NEW APPROACHES FOR AN INTRODUCTORY MATERIALS SCIENCE COURSE

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ABSTRACT

A materials science course for general engineering students has been developed over the last several years, so that the course serves not as an introduction to the discipline for materials majors, but a course that allows the general engineering student to apply the principles of materials science to their discipline. This course is the second semester of an integrated Materials Science and Chemistry sequence which demonstrates the link between science and engineering. The topics are arranged so that the students; first learn about the structure of materials, then how processing effects this structure, and finally how structure effects properties and performance. The application to real engineering is illustrated by a series of property-performance explorations. We will discuss the development of this course, evaluate its success and discuss future directions.

INTRODUCTION

Background

During the last ten years engineering curricula have been undergoing revision. This change has been in response to many factors including, evolution of the field, the growing importance of the microelectronics industry, the advent of computer based learning technology, economics, and a declining interest in engineering education among graduating high school students. Much of the 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. These courses are typically large introductory courses in mathematics, chemistry, physics, and computing. The National Science Foundation has identified several reasons why beginning students who identify the content of these courses with their intended major, dislike engineering[1]. These include,

1. Nine out of 10 one-time engineering majors who switched to a non-engineering major, and three out of four who persevered, described the quality of teaching as poor overall.
2. Lack of student-teacher dialogue, which was thought also to reflect faculty indifference. Classes were mainly one-way lectures, which

students compared unfavorably to the high school experiences of many of them, in which there was considerable dialogue.

3. Seniors who were going to graduate in engineering made it clear that the focus on weed-out objectives and use of poor teaching practices in the first two years had given them a shaky foundation for higher level work.
4. Ineffective use of instructional technology.

Consider point number two above, Bloom, a noted educational specialist identified a hierarchy of educational levels, each one required to the next, and each higher level being more rewarding[2]. These are,

1. Knowledge (memorization of facts),
2. Comprehension (restating learned facts),
3. Application (simple one-step application of abstract concepts),
4. Analysis (breaking down a problem into parts and solving it),
5. Synthesis (tying together distinct concepts), and
6. Evaluation (judging the work of others).

The large introductory courses which are typical of the beginning students engineering education, and where there is a notable lack of student-teacher dialogue focus on the first three levels. This does not seem remarkable, until one considers (based on their own educational experience) that first graders learn at the knowledge level, by the third grade children are asked to perform at the comprehension level, by junior high students are able to perform analysis in English and social studies courses, and by high school advanced students are performing at the synthesis level. Certainly most beginning college students are expected to perform at the synthesis level by their liberal arts professors. Because these learning activities are more rewarding and more appropriate for college age students, it is hardly surprising that students prefer alternatives to engineering and science courses, and that students rate the teaching in introductory courses as poor and ineffective.

Equally disturbing are the results of a recently published long term study which finds that as engineering educators we do not teach effective problem solving in the classroom[3]. This is in spite of our good efforts demonstrating sample problems, high reviews by students, and agreement by faculty that the classroom is rewarding. The students simply copy our examples and regurgitate them. This observation correlates with NSF suggestions that more “real-world” examples be integrated into engineering courses at the introductory levels, and that technology needs to be more effectively used both inside and outside of the classroom.

For years there have been efforts to expose engineering students to the “soft-skills” required for a successful career, oral, visual, and written communication skills, ethics, business issues, leadership and teamwork. One response has been to require courses in these areas, however given recent demands to reduce the courseload of students this may not be the best approach. John M. Kucharski chairman of the board, CEO, of EG&G, Inc. reiterated these challenges during the 1997 ASEE Main Plenary but added the proviso, that we do so without sacrificing technical content[4].

The Chemistry of Materials sequence originally developed at Rensselaer Polytechnic Institute[5] has been developed to respond to these needs. This course has evolved over the last eight years in response to the changing demands listed above, and is now taught at both Rensselaer and Virginia Commonwealth University. During the first semester the students are exposed to chemical principles focusing on the solid and liquid states as the scale of interests moves from the microscopic to the macroscopic[6]. In the second semester these concepts are applied to the study of materials science. The purpose of this paper is to present the content of the second semester course, which responds to many of the issues raised previously.

Course 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[7] and the chain[8] as shown in Figure 1.

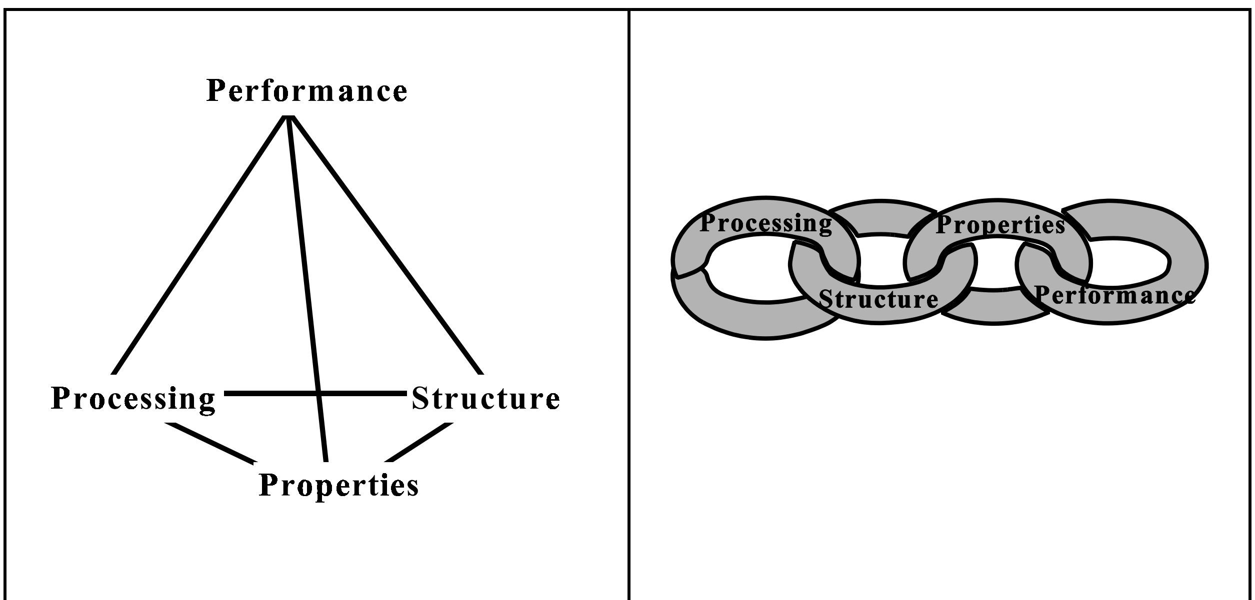

Figure 1: Two Models of Interrelationship Between Materials Science and Engineering Topics.

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 effects what. The chain model however 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. A student learns that by heat treating a steel, the underlying structure changes which causes the material to have different properties. Such a sequence of events is easier for undergraduates to comprehend.

THE COURSE

Our course is broken into three phases,

Phase 1 - Structure and Composition	Phase 2 - Processing and Synthesis	Phase 3 - Property and Performance Relationships
Crystallography Ionic Solids Complex Crystal Systems Point Defects 1, 2, and 3 D - Defects Organic Chemistry Polymer Chemistry Glasses and Amorphous Materials Phase Diagrams	Diffusion Nucleation and Growth TTT Diagrams Annealing Strengthening	Elastic Deformation and Brittle Fracture Plastic Deformation of Metals Temperature Dependent Properties Time Dependent Mechanical Failure Electrochemistry Corrosion Electrical Conductivity Dielectric Behavior Semiconductors Rectifying Junctions Transistors, and Integrated Circuits

This order differs from the order of topics shown in Figure 1b. We felt that it was impossible to discuss processing before introducing the students to structure. However one can discuss structure and make references to the material properties such as strength, ductility and conductivity, as the students have a “feeling” for these concepts. If performance and materials selection were placed at the end of the course, it is likely that either a) the topic may never be covered in any detail, or b) the students would be left asking “so what am I learning this for?” for six or more weeks.

Examination of the course syllabus shows that the order of topics differs from the order found in most introductory materials texts. Most notably,

- the structure of polymers and glasses are discussed at the beginning of

the course when the structure of crystalline solids is presented,
- there is integration between the chemistry and materials science where polymers follow organic chemistry, and corrosion follows electrochemistry,
- the discussion of diffusion is included in the processing and synthesis portion of the course and not immediately following the discussion of vacancies,
- any discussions of materials selection are incorporated into the discussion of relevant material properties.

In the discussion which follows we present not only the content of our course, but by providing examples of the typical problems assigned to students on homeworks, quizzes, tests, or exams illustrate how the course responds to the issues raised earlier. The problems require the students to think, make decisions, and communicate effectively. The simple one-step problem, or easy to grade examination question has been eliminated from this course! To assist the students we have prepared internet aids which serve as tips to guide the student through the assignment[9,10]. This has enabled us to incorporate writing into the course, requiring the students to write effective technical paragraphs[11].

Structure

Crystallography should expose the students to more than Miller indices of planes and directions. Because this is an introductory course required of all engineers, we restrict our discussion of crystallography to the cubic crystal systems: simple cubic, body centered cubic, face centered cubic, cesium chloride, sodium chloride, diamond cubic, zinc blende, calcium fluorite, and barium titanate. This permits the discussion of metals, intermetallics, ionic solids, and covalent network solids. Because we are only focusing on cubic systems the basics of crystallography are reinforced, and the students can be asked to think about the results of different structures.

Consider Sample Problem 1. In solving this problem the students do more than simply draw a crystal structure and a plane. They are asked to verify the important crystallographic relationship where by a direction [uvw] is in the plane (hkl) in a cubic system iff hu+kv+lw=0. This can be discussed in class, or on a quiz. By answering part d, the importance of structural differences are emphasized. In this course we require the students to write their answers using proper English

<u>Sample Problem 1</u>

Draw the (110) plane in the CaF_2 unit cell

a) Determine the planar density of atoms in the plane.
b) Identify directions from three different families which are in this plane.
c) Determine the linear density in these directions.
d) How would you expect the solubility of atoms such as He in CaF_2 to compare with metals such as Fe?

thus the answer “more than Fe” would not be accepted. Thus, the non-technical skills required of engineers are integrated into the course without sacrificing technical vigor. This is what industry is demanding of engineering educators[4].

After the students are exposed to crystallography, the discussion of structure branches, first crystal defects (point, line, surface, and bulk) are discussed and following this discussion amorphous solids and polymers are introduced. Rather than discuss the difference between edge and screw dislocations, we focus on how dislocations are the cause of a metal’s ability to plastically deform. Because of the integration with chemistry, thermodynamics has been used to explain, 1) the stability of point defects, 2) the extra energy associated with dislocations, surfaces, and second phases and 3) the stability of solid solutions and multiple phases as shown in binary phase diagrams.

This order of presentation incorporates a discussion of polymers and glasses with the crystalline solids. Too often, polymers which account for a large percentage of today’s materials are discussed at the end of the course, and in a special chapter of the text. This is due to the evolution of the field of materials science, but does not make sense. If a student is to learn that the properties of material depend on its structure and composition; why are polymers different from other materials? In our approach there is no disjunct when the properties of various materials are discussed.

Processing and Synthesis

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. Processing effects structure. Many of the concepts associated with the processing topics are non-trivial and counter-intuitive. These include

- systems are not always thermodynamically stable,
- atoms mix in the solid state (diffusion),
- during solidification, the atoms must coalesce to form a nucleus of critical size before being stable, below the melting temperature (nucleation and growth), and
- the strength of a material can be changed by thermal processing (strengthening).

Too often, the mathematics necessary to develop these concepts are ignored. Some mathematics is necessary if the students are to be presented with more than “just accept it on faith”. Since first year engineering students almost always take calculus, the mathematics can be integrated into the course and as a consequence reinforce the mathematics they are learning. Tools such as spreadsheets, and symbolic math packages are used to allow the students to answer the questions “so-what". Sample Problem(s) 2 illustrates this point.

To determine the atomic flow rate of copper atoms, the students must know how to calculate the flux, and apply its definition. Hints are given over the internet[9,10]. The students must present their answers clearly for full credit, thus emphasizing writing and communication skills[4].

<u>Sample Problem(s) 2</u>

1) Copper is often added to aluminum to strengthen the alloy. At 250∘C the diffusion coefficient for Al in Cu is 1.3×10^{-20} cm^2/sec. Consider a piece of alloy 1cm thick. At one end the concentration of Cu in Al is 1.5 w/o. At the other end the concentration is 0.5 w/o. If this sample is a square slab with an edge length of 1cm, calculate the atomic flow rate of copper atoms.

2) How is the critical radius for nucleation effected by transformation temperature? Prepare a plot detailing the critical radius as a function of undercooling for several enthalpy changes.

3) Why does the grain size of a solidified alloy decrease as the undercooling increases?

Our discussion of TTT diagrams focus only on eutectoid steel. Neither continuous cooling curves nor TTT's for hypo and hyper eutectic steels are discussed.

Property - Performance Relationships

Engineers design for performance. The properties of materials will determine if an engineer selects the material and will determine how the final product will perform. It is unrealistic to expect first year students to see this connection. In this segment of the course we hope that the engineering student will learn how to use the results of a material test in order to make design decisions. This includes a discussion of factor of safety, yet we allow the student to decide on their own what is an appropriate value for a safety factor – they will do this as engineers. In this course we focus on mechanical, chemical, and electrical properties.

Mechanical Properties

The mechanical properties of metals, ceramics, glasses, and polymers are discussed and compared. The students are asked to explain the results of their comparison by applying what they learned in the first two phases of the course. In two weeks the students are exposed to the following progression of topics: Brittle and Elastic Failure, Plastic Deformation, Temperature Dependent Properties (polymers), and Time Dependent Properties. In contrast to many texts we discuss brittle fracture, typically associated with ceramics, before discussing the generalized stress-strain diagram for a typical metal. We feel this progression allows the students to learn the subject matter in reasonable portions.

Illustrative problems are shown in Sample Problem(s) 3. In class we derive the condition for crack growth and brittle failure, reinforcing a the mathematics and physical concepts used to derive the critical radius for an undercooled solid. This allows one to show that K_{IC} is a material property. In this problem, students are 1) given "experimental" data, 2) asked to interpret this data, 3) asked to apply the results of this analysis to a design situation, and 4) asked to make design decisions. The students will have similar experience interpreting graphical data in the form of, tensile test curves, creep curves, E(T) curves for polymers, and fatigue curves.

> Sample Problems (3)
>
> 1) A silica (quartz) bar with a cross sectional area of $1cm^2$ fails under a load of 12,000N due to the presence of a crack 1.5µm in length.
>
> a. Assuming the crack tip radius is 5nm, predict the minimum cross sectional area required for an silica bar to maintain a load of 13,000N without failing when the sample has cracks 5µm in length present.
>
> b. As a design engineer what cross–sectional area would you specify for these loading conditions? Explain your answer.
>
> 2) As alternative materials consider, mild steel, aluminum, polycarbonate at room temperature and polycarbonate at 150℃. Explain the reasons for the differences in performance.

To make this experience successful the students access to similar problems, and numerical answers are provided, for their practice and review. More importantly by providing students with numerical answers we can incorporate a thought question into the assignment which requires the students to compare the behavior of various materials. The students are not required to perform five calculations but are still asked to interpret results.

> Sample Problem 4
>
> Consider the rusting of an iron nail in water.
>
> Draw a model galvanic cell using Pt as an inert electrode. Determine the standard cell potential, and the anodic and cathodic reactions.
>
> Evaluate the practicality of inhibiting corrosion of iron by a) changing the temperature, b) changing the concentration within the electrolyte, c) using potential sacrificial anodes, and d) other methods of your choice.
>
> Identify an acceptable current density such that a 0.1 cm diameter nail loses only 10% of its diameter in 10 yrs.

Chemical Properties

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. Consider Sample Problem 4, the students are shown that any electrochemical reaction can be modeled as a galvanic cell. The kinetics associated with corrosion where current flow can be related to species loss is also discussed. For example one of the issues the student might raise in part c) of their evaluation is the mass of the sacrificial anode. The study of electrochemistry is not limited to corrosion, but also includes batteries and deposition.

Electrical Properties

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. The students are given exercises similar to those shown in Sample Problem(s) 5. Very few introductory courses expose the students to any sort of design analysis associated with p-n junctions. By doing this the students can be exposed to transistors in the introductory course.

In contrast to many materials texts the behavior of semiconductors and devices is explained using the band theory of solids. In the first semester the "sea of electrons" model is dismissed as wrong. 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.

<u>Sample Problem(s) 5</u>

1) Compare the current which will flow when a voltage of 10 V is applied to a chunk of Si 3cm long, 1cm in diameter at 100℃ if the silicon is a) intrinsic b) doped with 10^{15} cm^{-3} Ga atoms, c) doped with 10^{15} cm^{-3} As atoms. Based on this calculation is there any way that d) the temperature of the intrinsic Si could be raised to a point where the conductivity was comparable to either of the doped versions. Is it possible to increase the amount of Ga so that one could achieve the same performance as in c) without using As. If so how?

2) A p-n junction is formed by joining Si doped with 10^{15} cm^{-3} As atoms and Si doped with 10^{15} cm^{-3} B atoms. a) Identify the p-type and n-type regions, b) Calculate the conductivity in each region, c) In each case the Fermi energy is 0.28eV from mid band gap. Draw a band diagram showing the device before it is joined and at equilibrium, d) Calculate the contact potential, e) Draw a band diagram showing the device under forward bias. What is the conductivity under forward bias? f) Draw a band diagram showing the device under reverse bias. What is the conductivity under reverse bias? g) Estimate the breakdown voltage, draw a band diagram for this condition.

DISCUSSION

All features of this course have been carried out previously, but the course as presented in this paper was taught for the first time this spring. The student response, as measured by student evaluations, to the selection of topics has been positive for several years. The student response to the order of topics is more difficult to measure. Fewer students have complained that the course "was a random collection of topics", but as this was not asked explicitly on course evaluations, and therefore such results are not conclusive.

Response to from students and faculty to the more difficult problems has been mixed. Students claim the homework is difficult and challenging. As expected not many students complained about homework being too easy in the past. As the course has evolved student feedback has been increasingly positive. We have observed that the students come to class with questions, showing they have thought about the homework. Most students have indicated that they feel they are learning something worthwhile.

In a large course, as at Rensselaer with multiple instructors, uniform support has never been achieved. This is not necessarily due to instructors being obstacles to progress. Many faculty simply want to be convinced that the new approach will work, and benefits the students. This reaction is fair, and should be expected of good faculty. A faculty member in the Chemistry Department at VCU, where this course is being implemented for the first time, noted that he was pleasantly surprised the students responded so well. His quote is, "We set high standards, and they met them".

The internet has been used as a key part of the course, and had students not had access to a well developed set of internet pages incorporating the more advanced problems would not have been possible. The internet resources were used to "engage the students in dialog - in abstentia". Many students do not do their homework when faculty have office hours. In this course the time between class discussion and the homework due date was short. Therefore they do not know what to ask until, most likely, the day before the assignment is due. Hints placed on the internet took the form of prodding we might have done in our office ("think about this", "here's how to write a paragraph", "some ideas you may want to consider").

The course will continue to evolve[12]. It is planned to 1) develop a series of hands-on laboratory experiments, 2) more fully develop the processing portion of the course, and 3) create more in depth property-performance modules now that easy to use software is available. A manufacturing exercise will be incorporated into the processing section next year.

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BIOGRAPHICAL INFORMATION

Mark A. Palmer recently joined the faculty at Virginia Commonwealth University as Assistant Professor of Mechanical Engineering. His research interests include electronics manufacturing particularly the development and characterization of new joining materials, and materials processing. His teaching interests include using electronic media to enhance engineering education.

Gary E. Wnek is Professor and Chair of Chemical Engineering at Virginia Commonwealth University. He has been involved in the combined chemistry - materials course for nine years, originally developing it at Rensselaer Polytechnic Institute. His research interests include polymers with interesting electrical and optical properties.

John B. Hudson has been on the faculty at Rensselaer Polytechnic Institute for 35 years, and is currently Professor of Materials Engineering. His professional interests include research in surface science and development of interactive approaches to the teaching of Materials Science and Engineering.