Applied Materials Science - A Fundamental Course for Engineers

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Abstract

Materials selection is a required part of design, and thus if design is to be incorporated throughout a curriculum it is necessary that the students be exposed to the fundamentals of materials science early in their careers. This has been done in a freshman-level materials engineering course designed to meet the needs of general engineering students and not those of materials scientists. The subject matter is presented in an order consistent with the "chain" pedagogy - that processing changes structure and structure determines properties. By presenting the structure and processing fundamentals early in the course, we are able to spend the last half of the term enabling students to make electrical, chemical and mechanical design decisions based on experimental data. Doing so allowed us to fully incorporate polymers into the course, rather than as an "add-on". The course concepts are taught through a studio-based recitation which includes simple laboratory experiments and demonstrations, supplemented by lecture. At Virginia Commonwealth University this allowed us to let freshman participate in semiconductor device fabrication. This paper focuses on the content and teaching of "Applied Materials Science".

Introduction

The purpose of engineering education is well described by the words of Stephen van Rensselaer, the founder of the first civilian engineering college :"...instructing persons, who may choose to apply themselves, in the application of science to the common purposes of life"[1]. This means design. Many engineering curricula are either introducing or attempting to introduce design throughout the various courses in their curricula[2], and those who do find it successful[3]. Design requires materials selection and the evaluation of alternative materials[4]. Thus, if design is going to be integrated throughout the engineering curricula, then students need to be taught how to select materials and evaluate potential alternatives earlier in their career. Over the last ten years a course, Applied Materials Science originally intended to be the second semester of an integrated chemistry-materials sequence[5] has been developed for first year students. The course description is below.

> **Students will learn how to specify materials for a given performance criterion based on experimental data. Mechanical, chemical (corrosion) and electrical property-performance issues will be discussed, as will the fundamental scientific principles**

needed to understand how structure and processing effects these properties[6].

This is a non-traditional approach to teaching introductory materials science. The course is designed to meet the needs of the general engineering student, not the needs of a materials science and engineering student first being exposed to their discipline of choice. It is not a survey course. The course has a well defined goal and requires the students to apply what they have learned in three areas.

It makes no sense to assume that a non-traditional course can be taught in the traditional manner. In fact there is evidence that the traditional approach may not be the best for teaching engineering students[7]. Typically the introductory science and mathematics course consists of a sequence of lectures combined with a series of assignments and examinations which require little more than rote memorization or repetition. We adopted the philosophy "Involve me and I'll not only learn but understand and remember"[8] Bloom, a noted educational specialist, identified a hierarchy of six educational levels, each higher level being more rewarding[9]. The typical course experience as described earlier focuses on the lower learning levels and are not appropriate for college students. We feel that college students should perform at the fourth level, Analysis (breaking down a problem into parts and solving it), and by the time they graduate at the fifth level, Synthesis (tying together distinct concepts).

Designing a course requiring the students to perform at the analysis level means enabling the students to become more involved in their own learning. This is an appropriate response to recent findings of the National Science Foundation which found that students are not being served well by typical methods of instruction[10]. This report found the following.

- Much of this dissatisfaction and disinterest in engineering occurs during the first two years of an engineer’s education when they are exposed to the scientific concepts they will apply during their careers.
- Ninety percent of engineering majors who switched to a non-engineering major, and seventy five percent who persevered, described the quality of teaching as poor overall.
- Seniors about to graduate in engineering made it clear their experience in these introductory courses had given them a shaky foundation for higher level work.

In a recent call for proposals (Action Agenda in Engineering) the National Science Foundation has identified several proposed changes to improve SMET education and particularly the introductory experience. These include,

1) active project-based learning inside and outside of the classroom,
2) increased student-teacher dialog,
3) horizontal and vertical integration of subject matter,
4) introduction of mathematical and scientific concepts in the context of engineering, and
5) the broad use of information technology.

Requiring the students to perform at the analysis requires items 1 and 2, and can be greatly enhanced by item 5 [11,12,13].

Materials science and engineering can be described as a combination of disciplines. Frequently physicists, chemists, mathematicians and other engineers make up a significant portion of the faculty of an MSE Program. In this course, scientific concepts specifically organic and electrochemistry were taught in the context of materials science, thus following recommendations numbers 3 and 4 of the Action Agenda.

We felt that it was important that the course have a solid pedagogical structure. There are two models used to describe the interrelationship between processing-structure-properties-performance which is the basis for materials science and engineering study. These are the tetrahedron[14] and the chain[15] as shown in Figure 1.

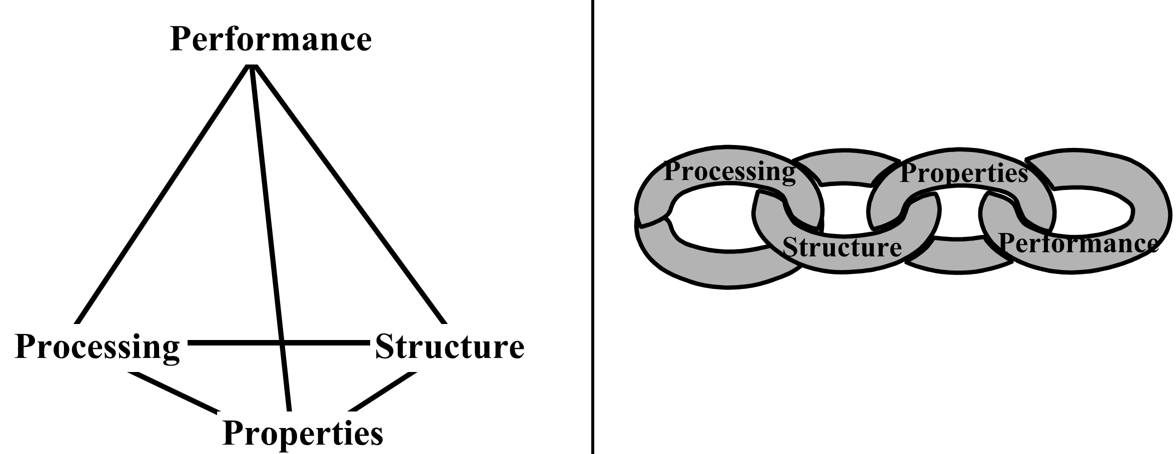

Figure 1: Two Models of Interrelationship Between Materials Science and Engineering Topics.

Many texts begin with an illustration of the former and explain that understanding materials requires an understanding of the complex relationships between these. If a course is organized in this manner the student can become confused as they attempt to determine what affects what. The chain model shows that the performance of a part depends on the properties of the materials used in its design. These properties are effected by the structure of the material, which can be altered through processing.

We tell the students that,

as engineers you design for performance, which requires you select materials based on

their properties, these properties depend on the internal structure of the material which can be altered through processing[16].

The Course

A first-year course sequence, "Materials Chemistry"specifically targeting engineering students, has been developed and refined over the last 10 years at Rensselaer Polytechnic Institute and Virginia Commonwealth University . The course design involves three aspects;

- Identifying appropriate subject matter[5,6],
- Presenting the subject matter in an order consistent with our pedagogical statement[16], and
- Increasing the involvement of students in their own learning[11,12,13].

The success of the course is based on more than the simple identification of subject matter.

Subject Matter

We found that it made no sense to discuss processing before structure, despite the order of topics in the "chain" shown in Figure 1. Once the students have been exposed to structure and processing fundamentals, we could focus on three property- performance relationships: mechanical, chemical and electrical. These relationships can be taught in any order. In 2001 for the first time, electrical property-performance relationships were covered first and mechanical property-performance relationships at the end of the course. There was no effect on student learning. We believe this shows that once the fundamentals are introduced - they can be applied and reinforced in any order[17,18].

Because this is a course for general engineers much of the subject matter found in introductory texts that is of interest only to materials engineers has been eliminated. Also as mentioned earlier in two cases chemistry was taught just in time. A brief introduction to organic chemistry preceded the discussion of polymer structure, and a brief introduction to electrochemistry preceded the discussion of corrosion.

Structure: It is important that engineers understand dislocations and surfaces as they have a profound effect on mechanical, chemical and electrical properties. Therefore a basic study of crystal structure is necessary. We only discussed cubic crystal systems and reduced our coverage of Miller Indices and only considered the following planes and directions: (100), (110), (111), [100], [110], and [111]. These are sufficient to cover anisotropic properties and the [111] direction and (110) plane are sufficient to illustrate the difference in various structures.

Students need to know that dislocations are extra sets of atoms wedged into the crystal, which respond to an applied stress breaking one chemical bond at a time. Therefore, they permanently deform the material and are responsible for plastic or permanent deformation. The difference between and edge and screw dislocation was not mentioned, nor was the circuit definition of the Burger's vector. The students were shown that the dislocation was unstable as were surfaces. We introduced surface energy so that the students knew a) that the underbonded atoms added energy to the crystal and b) they were familiar enough with the concept to understand nucleation phenomenon and coarsening.

Polymers were included as another material. By introducing the students to organic chemistry we were able to lead them through the formation of long chain molecules by polymerization and from this they could see how structure affected the strength of polymers. The importance of polymer science is stressed, as polymers constitute the greatest volume fraction of in-use materials. The concept of monomer vs. polymer is explained emphasizing polyolefins, which are by far the largest class of polymeric materials in use. The concept of chain molecule is introduced by calculating contour lengths of rigid chain molecules using geometric relationships of bond distances and angles. The contour length problems apply knowledge of bonding learned in basic chemistry. The large aspect ratios of polymer chains are brought to focus by calculating comparable lengths of pieces of uncooked spaggetti. The morphology of semicrystalline polymers and network (rubbery) polymers is discussed narrating the latter with Goodyear's discovery of vulcanization. Overall, the introduction to polymeric materials provides a sense of structure, properties, and utility.

Students need to know how to read phase diagrams so that they can predict microstructure and therefore assess properties of a given alloy. We focused our coverage on simple but important binary diagrams,

Processing: One of the most fascinating aspects of materials science is that one can change the properties of a material by simply changing the rate at which it cools from the melt. This is because processing affects structure. Many of the concepts associated with the processing topics are non-trivial and counter-intuitive. The most important of these is that atoms can move in the solid state, as this is the basis for most processing. We discussed diffusion, and then applied it to microstructure through nucleation and growth. We applied second phase particle growth by the eutectoid (and only the eutectoid) TTT diagram. Finally we examined grain growth, coarsening of second phase particles and sintering all demonstrations of atomic motion[19]. In each case the material was supplemented by laboratory demonstrations and experiments.

We did not focus on many of the traditional metallurgical topics such as martempering, and austmepering.

Property-Performance Relationships: During the last one-half of the course the we showed students how they could apply their knowledge of structure and processing to evaluate materials for a given application. Most commonly texts focus on mechanical properties, and there is much debate as to whether or not one can adequately cover structure and processing without explaining the strength. We feel the answer is yes and no, students need to see the “so-what” and therefore when discussing structure and processing it is important to mention the effect, but students have an intuitive knowledge of strength and thus a detailed discussion is not necessary. Our discussion of strength focused first on brittle fracture, and then permanent deformation of metals. Creep, fatigue and temperature dependent properties of polymers were also discussed. The contrasting mechanical properties of semicrystalline polymers and network polymers is illustrated by classroom demonstration coupled with a stress-strain diagram. We did not cover hardness or composite materials.

Corrosion is the leading cause of material failure. Designing for corrosion prevention, or conversely recyclability is important for any engineer. This is one area where the integration between chemistry and materials science is obvious. In this course the students apply the concepts of electrochemistry to corrosion.

As 40% of graduating engineers will be employed in the microelectronics industry it is important that electrical properties of materials be given equal weight with mechanical properties. There are three aspects of electrical properties discussed; the behavior of metals, insulators, and both semiconductors and devices. In contrast to many materials texts the behavior of semiconductors and devices is explained using the band theory of solids. The Fermi Energy, which many of us find as ambiguous is presented to the students as a "gage" of the energy of the electrons in a material. As such the performance of metals and semiconductors can be explained in terms of electrons reducing their energy. This allows the students to apply what they have learned about energy throughout the two course sequence to this topic. Explaining the rectifying behavior of a p-n junction in terms of a depletion region is confusing, and explains neither the breakdown potential associated with a diode or the behavior of a transistor[6].

Course Format

From the time the course was initiated it was recognized that increased involvement of students was necessary if they were to master the subject matter. The recitation was the key learning experience of the course and only faculty, post-doctoral associates, or advanced graduate students were allowed to teach the recitation section. All instructors were expected to be involved with all aspects of the course, and directly involved with students. Between 1996 and 1998 at Rensselaer recognizing the need to involve students further, the course was completely converted to the studio format, where lecture-group discussion-problem solving and laboratory experiments are combined into a single learning experience[11]. This had been successful in other basic courses in mathematics[20,21] and physics[22].

At Virginia Commonwealth University it was seen that such increased student involvement was necessary, but that the common lecture was valuable and ought not be eliminated. Building on experience in a basic statics course where it was shown that in-class problem solving and self-directed laboratories enhanced learning in engineering courses[23], it was decided to develop two two-hour studio-based recitation as the key learning experience. For many years students had commented that the recitation was where they learned everything, and that lecture was a waste of time. We recognized the former and told the students that the purpose of lecture was to prepare them for recitation where they would apply what they have learned. Each recitation therefore consisted of 2-3 cycles of review of lecture material, in-class problems solved by the students and discussion. Experiments were performed in recitation as necessary and if time was required outside of class students would sign up for 20 minute one-on-one sessions with the instructor. This was found to be very successful. Student teams signed up for one part of the microelectronics fabrication process and then presented their findings to the class. This was a means by which students could be exposed to the clean room, with the necessary small group instruction and all benefit.

In addition to the in-class problems the students had multiple opportunities to demonstrate their knowledge. In-class problems prepared the students for homework, which in turn prepared them for quizzes, subsequently tests and then the final examination. This constant feedback was important to the success of the students. One step drill problems were not assigned as homework students were assigned multi-step problems which required the students to think and perform at the Analysis level of Bloom's Taxonomy. To make this successful an internet tip for each problem was prepared[12], these served as "after-hours office-hours" and asked the students questions we as faculty would in our office to help them through the steps of a problem. Another form of feedback was to develop a set of homework solutions that taught solution strategy. Neither simply demonstrating the correct solution to these problems, in the form of mathematical equations, on the board[24]nor photocopying the solutions provided to the instructor for student use[25] was felt to be sufficient. Recognizing that the student needs to learn the thought process and the method of solution, detailed narrative solutions were prepared.

Laboratory Experience

The laboratory was so fully integrated into the course that it was difficult to determine where there was a division. With few exceptions the experiments were conducted during the recitation. The laboratory experience was designed to eliminate the cook-book laboratory experiment and replace it with a series of activities structured in a manner such that they reinforce the material presented in class in conjunction with the scientific learning cycle[26]. Laboratory experiments, were student-directed. In most cases students had to decide what data to collect and report their findings.

The following experiments and demonstrations were included while structure was being covered.

- Styrofoam balls were used to create metallic and ionic crystal structures. These were then used to illustrate why dislocation motion occurred on a given plane and in a given direction, and how one could calculate surface energy.
- Animations of crystal structure and polymer chain formation were incorporated into lecture, and provide to the students as outside of class learning aids.
- Polymer kits were first used to illustrate the SiO_2 crystal structure and explain glass formation. These were then used to demonstrate polymerization and the properties of various polymers.
- Following an in-class demonstration where solid Sn and Bi were placed in contact with each other and due to diffusion melted after a given time period, the students mixed their own alloy and measured the amount of proeutectic constituent[19]. This was the first of several "sign-up" labs.

The following experiments, based on the Sn-Bi system, were included while processing was being covered.

- Students would either coarsen the alloy they prepared earlier, or
- sinter eutectic Sn-Bi powder at 100°C, or
- examine grain growth in Sn at 200°C.

All experiments could be performed in as little as three hours, and frequently the students simply returned to take a new picture.

The following experiments and demonstrations were included while property-performance relationships were being covered.

- An axe was used to demonstrate how strong materials could be brittle.
- All students performed a tensile test on a variety of materials including ceramics.
- The students derived their own galvanic series based on copper, and then determined if they could predict the voltage difference between two other metals in salt water and which one would corrode.

Exposure to Clean Room

All students participated in at least one step of the fabrication of a microelectronic chip containing four resistors and two diodes. Following a safety lecture and project overview the teams performed the following operations: wafer cleaning, masking (diffusion barrier) oxidation, lithographic patterning to open "windows" in the silicon dioxide for diffusion, diffusion, metal deposition and patterning, and metal etching and heat treatment. All groups participated in electrical testing where rectification and how dimensions affect resistance were illustrated. Each group prepared a 3-5 minute presentation for the class as a whole entitled "Our Chip- Where is it Now?"

The clean room experience also reinforced previously covered course material. Photo-sensitive polymers were in microlithography, and thus polymerization and the properties of polymers was discussed in the context of semiconductor processing, reinforcing the subject matter. Students performed actual solid phase diffusion during the fabrication of the p-n junction diodes in the cleanroom. They were able to observe the effects of time and temperature through the use of split lots processed under different conditions. Again previously discussed subject matter was presented in the context of semiconductor processing, and thus abstract subject matter was reinforced.

Discussion

Assessment of Course Effectiveness

A detailed assessment, based upon the handout describing the recent workshop at Rose-Hullman[27], as distributed at the 1998 ASEE conference was conducted.

- First, four to five broad goals were identified, based on the course description. the course description was rewritten to tell the students what they could expect to do as a result of taking the course.
- Based on these goals a list of 12 objectives was developed, which are similar to the material found in course descriptions in many college catalogs.
- Specific metrics, based on the activities listed in the course syllabus were identified to measure these objectives. This included graded performance records (histograms of individual test questions), student comments on course objectives and general survey responses.
- The information in the course portfolio was used to measure the success of these objectives and then the course goals, and identify appropriate action.
- Finally an evaluation of the course was prepared based on the measurements. This evaluation is similar to a reflective memo, which has been suggested as the second step

of the assessment process[28].

This assessment was completed at VCU following the Spring 2001 term. The evaluations show that the course goals were met satisfactorily. The clean room experience was highlighted internally in a campus news announcement. The results of the assessment show that the incorporation of active learning, integrating the laboratory, just-in-time teaching of necessary chemistry, and the clean-room experience contributed significantly to the success of the course.

Incorporation of Active Learning into Course

Active learning which leads to increased student involvement in the learning process is necessary for a course such as this to succeed. The increased emphasis on recitation, with a hands-on laboratory, as the key learning experience has been successful and well received by students. This needs to be followed up with multiple opportunities (graded assignments) for feedback. The students cannot be expected to master topics instantly, but with homework quizzes, and tests, they can gradually learn the subject matter. We believe that experience and feedback are more important than reading and lecture in the learning process. However, we recognize that the reading and lecture is necessary to introduce the student to the experience and cannot be eliminated. Outside of class resources such as the internet tips, well graded homework assignments (as well as quizzes, and tests), and instructional homework solutions are also necessary to assist the students in their learning. The students liked the instructional homework solutions. There were no negative comments on well graded assignments, but in the past there had been comments such as “all the grader does is mark with a check or an x”.

Comments on the tips were negative. Students wished that all the tips could be handed out at once, or that the tips actually said “try this or do that”. We feel this would defeat the purpose, the tip is supposed to be an aid not a crutch. They are more effective when the student thinks about the problem. This is similar to what many of us do when a student comes in and the following dialog occurs,

“I’m lost” –> “What don’t you understand?” –> “Problem 1" –> “What about Problem 1"–> “The problem, where to begin”.

Quite often we then ask the student to read us the problem, pick on simple stuff we know they understand and involve them in the problem. Once we find out where they are confused we rarely say “Oh, here just plug this in and do this step”, we ask probing questions to make them think so they will remember. One renowned educator recently stated that his most effective instructor never answered his questions, but simply asked him questions until he found the solution[29]. The tips are meant to do just that.

Incorporation of Chemistry

Originally this course was developed as the second of a two-course sequence to fully integrate chemistry and materials science[5]. During the last 3-4 years it has become apparent that the course discussed in this paper is really a materials science course which requires a solid foundation in chemistry. However, it is not possible for all necessary chemistry topics to be taught in a single semester, and it was our feeling that certain topics would be better taught if immediately reinforced with applications. To do this two chemistry topics are taught as "just-in-time" topics. Organic chemistry was immediately applied to polymers and electrochemistry immediately applied to corrosion. The assessment of course objectives shows that the students learned both the materials science concepts (polymers and corrosion), and the chemistry concepts (organic and electro chemistry).

A solid foundation in chemistry is required if the student is to learn the subject matter in this course. Thermodynamics, kinetics, equilibrium, bonding, and atomic structure are all required to understand the materials structure and processing.

Incorporation of Laboratories into Recitation

The course assessment (all aspects) show that eliminating the separate laboratory experience was successful. Graded performance records indicate that the students understand the structure and processing topics. We feel this is due to both, the inclusion of relevant laboratories and their incorporation into the course assignments. It is difficult to separate the two effects, however, requiring the students to continually review the laboratory results must have contributed to the success of the course.

Using the small group lab experience when equipment prevented incorporating the laboratory experiment in recitation (tensile testing and microscopy) was also successful. In these experiences one student team worked with the course instructor for 15-20 minutes. With such a small student-faculty ratio all students participated in the exercises and related discussion. This participation enhanced the learning experience.

Clean Room Experience

Students enjoyed being in the clean room. Mechanical and chemical engineers saw how their discipline was relevant to semiconductor processing. Many students were amazed that they could, during their first year in engineering school, not only help make a semiconductor device but understand the associated principles (structure, processing, and properties). The small student-faculty ratio ensured that all students participated in the production step and related discussion. The instructor made a conscious effort to discuss relevant course subject matter while the students were preparing for or performing the production step.

Conclusion

Our experience shows that applied materials science can be effectively taught to first year students. However to do so, one cannot use the traditional approach to teaching large classes. It is necessary to involve the students in their own learning, by employing active learning techniques, emphasizing small group interaction with the instructor and developing effective hands-on experiences. Although this course was begun as an effort to combine chemistry and materials science, this is not a chemistry course and should not be labeled as such. It is an excellent applied science course for first year engineering students which requires the students have a strong foundation in chemistry.

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