2006-1921: INCORPORATION OF BIOLOGICAL MATERIALS INTO AN INTRODUCTORY MATERIALS ENGINEERING COURSE

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Incorporation of Biological Materials into an Introductory Materials Engineering Course

As biology continues to establish itself as a scientific pillar of engineering alongside chemistry, physics, and mathematics, materials science and engineering instructors must find ways to accommodate the influence biology is having on their discipline. Specific examples are given of how fundamental materials science and engineering topics such as crystal structure and phase diagrams can be adapted to describe biological materials. Moreover, a holistic approach to the incorporation of biological materials into an introductory-level materials science and engineering course is described that goes beyond the mere use of example problems, and treats biological materials on the same level as metals, ceramics, polymers and composites. The prerequisite topics required to treat biological materials on this level, and the resulting level of depth with which they may be covered, particularly for chemical engineering students, are also described.

Introduction

Materials science is not only a discipline of its own with a fascinating history of development[1], but is a sub-discipline of most of the engineering disciplines. As such, it is taught alongside such topics as Thermodynamics, Statics and Dynamics, Separation Processes, and Computer Science. One difficulty with this approach is that the entire discipline is often boiled down to a one-, or two-semester introductory level course. Such courses in Thermodynamics are also common, but the First and Second Laws don't change much from year to year. How we teach them might (and should) change, but the fundamental properties are universal. Similarly, new computer languages and programming codes replace older ones (C++ for Fortran, for example), but the end goal is the same: to write a program that performs a specified function and to understand the implicit logic behind this process. Materials science, in contrast, is a cumulative discipline, and the incorporation of new topics such as self-assembly and nanocomposites proves to be difficult if the fundamental topics such as structure, phase equilibrium and mechanical properties are replaced. As a greater number of concepts are incorporated into an introductory materials science course, there is necessarily a reduction in the level with which pre-existing concepts can be taught. The struggle, then, is to retain the necessary fundamental topics with sufficient rigor such that new topics can at least be introduced to the students.

In response to the increase in required topics, introductory materials texts have a correspondingly larger number of chapters on such topics as environmental issues (recycling, corrosion) and materials selection. Recent editions of two of the most widely utilized textbooks for introductory materials science courses contain 20 and 23 chapters, respectively[2,3]. Such modularization is convenient for the instructor, but may not present the material in the most unified manner possible for the student, especially if the instructor opts to present the material out of order from the text (on which many students heavily rely).

The burgeoning of biology as a pillar of engineering disciplines, particularly in chemical engineering[4,5], threatens to exacerbate this difficulty. The incorporation of biological materials into an introductory materials science course is a completely logical consequence - research on biological materials has been carried out for many decades now, and there are well-established textbook devoted solely to these types of materials[6], just as there are introductory texts on metallurgy[7], polymer science[8], ceramics[9], and composites[10]. The question is how to effectively integrated biological materials into this classification system, and perhaps more importantly, how to deliver this information in an effective manner to the intended audience.

A New Paradigm

The easiest way to incorporate biological materials into an introductory materials science and engineering course is to consider them equivalent to all other broad materials classes. While there is understandable controversy over what those classes should be titled, a more all-inclusive list might consist of the following five classes: metals and alloys; glasses and ceramics; polymers; composites; and biological materials. Note the awkwardness of "biological materials" in a list that includes such succinct terms as "metals," "ceramics," and "polymers." Why not just call them "biologics?" Such is the nomenclature preferred by one author[11], which will be adopted here. (Biologics refer to materials that are biologically-generated; e.g., soft and hard tissues, whereas "biomaterials" generally refer to materials of all classes that can be used in biological applications; e.g., hip implants.) The drawback to this organizational scheme is that, as pointed out previously, textbooks are not generally organized in such a fashion. There is growing sentiment for this approach however, as reflected in a recent edition of one well-known introductory materials science text[12]. The presentation of topics by engineering topic rather than materials class is termed an "integrated approach."

At this point, the instructor may be asking "How do I fit this all into a one-semester course?" Obviously, something must be sacrificed. Which topics get reduced (or removed) can be discipline specific. For example, for chemical engineers, coverage of polymers and biologics is important enough to eliminate some coverage of metals and alloys. Certainly metals and alloys are important from a materials selection standpoint, but there is little additional to be learned by intensive study of the iron-carbon phase diagram, for example. For mechanical engineers, this may not be the case. A proposed shift in emphasis by materials class that is appropriate for chemical engineers is shown in Table 1.

Table 1 Example redistribution of materials science topics to include biologics.

	Typical	Revised
Metals/Alloys	40%	25%
Ceramics/Glasses	25%	25%
Polymers	25%	25%
Composites	10%	15%
Biologics	-	10%

While the integrated approach is perfectly logical, it presents some logistical challenges. First and foremost, it distributes traditional topics of structure, phase transformations, mechanical properties, electrical properties, etc. across the material classes. For example, the concepts of elasticity and modulus can be described in the context of metals, alloys and even ceramics, but the concept of viscoelasticity cannot be adequately described until polymers are discussed. There are numerous other examples in the areas of structure (crystalline vs. semicrystalline), electrical properties (conductor vs. dielectric) and kinetics (nucleation and growth vs. chemical vapor deposition) that require separate descriptions in the context of different materials classes. The ability to compare and contrast is continually delayed until all topics have been described. Thus, an additional organizational structure is required.

The new paradigm is to organize topics on two levels: by not only by material class, but by engineering subject area as well. What constituted an "engineering subject" is open to interpretation, and changes substantially by engineering discipline. The illustration used here is that of the chemical engineering discipline, and closely-related disciplines such as materials engineering. The traditional subject areas in chemical engineering generally include thermodynamics, kinetics, transport processes (phenomena), unit operations, process control and process design. Virtually all undergraduate chemical engineering curricula contain these subjects in some form, and chemical engineering students very clearly identify with them. Unit operations, process control and process design are primarily process-oriented subjects, and as such, do not lend themselves well to a product-oriented survey course like materials science. That leaves thermodynamics, kinetics, and transport processes in which to organize all materials science topics. These subject areas certainly do not cover all of the materials science topics (see Table 2), but they come surprisingly close.

Table 2 Organization of materials science topics by both materials class and chemical engineering subject area.

	Metals/ Alloys	Ceramics/ Glasses	Polymers	Composites	Biologics
Structure	Crystal structures, Point defects, Dislocations	Crystal structures, Defect reactions, The glassy state	Configuration, Conformation, Molecular Weight	Matrix, Reinforcement	Amino acids, Soft tissue, Hard tissue
Thermodynamics	Phase equilibria, Gibb's phase rule, Lever rule	Ternary systems, Surface energy, Sintering	Phase separation, Polymer solutions, Polymer blends	Adhesion, Cohesion, Spreading	Cell adhesion, Cell spreading
Kinetics	Transformations, Corrosion	Devitrification, Nucleation & Growth	Polymerization, Degradation	CVD, CVI	Receptors, Ligand binding
Transport Processes	Inviscid systems, Heat capacity, Diffusion	Newtonian flow, Heat capacity, Diffusion	Non-Newtonian flow, Heat capacity, Diffusion	Porous flow, Heat capacity, Diffusion	Convection, Diffusion
Mechanical Properties	Stress-strain, Elasticity, Ductility	Fatigue, Fracture, Creep	Viscoelasticity, Elastomers	Laminates	Sutures, Bone, Teeth
Electrical/ Magnetic/Optical Properties	Resistivity, Magnetism, Reflectance	Dielectrics, Ferrites, Absorbance	Ion conductors, Molecular magnets, LCDs	Dielectrics, Storage media	Biosensors, MRI
Processing	Casting, Rolling	Pressing, CVD/CVI, Sol-gel	Extrusion, Injection molding	Pultrusion, RTM	Surface modification

The largest topical area that is not addressed directly by thermodynamics, kinetics and transport processes is that of structure. This is a large subject area, to be sure, and includes many topics such as bonding, crystal structures, and defects. One could attempt to extend the engineering subject area organizational theme and call these topics "Materials Chemistry," for example, but that would defeat the purpose of including biologics. Certainly, there is a great deal of overlap between biology and chemistry, but the choice of one name over the other creates more confusion than it eliminates. The term “Structure” is sufficiently descriptive. Similarly, Mechanical Properties could be organized and named “Statics and Dynamics,” and this could indeed make sense for mechanical and structural engineers. For the current illustration of chemical engineering students, however, statics and dynamics are becoming less relevant as these courses are eliminated from most chemical engineering curricula. Electrical, magnetic, and optical properties are so intimately related that it does not make sense to treat them separately in this organizational methodology. Again, a term such as “Materials Physics” could be used here to enhance organizational structure, but is neither appropriate nor completely descriptive. Finally, if one wishes to include materials processing concepts, which some introductory texts do not, but which are vital to a chemical engineer’s education, then a separate organizational section is required. The organization of representative materials science topics into these engineering subject areas for chemical engineers is presented in Table 2.

In terms of topic coverage, this organization is transparent; i.e., the student will be exposed to many of the traditional topics, as well as many new ones. To the student, however, the organization is intended to facilitate a deeper understanding of the subject matter, since it is presented in the context of courses they have already had or are currently taking. To the instructor, the organization means that, in principle, the material can be presented either in the traditional subject-oriented sequences (in rows) or in a materials-oriented sequence (in columns). The latter is recommended for a two-semester course, with the first two columns covered in the first semester and the final three columns covered in the second. In this way, many of the “traditional” materials science concepts are covered in the column on metals and ceramics, whereas many of the more advanced topics are found in the sections on polymers, composites and biological materials. This cross-classification concept is not new. The landmark chemical engineering text Transport Phenomena by Bird, Stewart and Lightfoot[13] utilizes this organization very effectively. In this way, biologics can not only be included and incorporated into a materials science textbook, but can be fully integrated with other traditional topics through direct analogies. In the following section, some examples are given of how these analogies are executed.

Examples

Two types of examples will be given to illustrate how biologics can be incorporated into an introductory materials science course using the bi-level organizational approach outlined in the previous section. The first type of example, of which there are two, illustrates how new biology-related concepts can be introduced as a natural extension of traditional materials science topics. The second type of example, of which there are also two, illustrates how the properties of biologics can be compared and contrasted with traditional materials using simple extensions of concepts. The section concludes with a Cooperative Learning example problem that is not only biologics-oriented, but illustrates how this active learning technique can be employed in an introductory materials science class.

With the inclusion of biologics in a materials science course, some new concepts and terminology must be introduced. Since most introductory materials science text and courses begin with at least a partial description of chemical structure, it is natural to include some descriptive biochemistry early in the course. A description of amino acids, proteins, collagen, and a differentiation between soft and hard biologics is appropriate, and extend from a description of primary and secondary bonds, and basic organic chemistry (functional groups, etc.) that constitute an introduction to polymer structure. Similarly, many of the principles related to polymer conformation and configuration apply to biological macromolecules, as well.

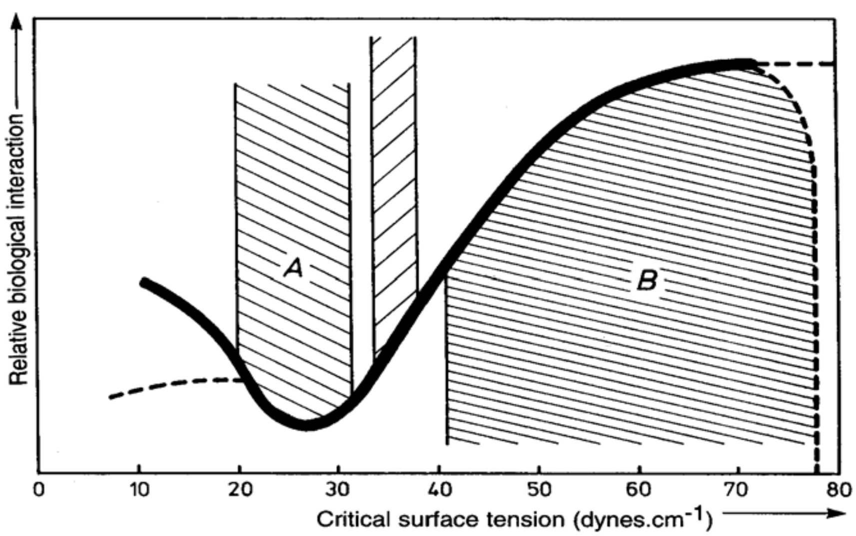


Figure 1 Phase diagram illustrating biocompatibility. Area A represents a nonadhesive zone; whereas area B represents biomaterials with good adhesive properties.

Phase diagrams are also generally described early in a materials text. Often, much time is spent not only introducing alloy phase diagrams, but describing a series of phase diagrams and their corresponding two- and three-phase transformations, such as Cu-Ni, Fe-C, Pb-Sn, not to mention oxide phase diagrams. Some of this material can be replaced with a biology-oriented phase diagram, while at the same time introducing a new concept. Phase diagrams exist for a variety of biological process, as illustrated in Figure 1 for biocompatibility. Here, the compatibility of foreign materials with biological materials is correlated with adhesion and surface tension of the two materials. Though not as straight-forward as a temperature (*T*)-composition phase diagram, such biological phase diagrams also come, in principle, from free energy arguments, and can be derived from thermodynamics. In this case, the link between surface tension and free energy can be made. Biocompatibility is an important materials concept, and should be part of any introductory materials science course. A similar concepts for which a phase diagram is useful is cell-cell adhesion, which is related to biocompatibility. Cell-cell adhesion, which can occur by a number of mechanisms including receptor-ligand binding, can provide useful instruction on biocompatibility from not only a thermodynamic sense, but also from the standpoint of kinetics.

The second illustration of how a new biological concept can be introduced comes in the form of physical properties. Thermal conductivity is a well known material property, and can either be described in the in terms of material structure, heat transfer properties, with analogy to electrical conductivity, or in a separate chapter on thermal properties. However it is introduced, it is by relatively simple extension that the biology-oriented property of thermal conductance is introduced. As illustrated in Table 3, thermal conductance is used to describe the heat-retaining capabilities of biological species, particularly hair- and fur-bearing animals. Whereas heat flow, Q, is related to thermal conductivity, k, cross-sectional area, A, and a temperature gradient, dT/dy, according to the following equation

Table 3 Selected values of thermal conductance for fur and feathers[a]

Animal	Condition	m (kg)	Thickness (mm)	C ($W/m^2 \cdot K$)
Rabbit	Back	2.5	9	2.4
Horse	Flank	650	8	4.1
Pig	Flank	100	5	2.8
Chicken	Well-feathered	2	25	1.6
Cow	—	600	10	3.2
Dog	Winter	50	44	1.2
Polar bear	In air	400	63	1.2
Polar bear	In water	400	57	27
Beaver	In air	26	44	1.2
Beaver	In water	26	40	14
Squirrel	Summer	—	3	9.0
Monkey	Summer	—	8	3.2

[a] Includes skin and still air layer.
Source: A. T. Johnson, *Biological Process Engineering*. Copyright © 1999 by John Wiley & Sons, Inc.

$$Q = -kA(dT/dy)$$

the same quantity is related to thermal conductance, C, as follows

$$Q = CA(T_s - T_\infty)$$

where $(T_s - T_\infty)$ is the difference between the surface temperature and temperature of the surroundings. Thus, thermal conductivity has SI units of W/m-K, whereas thermal conductance has units of W/m^2-K.

An illustration of how biologics can be included on a comparative basis is shown in Figure 2. The plot on the left shows a well-known relationship between solution viscosity and volume fraction solids for a variety of hydrodynamic shape factors. These types of relationships are widely used in the processing of ceramic slurries. Notice the similarity to the plot on the right, which is a relationship between blood viscosity and the percentage hematocrit for different tube sizes. With only the need to define a simple term - hematocrit, the fraction of the blood volume represented by bloods cells - a concept from traditional materials processing, in this case ceramic slurries, is easily extended to biologics.

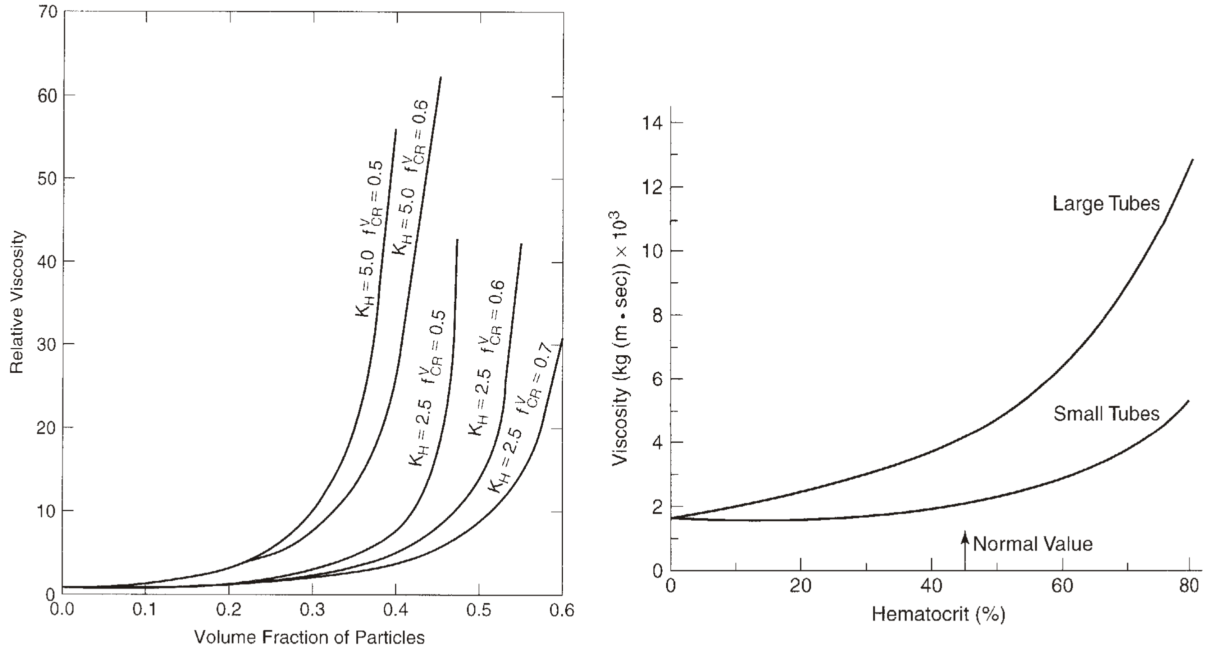


Figure 2 Relative viscosity of ceramic slurries as a function of solids concentration for several apparent hydrodynamic shape factors (left), and viscosity of blood as a function of percentage blood volume, hematocrit (right).

A second illustration of comparative properties is shown in Figure 3. The figure on the left,

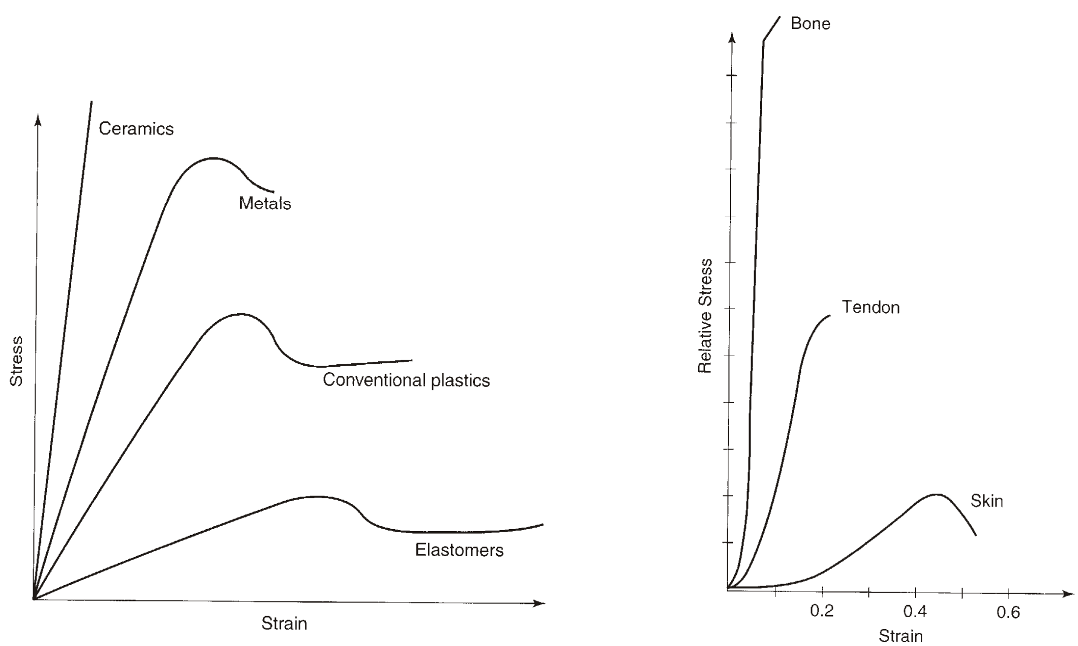


Figure 3 Comparison of stress-strain diagrams for “traditional” materials (left) and biologics (right).

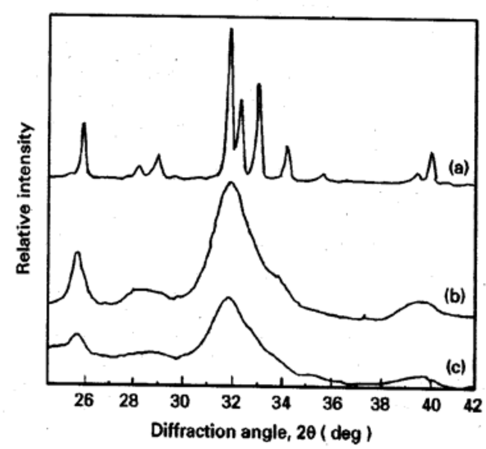
which is found in some form in virtually all introductory materials texts, shows the qualitative differences between metals, ceramics and various types of polymers. Such diagrams are used to discuss related concepts such as elasticity, modulus, yield point, strength, rupture, and percent elongation. Again, notice the similarity in shape of the curves in the figure on the right, which are stress-strain plots of three types of biological materials (bone, tendon and skin). The opportunities for comparison between biologics, metals, ceramics and polymers are enormous in these two very simple, qualitative diagrams.

Finally, an example Cooperative Learning Exercise (CLE) is shown in Figure 4. It illustrates how concepts traditionally limited to metals and ceramics can be applied to biologics. It utilizes the concepts of hexagonal crystal structure, lattice parameters, Bragg's Law, *d*-spacing, and Miller indices. In fact, it introduces a relationship between *d*-spacing, lattice parameters and Miller indices for hexagonal structures that is not found in all introductory texts. As is common with CLEs, the problem is broken down into two parts, to be solved independently by each team member, followed by a third problem which relies upon the combination of individual contributions. The biological aspect of this problem, of course, is that the X-ray diffraction patterns, which are taken directly from the literature, are for hydroxyapatite.

The crystal structure of hydroxyapatite is a hexagonal unit cell with $a = 9.88$ Å and $c = 6.44$ Å. The relationship between interplanar diffraction spacing, d, and the lattice parameters for the HCP structure is

$$d = \frac{1}{\sqrt{\frac{4}{3}\left(\frac{h^2 + hk + k^2}{a^2} + \frac{l^2}{c^2}\right)}}$$

The diffraction pattern for various forms of hydroxyapatite is shown at right; (a) synthetic crystalline, (b) synthetic amorphous, and (c) from bone.



Use this information to calculate the following.

<u>Person 1</u> Use Bragg's Law to calculate the *d*-spacing (in nm) for the first diffraction peak in hydroxyapatite. Assume a first-order diffraction, and an X-ray source of $\lambda = 0.1542$ nm.

<u>Person 2</u> Derive a relationship in simplest terms for the *d*-spacing of hydroxyapatite in terms of the Miller indices only (h, k and l). Use the cell parameters in nm.

Combine your information to determine the Miller indices of the first diffraction peak for hydroxyapatite.

Figure 4 Cooperative Learning Exercise illustrating the combination of traditional materials science techniques related to crystal structure, and biologics.

Conclusion

A method is described for incorporating biologics into an introductory materials science course, in which biological materials are treated like other material classes. A cross-referencing system, in which subjects are alternatively grouped by engineering subject area provides additional organizational structure for the student. Some knowledge of biochemistry is required, but beyond structure, few new fundamental materials concepts need to be introduced. Those concepts that are new can be introduced through simple extensions of previously-taught principles. The inclusion of biologics provides unique opportunities to compare and contrast properties with materials from traditional classifications.

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