Materials Processing in the New DMSE Undergraduate Curriculum

Adam Powell, Randolph Kirchain, Donald Sadoway

April 13-14, 2004; Updated May 25-26, 2004 and September 1, 2004

Introduction

The new Materials Processing subject 3.044, to be taught in the Spring semester of the Junior year, takes the place of Transport Phenomena (3.185), but has quite different goals. Where 3.185 taught transport phenomena (diffusion, heat conduction, fluid dynamics, and heat and mass transfer), 3.044 will teach cost-effective and sustainable production of solid material with a desired geometry, structure or distribution of structures, and production volume. With such a different starting point, the entire organization of the course must be re-thought, and with several new goals, many of the topics taught in 3.185 must be removed. This document provides a first cut at an organizational framework intended to best satisfy the new goals of 3.044, while drawing on the pedagogical lessons learned in the course of teaching similar topics in 3.185.

Framework Overview

There are several ways of thinking about classifying and organizing the material in a processing subject. One is a historical view, which might look like:

ceramics ⇨ metals ⇨ polymers ⇨ electronic materials ⇨ biomaterials

Such distinctions are useful for describing our field to outsiders, but the basic point of this MSE thing is that processing-structure-properties phenomena cut across these materials classes, and can thus be taught as they are with examples drawn from each of these throughout. A second way of classifying processing material is by increasing order of pedagogical complexity, from the simple and familiar to the complex, *e.g.*:

diffusion ⇨ heat conduction ⇨ fluid dynamics ⇨ heat and mass transfer

This order is organized around facility of understanding for students, making it very useful. Furthermore, it highlights the similarities between many of these phenomena, such as conservation laws and flux down a potential gradient. For these reasons, Julian Szekely introduced this order to 3.185 in 1994, and it has served us well ever since; it has allowed our students to learn and retain nearly as much material in one semester as mechanical and chemical engineers learn in two. But this framework is geared toward engineering of whole processes from what might be called a chemical engineering approach; included in the above theme for our new Materials Processing subject is the notion of structure, which is central to our field of materials science.

This leads us to a radically new classification scheme based on the richness of structures produced by various phase transformations, which can be summarized as follows:

heat treat ⇨ liquid-solid ⇨ fluids ⇨ solid deformation ⇨ vapor-solid ⇨ advanced economics

We begin with heat treatment of solids, in order to introduce heat conduction by analogy with diffusion (for pedagogical reasons), and to describe the thermal transport behind solid-state phase transformations taught in 3.022. Liquid-solid transformations come next, because the entropy, energy, and volume changes involved are relatively small and the structure changes more straightforward than the others. Fluid behavior further enriches the liquid-solid section, and provides a background in this topic which is necessary for understanding many processes. Solid deformation processes are very dependent on microstructure and very complex, but with unique capability to cost-effectively produce advantageous structures on a large scale. Vapor-solid transformations can achieve a very wide range of structures from (strained) epitaxial to columnar to equiaxed grains in all classes of materials, and the ability to control this structure both in the thickness direction and also tangential to the surface by various masking techniques makes this somewhat richer than liquid-solid transformations; but all of this comes at higher cost and with less geometric flexibility than are available elsewhere. Finally, advanced economics brings this multitude of materials processes into a broader context, with life cycle analysis (LCA) and input/output modeling enabling our students to analyze their effects on systems of production and consumption, and ultimately, provide greater sustainability for human activity.

Omitted from the above broad outline are three crucial themes of dimensional analysis, technical cost modeling (TCM), and computation. This is because these three should be introduced right up front in the heat treatment section and taught throughout the semester in parallel with the technical topics.

It is worth noting that this is a very ambitious agenda for a single twelve-unit subject. Although one can cram as much material as one likes into a semester, information retention rate and the learning experience are not worth sacrificing for an overloaded subject. The technical material ties nicely together from the standpoint of conservation laws and constitutive relations which relate fluxes to gradients in potential; these provide a common theme which helps students to understand and re-derive the transport equations as necessary. Experience from 3.185 and from Randolph Kirchain's experience in teaching engineering economics will inform the amount of time needed to teach that material. Nonetheless, only teaching the actual subject will tell us whether this is a realistic single-subject agenda for our students.

Detailed Learning Objectives

A rough outline of the detailed learning objectives follows:

I. Introduction (1 lecture)
  A. Subject outline.
  B. Significance: "Structure is irrelevant", important things are properties, cost, quality, sustainability.
  C. Unifying technical theme of conservation laws: accumulation = in – out + generation.
  D. Assignments, tests, grading.
  E. Required math.

II. Solid Heat Treatment (8 lectures)
  A. Heat Equation
    i. Conservation of thermal energy.
    ii. Constitutive law for heat conduction (Fourier's Law), with analogy to diffusion (Fick's Law) and electrical current (Ohm's Law).
    iii. Thermal conductivity and diffusivity.
    iv. Closure: a PDE which looks like the diffusion equation.
    v. Boundary conditions: Dirichlet, Neumann, Robin.
    vi. Review of 1-D conduction solutions by analogy with diffusion, including steady and unsteady, multilayer walls, the Biot number.

B. Dimensional analysis: dimensionless flux and the Biot number.
C. Dimensionless temperature-location-time-Biot number graphs.
D. Relationship to 3.022 solid-state phase transformations, TTT diagrams; temperature uniformity and thermal stress.
E. Finite differences for approximate solution of the heat equation.
F. Introduction to engineering economics.
G. Cost modeling: unit operations, capital, labor, energy. Scale and energy efficiency.

III. Liquid-Solid Processing (5 lectures)
   A. Introduction to convection and the substantial derivative in a moving solid.
      i. VAR: convection and diffusion in same direction, exponential solution.
      ii. Extrusion/continuous casting: solid motion and simple boundary layers.
   B. Solidification limited by heat conduction through the solid, with analogy to diffusion-limited layer growth (oxidation, etc.).
      i. Radiation heat transfer (no view factors).
   C. Solidification limited by heat conduction or diffusion through the liquid.
      i. Interface instability, cellular and dendritic growth.
      ii. Semi-solid dendrite to spheroid structure change, rheocasting and thixocasting.

IV. Fluid Behavior (6 lectures)
   A. Momentum diffusion (shear stress) with examples: laminar couette flow, channel flow, inclined plane, Poiseuille flow; polymer extrusion.
   B. Drag force: linear (viscous) and quadratic (inertial) terms.
      i. Flow past a sphere, precipitation and bubbles, friction factor and drag coefficient.
      ii. Drag force in a tube.
      iii. Laminar boundary layers and the friction factor.
      iv. Porous media and Darcy's Law.
   C. Batch and continuous flow reactors.
      i. Peclet number and conversion for batch, plug flow, perfectly-mixed reactors.
      ii. Cost, flexibility and quality considerations.

V. Deformation Processing (6 lectures)
   A. Review: deformation mechanisms and strengthening in polymers, metals (ceramics?).
   B. Non-Newtonian rheology.
      i. 1-D flow profiles during polymer, metal extrusion.
      ii. Viscoelastic behavior.
      iii. Concave stress-strain behavior and stability during polymer and metal sheet forming.
   C. Consolidation processes: sintering, HIP, compression molding.

VI. Vapor-Solid Processing (5 lectures)
   A. Evaporation kinetics, heat transfer, flux distribution.
   B. Knudsen number and vapor phase transport.
   C. Physical vs. chemical vapor deposition.
   D. Thin films: epitaxial/strained, incoherent growth.
   E. Condensation rate, substrate temperature, and resulting deposit structure.
      i. Polymer sputtering.

VII. Advanced Economics (2 lectures)
   A. Materials cycles and sustainability.
      i. Recycling and quality degradation in metals and polymers; design for disassembly.

These topics come to a total of 33 lectures, plus two tests make 35, which just fits. Although this is better than the initial design of 40 lectures, one to two lectures' worth of material could stand to be trimmed to account for unexpected overruns. The obvious ways to do this are by abbreviating the sections which correspond to 3.022 and 3.032, which are the solid/liquid processing (III) and deformation processing (V) sections respectively. Liquid/solid processing and deformation processing are already somewhat truncated, and are natural fits for this subject in terms of stability and flow behavior and stress vs. strain rate (as opposed to stress vs. strain in elastic mechanics). So this decision will be difficult.

It is worth noting that biological formation of structure is omitted from the above outline. If sections III and V can be streamlined considerably, then this might comprise a new section between VI and VII, with some thought needed to intelligently link this material with 3.034.

Also, although heat treatment (II) and deformation processing (V) are closely coupled in many processes, they are separated here for pedagogical reasons: heat conduction is easy, and non-Newtonian flow with structure changes is hard. In spite of their temporal separation in the outline, it will be important to connect the two in lecture examples and assignments, and to build bridges with laboratory experiences with thermomechanical processing in the 3.042 laboratory.

At this point, it is instructive to list the 3.185 topics omitted from 3.044:

1. All of diffusion.
2. Radiation view factors.
3. The Navier-Stokes equations.
4. Turbulence, turbulent boundary layers, turbulence modeling.
5. Bernoulli equation.
6. Nusselt number and estimating heat and mass transfer coefficients.
7. Natural convection, Grashof and Rayleigh numbers.

If the department decides to go ahead with part-semester electives, these topics (minus diffusion) can collectively be taught thoroughly in about a half semester, which would both round out students' transport education and also leave them in good shape to succeed in graduate subjects in advanced fluid mechanics and transport.

One other property of the large change in content vs. 3.185 is that it will be harder for chemical and mechanical engineers to transfer subjects from their respective departments. For example, whereas 10.301 and 10.302 covered all of the material in 3.185, they cover a fraction of the material planned for 3.044. This can also be seen as a benefit, in that it further distinguishes our department and curriculum from those of the other departments.

Homework

As with the rest of the subject, significant changes in delivery of problem sets can have a big impact on student learning. This area can capitalize on synergies with the concurrent laboratory subject 3.042 in interesting ways:

1. Authorship of new problems. Have the students learn to construct well-posed problems by requiring each laboratory group to contribute one new problem to this subject at some point in the semester.
2. Choice of problems. Allow students to focus their energies on a subset of the problems which one would otherwise assign in this subject, doing a thorough job and typesetting and electronically submitting the result.
3. Critiques of each other's work. Use the Stellar feature which allows students to view each others' work, and assign each to critique the work of those who did not work on the same problems in each assignment. This would expose them to the full range of material on the assignment, provide a peer review incentive to put more into assignments, and place students in a new role.

The last two of these would change the nature of homework assignments considerably, and need to be carefully considered before implementation.

Other Pedagogical Tools

Two tools used with great success in 3.185 were double-testing and “muddy cards”. For the former, students sit a one-hour exam during lecture time as usual, and then their test is returned to them for a second sitting during recitation in which they re-do the parts of problems with errors. The test is then re-graded to account for updates, and the mean of the first and second sitting scores counts toward the final grade. Though it takes more class time, this process changes tests from purely evaluative into a part of the learning process, and provides strong motivation for students to work in groups between tests sittings in order to fill in each other's gaps in understanding. The near-100% performance of almost all students on the second sitting also boosts confidence in their mastery of the material.

“Muddy cards” are an innovation developed by the Aero-Astro department, in which students are given blank index cards at the beginning of each lecture, and asked to write on them everything from questions to points needing clarification to alternative explanations of some of the material, even random points such as “Your twos look like zs; could you please cross the zs to help us distinguish between them?” These cards provides a mechanism for student feedback which is far more immediate than even mid-term evaluations, and which can be used for fine-grained tuning of each lecture from year to year. Furthermore, demonstrating responsiveness to written questions increases confidence and boosts oral participation in lecture as well.

Tasks Ahead

Several tasks remain in the planning of this subject. First and foremost, close coordination with the 3.042 instructors will inform final changes to the outline, which could potentially be substantial. Second, each item in the outline needs corresponding processes to serve as motivating examples in lectures, homework problems, and test questions. Lecture content needs detailed planning, based in part on 3.185 input, as do homework assignments and tests.

But the above framework and outline represent a major step forward in the fundamental rethinking of how we teach our undergraduates about transport and processing, and an exciting component of the new curriculum.