively reliable (Cronbach's $\alpha \approx 0.8$ or > 0.8). High reliability scores supported our assumption that the questions under the same sub-construct were closely related. Because the reliability coefficients for subscales "general impression" of the post-PEAS-R and "social prestige" of the pre-PEAS-R were not significant enough (Cronbach's $\alpha < 0.6$), results derived from the two subscales were not considered reliable. Paired t-tests between pre- and post-PEAS-R scores on all seven subscales (Table 4) indicate that student's enjoyment of math and science was significantly decreased at the end of semester when compared to that at the beginning of semester ($p = 0.027$). We also observed a change of increased financial influences and decreased agreement of "engineering as exact science". However, such changes were not large enough to be detected by the paired t-test. The detected effect size of the Financial influences is Cohen's $d = 0.15$, and the detected effect size of Agreement of Engineering as Exact Science is Cohen's $d = 0.10$. A post hoc power analysis revealed that the actual powers for these two paired t-tests were too low to be detected (0.17 and 0.10, respectively).

3.4 Post hoc research survey

The first nine questions of the *post hoc* research survey were designed to collect student's general opinion on the embedded research project. Table 5 shows the cumulative percentage of agreement, neutral, and disagreement. The survey results show that over 70% of students admitted that they were willing to spent time outside of class on learning about materials sciences with other team members, and on seeking answers from other resources. Additionally, the majority of students agreed that research projects were helpful in discovering and developing connections among core subjects (60.4%), that research projects were able to enhance critical thinking abilities (64.2%), that research projects helped in improving oral and written communication skills (66.0%), and that research projects enhanced the quality of learning in this course (71.2%).

Questions 10 to 12 further collected the students' gains and losses from the research projects (See Table 6). One hundred percent of students agreed that they have some positive memories of the research project. These positive memories include gaining knowledge, research, team-work experience, and self-fulfillment. For all categories, the total percentages of agreements are all above 60%. On the contrary, with respect to the research projects, 70% of the student admitted that they have some negative memories, which include time consumption, difficulty around team coordination, and a sense of frustration. The most prevalent problem students encountered during research project participation was coordinating with other members (45.3% agreed); for all other options, the total

Table 4. Cronbach's α Coefficients and Paired t-test Results for the Seven Subscales of the PEAS-R

	Cronbach's α				**95% CI of ΔM**				
Subscales	**Pretest**	**Posttest**	ΔM	***SE***	**Lower**	**Upper**	***p*-value**	**Cohen's *d***	**Power**
General impression	0.80	0.57	–0.17	0.38	–0.93	0.59	0.65	0.06	0.11
Financial influences	0.88	0.79	0.26	0.32	–0.39	0.91	0.42	0.11	0.20
Engineering as exact science	0.81	0.80	–0.20	0.47	–1.14	0.74	0.67	0.10	0.15
Societal contributions	0.86	0.80	–0.18	0.23	–0.64	0.28	0.44	0.11	0.19
Social prestige	0.56	0.64	0.04	0.24	–0.43	0.51	0.87	0.02	0.07
Enjoyment of math and science	0.85	0.80	–0.92	0.34	–1.60	–0.24	0.01	0.39	0.85
Parental pressure	0.79	0.85	0.38	0.30	–0.22	–0.98	0.21	0.18	0.35

Note. ΔM = mean difference; SE = standard error; CI = confidence interval.

Table 5. Percentage of Agreement on Questions 1–9

Questions	Percentage (%)		
	Agree	Neutral	Disagree
Q1: Research project helped me discover and develop significant connections among my program (major) core subjects.	60.4	32.1	7.5
Q2: Research project helped me to enhance my critical thinking abilities and apply them in variety of context.	64.2	26.4	9.4
Q3: Research project helped me to improve my oral and written communication skills.	66.0	28.3	5.7
Q4: I spent time outside of class socializing with members of my research team.	69.8	20.8	9.4
Q5: I spent time outside of class learning about materials science with members of my research team.	73.6	15.1	11.3
Q6: I spent time outside of class seeking answers from reference books or through Internet searches.	81.1	13.2	5.7
Q7: The quality of my learning at MEEN222 was enhanced by team research project.	67.9	15.1	17.0
Q8: The quality of my learning at MEEN222 was enhanced by working with other students on team research project.	71.2	20.8	8.0
Q9: We had enough support from our professor and graduate assistants to conduct our research project.	83.0	13.2	3.8

percentage of student agreement was below 20%. The results reveal the fact that even though some students may have some negative associations with the research project, all students also reported experiencing positive memories associated with the project. We contend that gains afforded by the research project outstrip reported losses. Students admitted that they had gained research skills (54.7% agreed), academic writing and presenting skills (39.6% agreed), solidified knowledge of real world applications (47.2%) and obtained deeper and more concrete understanding on certain subject (37.7%

Table 6. Percentage of Agreement on Questions 10–12

Questions	Options	Percentage (%)
What positive memories, if any, do you have of your research project	Gained a more realistic view of topics discussed in class	60.4
	Gained a deeper understanding of some subjects	67.9
	Got first hand exposure to research and gained some problem solving	56.6
	Made friends with group members	79.3
	Gained experience to work with a group	81.1
	Gained a sense of achievement from hard working on a topic and finally get it done on time	60.4
	None	0.0
What negative memories, if any, do you have of your research project	Too much time spent on writing report and doing experiment	20.8
	Because of the pressure of project, I couldn't fully enjoy the Thanksgiving holiday	15.1
	Difficult to coordinate with all other group members	45.3
	Some group member didn't help as much as others but complained a lot	15.1
	Felt frustrating when already working hard but still couldn't finish	9.4
	Didn't like presenting in front of other students	13.2
	None	30.2
What influence, if any, did your research project have on your educational experience at MEEN 222 or elsewhere	Learned some research skills, like how to properly collect data, how to set up equipment, etc.	54.7
	Learned some basic skills on academic writing and presenting	39.6
	Gained a deeper and more concrete understanding on some subject	56.6
	Helped solidify knowledge of real world applications	47.2
	Made the learning of materials science more interesting and consequently more enjoyable	37.7
	Gained some communication, cooperation and organization skills	60.4
	Minimal	15.1

agreed). In addition, their ability to communicate, cooperate and organize had improved during the research project (60.4%).

4. Discussion

4.1 Summary of findings

Compared with traditional lecture-based classes, we found that inclusion of student research experience resulted in higher conceptual knowledge gain, as measured by the MCI. The results from the multiple regression analysis indicated that the redesigned class sections showed consistently higher post-MCI scores than the traditional section within this study. Furthermore, the redesigned class demonstrated greater knowledge gain on the MCI than most of the traditional classes that published in the engineering education literature. Knowledge gain was comparable to, or by some measures, exceeded gains demonstrated by incorporating active in-class pedagogies. It is worth pointing out that the cooperative effects of combining student research experiences with active in-class pedagogies has not yet been quantified and could be an interested focus for future study.

Seventy-eight percent completeness of the pre- and post-PEAS-Rs in Fall 2012 facilitated the analysis of changing of attitude towards engineering. The participants actually showed an increasing trend of negative emotion on engineering: their enjoyment of math and science decreased significantly at the ending of class, and they were slightly more motivated by the potential higher income after graduation other than inner preference. This increase of negative emotion was inconsistent with the *post hoc* research survey, in which, students highly appraised the research project, admitting that research projects enriched their scientific research experiences and improved their abilities in multiple aspects. One potential reason for this inconsistency is that the interest aroused during the research project was immersed in the negative influence of intensive course load for engineering students. We also believe that classroom fatigue is especially prevalent towards the end of the semester, and may have affected student attitudes on the survey.

The locally-constructed research survey directly collects students' opinion on the research projects. Most students held positive views for their course-wide scientific research experience. They agreed that the research project could enhance their (1) critical thinking, (2) quality of learning, and (3) oral, written, and communication skills. Compared with the traditional lecture-based teaching, students indicated that they could gain more realistic views of course content in our redesigned class. We infer that the research experience was effective because it played a ''mediator'' role, helping the students assemble scattered knowledge into a coherent picture. Although introduction of the research project may introduce some negative student perceptions (such as time consumption, cooperation problems, emotional frustration, etc.), these drawbacks are potentially outweighed by multiple positive gains due to the research experience. Fig. 3 shows comparisons of students' opinion on seven pairs of gain and loss: all students agreed that they had some gains among the six gain options. For each option, the percentages of agreement were all over 50%. In contrast, nearly 30% of students believed that they had no loss at all during the research project participation. For most loss options, the percentage

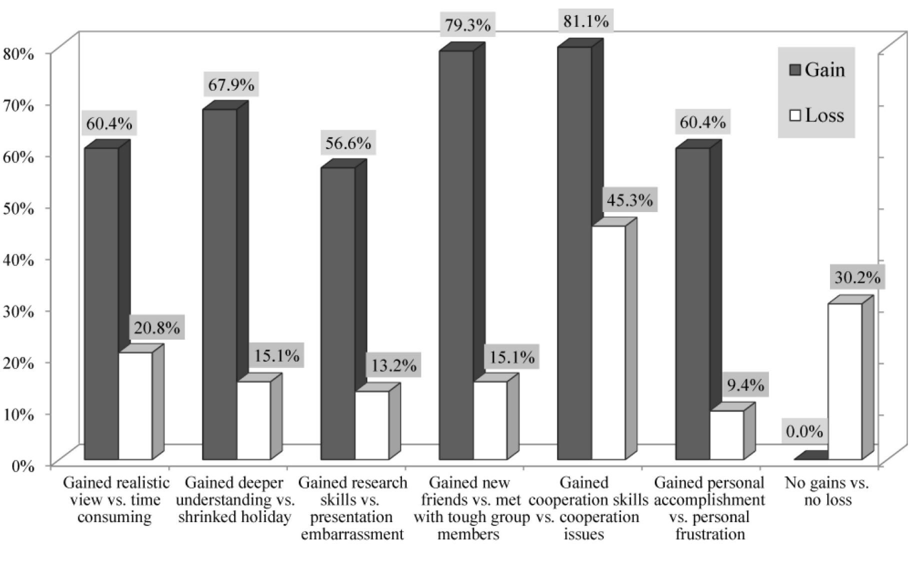

Fig. 3. Student's opinion on the gain and loss of research project.

of agreements was below 20%. Thus, we conclude that incorporating a course-wide research experience in an introductory materials science course engaged students with minimal negative impact. It is our belief that animating the subject matter led to greater student enthusiasm, which improved course-learning outcomes.

4.2 Limitations

The present research was conducted in a real classroom environment while the measurements were embedded within regular teaching activities. Hence, confounding factors could not be excluded completely. These include following major limitations: (1) it was not possible to randomly assign students to experimental and control sections to control for variable class composition, and to balance class size, and (2) it was not possible to quantify externalities effecting course instructors (teaching load, various other research or administrative demands). Despite these shortcomings, the results are important in light of this study's unique contributions to the cumulative knowledge of materials science education.

While the MCI is the only existing instrument used to measure knowledge gain in introductory materials science courses, and has been utilized a number of times in the education literature, questions remain concerning the validity of this instrument. Specifically, a large-scale study of the validity of the instrument does not yet exist. We believe that our research can contribute an important data set towards the completion of such a validation study.

5. Conclusions

This study investigated the impact of the course-wide research experience on students' conceptual knowledge gain, attitudinal change toward the engineering major, and students' evaluation on the course-wide research experience in an introductory materials science class. Students in the redesigned class generally showed greater improvement in their conceptual knowledge in materials science than those in the traditional lecture-only class; these findings were consistent with improvements in knowledge gain reported in other classes that incorporated different in-class active learning pedagogies. Students also received the research experience favorably, and reported numerous positive effects of the course-wide research design on their learning. As a concluding remark, we recommend incorporation of the course-wide research project into a curriculum of an introductory materials science class to promote students' deeper understanding of the topics discussed in the class as well as to allow them to develop collaborative (or cooperative) skills.

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References

1. W. Perry, A. Broers, F. El-Baz, W. Harris, B. Healy and W. D. Hillis, Grand challenges for engineering, *National Academy of Engineering*, Washington, DC, 2008.
2. A. Goetzberger, C. Hebling and H. W. Schock, Photovoltaic materials, history, status and outlook, *Materials Science and Engineering: R: Reports*, **40**, 2003, pp. 1–46.
3. S. J. Zinkle and N. M. Ghoniem, Operating temperature windows for fusion reactor structural materials, *Fusion Engineering and Design*, **51**, 2000, pp. 55–71.
4. M. Goldberg, R. Langer and X. Jia, Nanostructured materials for applications in drug delivery and tissue engineering, *Journal of Biomaterials Science, Polymer Edition*, **18**, 2007, pp. 241–268.
5. C. Demetry, Understanding interactions between instructional design, student learning styles, and student motivation and achievement in an introductory materials science course, *Frontiers in Education Conference*, Boston, MA, 2002, pp. S1H-8.
6. E. F. Redish, J. M. Saul and R. N. Steinberg, Student expectations in introductory physics, *American Journal of Physics*, **66**, 1998, pp. 212–224.
7. P. Yang and J. M. Tarascon, Towards systems materials engineering, *Nature Materials*, **11**, 2012, pp. 560–563.
8. M. Radovic, R. Arroyave and J. E. Froyd, Classroom-wide Student-led Undergraduate Research Experience for the Introductory Materials Science Course, *ASEE Gulf-Southwest Annual Conference*, Baylor, TX, 2009.
9. K. Kim, P. Sharma, S. M. Land and K. P. Furlong, Effects of active learning on enhancing student critical thinking in an undergraduate general science course, *Innovative Higher Education*, **38**, 2013, pp. 223–235.
10. R. J. Beichner, J. M. Saul, R. J. Allain, D. L. Deardorff and D. S. Abbott, Introduction to SCALE-UP: Student-centered activities for large enrollment university physics, *The 2000 Annual Meeting of the American Society for Engineering Education*, St. Louis, Missouri, 2000.
11. S. Freeman, S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt and M. P. Wenderoth, Active learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences of the United States of America*, 2014, pp. 8410–8415.
12. M. Prince, M. Does active learning work? A review of the research, *Journal of Engineering Education*, **93**, 2004, pp. 223–231.
13. S. M. Lord, M. J. Prince, C. R. Stefanou, J. D. Stolk and J. C. Chen, The effect of different active learning environments on student outcomes related to lifelong learning, *International Journal of Engineering Education*, **28**, 2012, pp. 606–620.

14. D. Fowler, D. Maxwell and J. Froyd, Learning strategy growth not what expected after two years through engineering curriculum, *ASEE Annual Conference and Exposition*, Nashville, Tenessee, 2003.
15. D. R. Woods, A. N. Hrymak, R. R. Marshall, P. E., Wood, C. M. Crowe, T. Hoffman, J. D. Wright, P. A. Taylor, K. A. Woodhouse and C. G. Bouchard, Developing problem solving skills: The McMaster problem solving program, *Journal of Engineering Education*, **86**, 1997, pp. 75–91.
16. S. Krause, J. C. Decker and R. Griffin, Using a materials concept inventory to assess conceptual gain in introductory materials engineering courses, *Frontiers in Education Conference*, Boulder, CO, 2003, pp. T3D-7.
17. R. M. Felder, D. R. Woods, J. E. Stice and A. Rugarcia, The future of engineering education II. Teaching methods that work, *Chemical Engineering Education*, **34**, 2000, pp. 26–39.
18. W. Hall, S. Palmer and M. Bennett, A longitudinal evaluation of a project-based learning initiative in an engineering undergraduate programme, *European Journal of Engineering Education*, **37**, 2012, pp. 155–165.
19. R. R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, *American journal of Physics*, **66**, 1998, pp. 64–74.
20. C. Baillie and S. Toohey, The 'power test': its impact on student learning in a materials science course for engineering students, *Assessment & Evaluation in Higher Education*, **22**, 1997, pp. 33–48.
21. A. B. Hunter, S. L. Laursen and E. Seymour, Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development, *Science Education*, **91**, 2007, pp. 36–74.
22. S. H. Russell, M. P. Hancock and J. McCullough, Benefits of undergraduate research experiences, *Science*, Washington, DC, **316**(5824), 2007, pp. 548–549.
23. J. Hilpert, G. Stump, J. Husman, W. Kim, W.T., Chung and J. Lee, Steps toward a sound measure of engineering student attitudes: Pittsburgh engineering attitudes scale-revised, *Frontiers in Education Conference*, San Antonio, TX, 2009, pp. 1–6.
24. S. Krause, J. C. Decker, J. Niska, T. Alford and R. Griffin, Identifying student misconceptions in introductory materials engineering classes, *ASEE Annual Conference*, Nashville TN, 2003.
25. D. Hestenes, M. Wells and G. Swackhamer, G. Force concept inventory, *The Physics Teacher*, **30**, 1992, pp. 141–158.
26. J. Corkins, The Psychometric Refinement of the Materials Concept Inventory (MCI), *Ph.D Dissertation*, Arizona State University, 2009.
27. W. Jordan, H. Cardenas and C. B. O'Neal, Using a materials concept inventory to assess an introductory materials class: Potential and problems. *Proceedings of the ASEE Annual Conference and Exposition*, Portland, OR, 2005.
28. J. C. Hilpert, G. Stump and J. Husman, A brief manual for the use of the Pittsburgh engineering attitudes scale-revised, 2010.
29. J. C. Hilpert, G. Stump and J. Husman, Pittsburgh engineering attitudes scale—Revised: Evidence for an improved instrument, *Frontiers in Education Conference*, Washington, DC, 2010.
30. E. Yang, A hybrid approach to teaching materials science using POGIL and active learning activities. *The 120th ASEE Annual Conference and Exposition*, Atlanta, GA, 2013.
31. E. P. Douglas, T. M. Raymond, C. K. Waters, W. L. Hughes, M. Koro-Ljungberg, and D. Miller, Use of process oriented guided inquiry learning for introduction to materials, *The 121st ASEE Annual Conference and Exposition: 360 Degrees of Engineering Education*, Indianapolis, IN, 2014.

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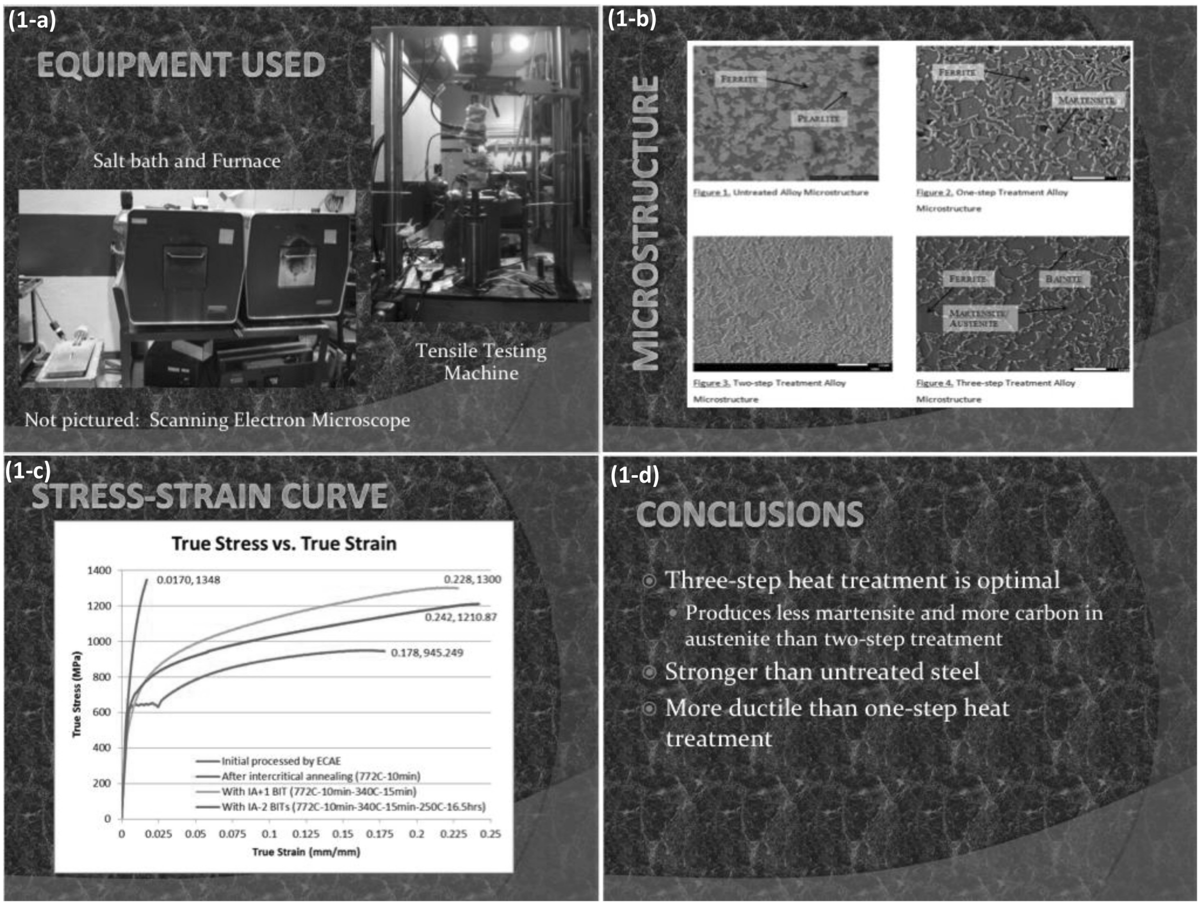
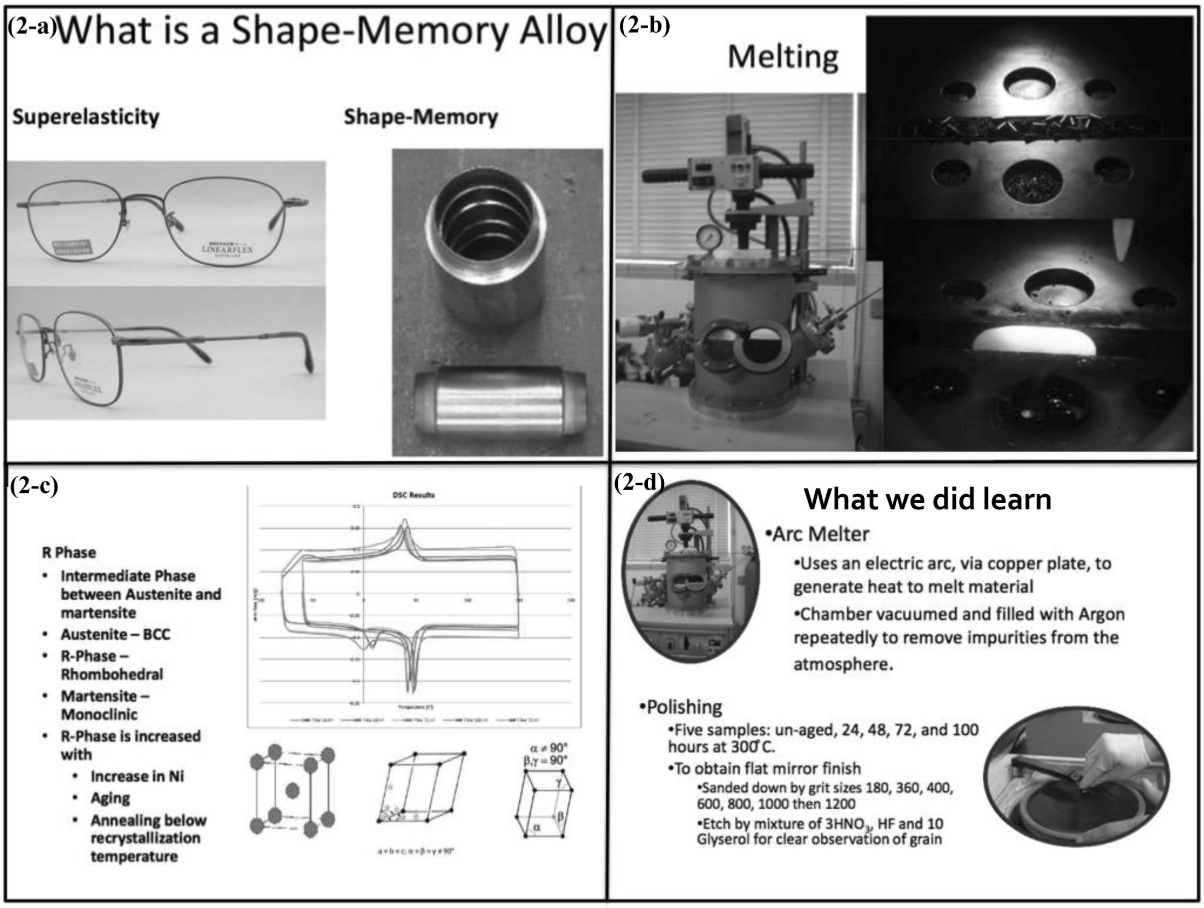
Patrick Shamberger has a background in functional inorganic materials, including interests in phase transformations, crystal structure/property relationships, and thermodynamics. These have been applied to a range of problems on both natural (geological) and engineered systems. Currently, he is a research assistant professor with the Department of Materials Science and Engineering at Texas A&M University, College Station. Prior to this, he served as a materials research engineer for the Air Force Research Lab in the Nanoelectronic Materials Branch (AFRL/RXAN) and Thermal Sciences and Materials Branch (AFRL/RXBT). His current areas of focus include: development of rapid, low-temperature thermal storage materials based on phase change, physisorption, and chemical dissociation processes; development of efficient magnetic refrigerants; and investigating variability mechanisms in electrical resistance switching devices. Patrick Shamberger received his Ph.D. in Materials Science & Engineering from the University of Washington in 2010, an M.S. in Geology & Geophysics from the University of Hawaii in 2004, and a B.S.E. in Civil & Environmental Engineering from Princeton University.

APPENDIX A: Example 1



Note. Selected Slides from the project, "Transformation induced plasticity (TRIP) steels," where students used some new methods to enhance TRIP steels were conceptualized and first performed in collaboration with graduate students at the Texas A & M University.

APPENDIX B: Example 2



Note. Selected Slides from the Project, "Synthesis and Characterization of NiTi Shape Memory Alloy" where students carried out the synthesis and characterization of the shape memory response of NiTi-based Shape Memory Alloys in a faculty's laboratory in the Department of Mechanical Engineering.