AC 2008-1606: INTRODUCING MATERIALS AND PROCESSES TO FIRST AND SECOND YEAR STUDENTS

Charles Bream, Granta Design, Ltd.

Mike Ashby, University of Cambridge

Introducing Materials and Processes to First and Second Year Students

Abstract

Introducing materials and processes to first and second year students is a challenge. At this level, students study a wide range of subjects that all compete for their time and attention. To stand out in this environment, a course must both stimulate the students' inherent interest in the subject and provide them with the tools and resources that will encourage them to develop this interest further.

This paper presents the methodology, tools and resources of CES EduPack. This teaching aid provides a simple, highly visual and engaging framework that enables students to build a perspective, understanding and an enthusiasm for the subject of materials and processes. The paper also illustrates how CES EduPack's tools can be used to complement a range of teaching and learning styles, including: design-led, science-led, and project-based techniques.

Approaches to materials teaching

There are two main approaches to teaching materials: the science and the design-led approaches. In many circumstances (for example, when teaching students of Physics or of Materials Science) it makes sense to use the traditional science-led approach. This starts with the structure of the atom, building upwards through the physics of bonding, crystal structure and band theory, the thermodynamics and kinetics of alloys, finally arriving at material properties (*Figure 1* - left to right) and their applications.

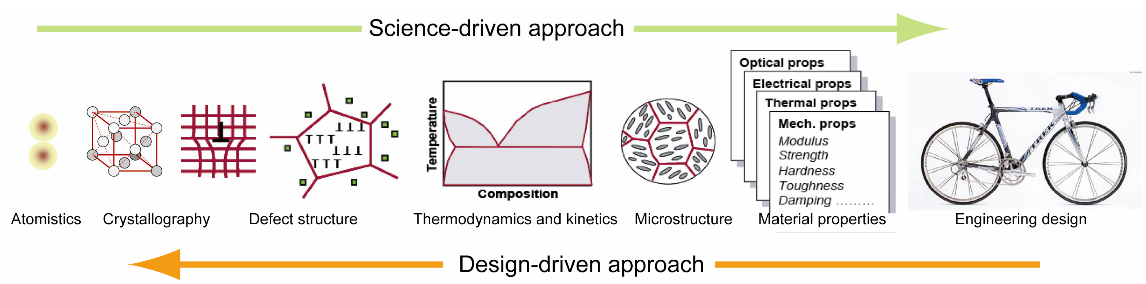


Figure 1. Two alternative approaches (much simplified) to the teaching of materials.

Students of Engineering can find this too remote from the goals that motivate them. Engineers make and manage things. They are interested in the uses and performance of materials. To select materials successfully, they need a perspective of the world of materials plus some understanding of the origin of materials' properties and the ways in which they can be manipulated and selected to meet the requirements of a design. To enable this they need information about materials and tools to enable effective use of this information in their studies.

At the University of Cambridge, working with Granta Design, and colleagues at many other universities, we have developed a design-led approach to teaching engineering students about materials and processes. This approach starts with an introduction to design methods and the ways in which information about materials enters the design process.

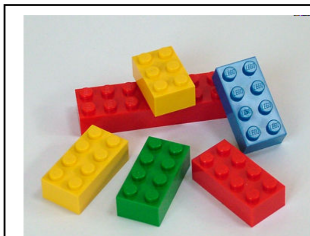
Material properties are presented in property charts that provide an overview of the ranges of the properties and become a selection tool for choosing materials to meet given design constraints. Once the relevance of a property to a design is established, it becomes logical to "drill down" to the underlying science, demonstrating where the property comes from and how it can be manipulated (*Figure 1*, reading right to left).

In developing our design-led courses we have created a number of teaching tools and resources that aim to engage students in the field of materials and processes. And, in recent years, we have optimized these tools to suit the teaching of first and second year courses. In the main, this has been achieved by focusing on four key questions: how to make students relate to materials, how to forge the link between materials and processes, how to prevent students becoming swamped with information, and how to offer the required level of flexibility so that students connect with and get the full benefits from the tools and resources?

These have been addressed as follows:

1) How to relate to materials? – 'The touchy feely effect'
To get a true appreciation or understanding of materials it helps to see, feel and touch them. This can be achieved by building-up a physical materials library but in reality, this is rarely practical: maintaining such a library is a considerable task.

Acrylonitrile butadiene styrene (ABS)



The Material
ABS (Acrylonitrile-butadiene-styrene) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

General properties

Density	1e3	-	1.2e3	kg/m^3
Price	2	-	2.7	USD/kg

Mechanical properties

Young's modulus	1.1	-	2.9	GPa
Hardness - Vickers	5.6	-	15	HV
Elastic limit	19	-	51	MPa
Tensile strength	28	-	55	MPa
Compressive strength	31	-	86	MPa
Elongation	1.5	-	1e2	%
Endurance limit	11	-	22	MPa
Fracture toughness	1.2	-	4.3	MPa.m$^{1/2}$

Thermal properties

Thermal conductivity	0.19	-	0.34	W/m.K
Thermal expansion	85	-	230	µstrain/°C
Specific heat	1400	-	1900	J/kg.K
Glass Temperature	88	-	130	°C
Max service temp.	62	-	90	°C

Electrical properties

Resistivity	2.3e21	-	3e22	µohm.cm
Dielectric constant	2.8	-	2.2	

Typical uses
Safety helmets; camper tops; automotive instrument panels and other interior components; pipe fittings; home-security devices and housings for small appliances; communications equipment; business machines; plumbing hardware; automobile grilles; wheel covers; mirror housings; refrigerator liners; luggage shells; tote trays; mower shrouds; boat hulls; large components for recreational vehicles; weather seals; glass beading; refrigerator breaker strips; conduit; pipe for drain-waste-vent (DWV) systems.

Figure 2. Datasheet for ABS showing the connection to an everyday object

Our solution to this problem is a computer-based materials database that links materials to everyday objects (*Figure 2*). This enables students to relate to the feel and performance of the material. Integrated charting tools (which are discussed further later in this paper) produce highly visual comparisons of the relative properties of materials, helping students to develop a more complete perspective on the different materials families.

2) Forging the link between materials and processes

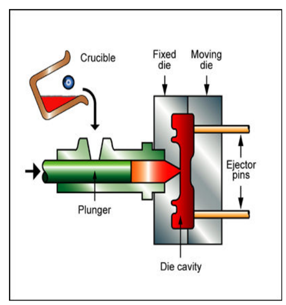
Materials and processes are inextricably linked. Once a particular material is selected for an application, only certain processes are applicable to its manufacture. Of these, the most suitable will depend on a number of additional factors including component shape, size and number required. Although this is an important aspect of component design, it is difficult to teach without going through the laborious task of describing each process and listing the benefits and limitations of each.

We address this issue by incorporating a second database of processes alongside that for materials, containing a similar level of information (*Figure 3*). Each process record in this database is linked to records in the materials database that can be shaped, formed or treated by this process. For example, the record for *die casting* is linked to all materials that can be shaped using the die casting process. Similarly, each material record is linked to the processes that can shape, join or finish it. The key benefit of this structure is that it enables students to explore the advantages and limitations of various processing techniques, in context, allowing them to learn about processes as part of the material selection process.

Die casting

The process

Most small aluminum, zinc or magnesium components with a complex shape - camera bodies, housings, the chassis of video recorders - are made by DIE CASTING. It is to metals what injection molding is to polymers, and the two compete directly. In the process, molten metal is injected under high pressure into a metal die through a system of sprues and runners. The pressure is maintained until the component is solid, when the die is opened and the component ejected. The dies are precision-machined from heat-resistant steel and are water cooled to increase life.



Shape

Circular prismatic	True
Non-circular prismatic	True
Solid 3-D	True
Hollow 3-D	True

Physical attributes

Mass range	0.022 - 110 lb
Range of section thickness	19.7 - 472 mil
Surface roughness (A=v. smooth)	A
Tolerance	5.91 - 19.7 mil

Economic attributes

Relative tooling cost	high
Relative equipment cost	high
Labor intensity	low
Economic batch size (units)	1e4 - 1e6

Typical uses

Record player and video player chassis, pulleys and drives, motor frames and cases, switch-gear housings, housings for small appliances and power tools, carburetor and distributor housings, housings for gearboxes and clutches.

Figure 3: Part of a record for Die casting showing the type of information stored in the Process database

3) Providing the correct level and balance of information

One of the main challenges in creating databases of materials and processes is that of balance and level of detail. The number of engineering materials, processes and process-variants is vast; making discrimination necessary to avoid swamping students in detail – a problem particularly acute in 1st and 2nd second year teaching. This balance has been achieved by structuring the information in the database in several ways.

Firstly, we have split our standard database into three levels so that the amount of available information can be selected to suit the level of student. Level 1, which is aimed at 1^{st} year students, contains just 66 materials and 77 processes. This increases through Level 2, reaching 2849 materials and 232 processes at Level 3.

In addition to this phased exposure to the number of materials and the links between materials and processes, that have already been discussed, additional information on each property listed in a datasheet is linked to a 'science note'. This enables students, if interested, to drill down to detailed information on; the meaning of the property, how it is measured and how it relates to the underlying material structure. In instances where further information is required, a 'Further Reading' section at the end of each science note directs students to the relevant chapter in key materials texts.

This structuring of information in the database ensures that students are never overloaded with information, but still allows them to readily explore the world ofmaterials in more depth if they desire.

4) Maximizing scope and flexibility

Students respond in different ways to different teaching approaches. What works for one student, may not work for the next. As mentioned in the introduction, Engineers often fail to connect with the science-led approach used for teaching Material Science students. As a result, it has become good practice to incorporate a range of teaching styles and techniques into a course, with a balanced combination of lectures, demonstrations and project work.

We have built a series of teaching resources around the databases introduced above. These include charting and selection software, standard PowerPoint lectures, solution sets, new textbooks, and textbook-style 'science notes' that are embedded within the software. This toolkit is called CES EduPack. Although we were initially guided by a design-led approach, we soon realized that, in developing CES EduPack, it was important to provide flexibility so that teachers could use its resources in a way that suits their needs, whatever their teaching approach (science or design-led) or style (lecture or project-based). We have aimed to do this, and we find users of EduPack 'mixing and matching' its elements in many different ways in order to support their diverse needs.

Using the CES EduPack

In the rest of this paper, we discuss some of the ways that the CES EduPack resources are used to introduce students to materials and processing.

Property charts, selection and science

Figure 4 is an example of a material property chart (elastic modulus, E, plotted against density, ρ) created within the CES EduPack selection software. The range of the axes is chosen to include all materials, from the lightest, softest foams to the stiffest, heaviest metals. The properties of a given family of materials (polymers, for example) cluster together; the *sub-range* associated with one family is, in all cases, much smaller than the *full range* for that property. Data for one family can be enclosed in a family-envelope, as the figure shows. Within it lie bubbles enclosing classes and sub-classes. All material properties can be presented in this way. They provide a tool-set for material selection to meet specified design constraints, the methods for which are integral to our design-led course.

Within introductory courses – whether design-led or not – the charts can be used to explore another set of questions. Why do members of material classes cluster in the way they do? What determines where clusters lie on the charts? Why are some properties so obviously correlated? How can properties be manipulated to better meet design requirements? These questions are a natural lead-in (and one the engineering student sees as relevant) to the underlying science of the material classes – the atomic bonding and packing determining density, melting point and stiffness; the defect structure determining hardness, strength, toughness; the transport properties and the magnetic behavior.

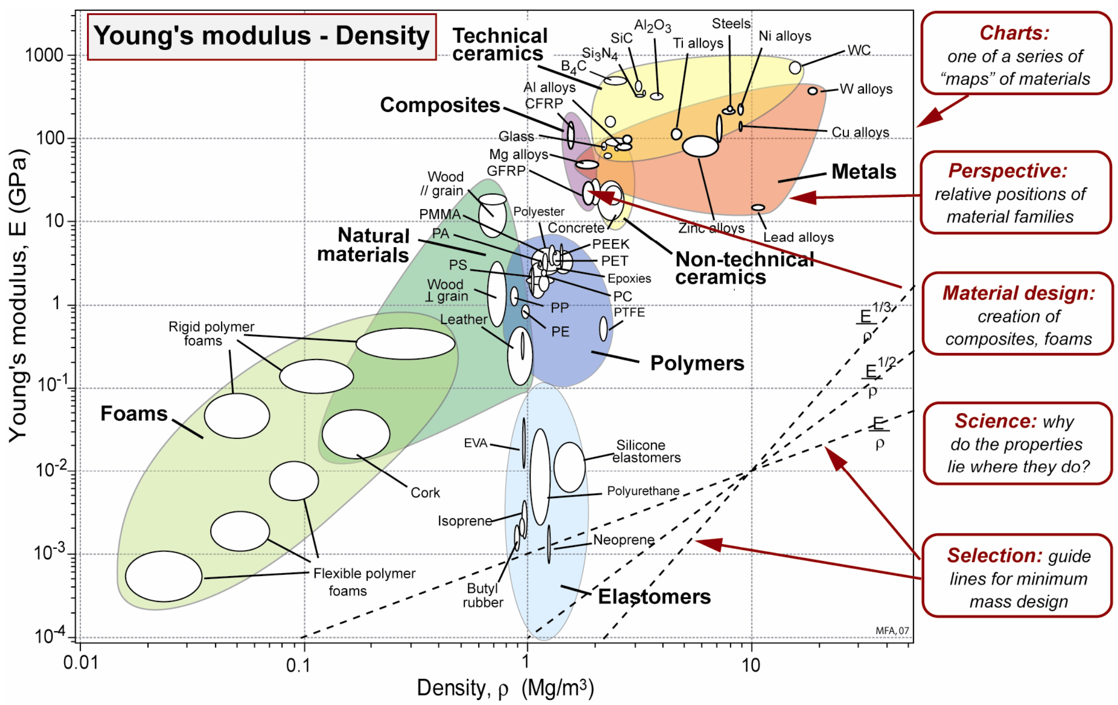
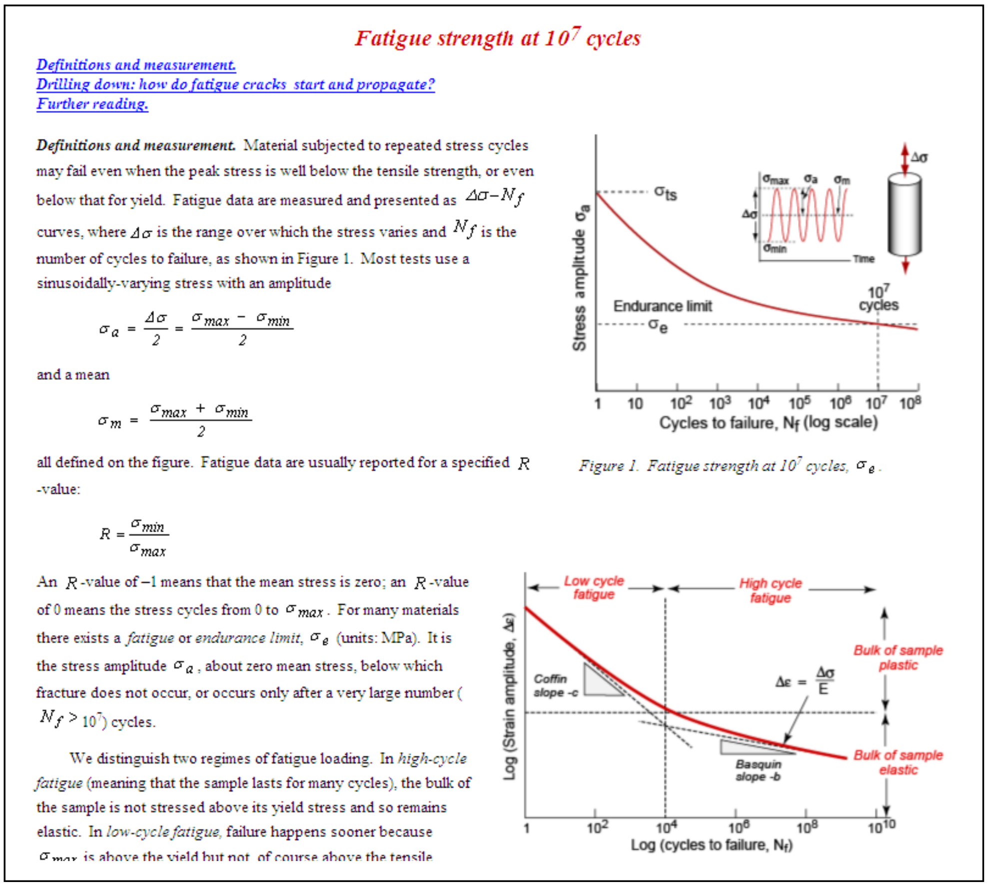


Figure 4. An example of a materials property chart and its use to give a perspective, to allow selection, to explore how properties are manipulated, and to introduce the underlying science.

Encouraging use of these charts to explore the materials world stimulates student interest. But, as understanding progresses, more detail is needed. The CES EduPack software, developed specifically for education, can help, allowing students to create charts with any combination of properties, to zoom in on any part to increase resolution, and to access records for the attributes of any material (*Figure 4* was created with the software).

This highly visual way of representing materials properties is enhanced by the ability to combine properties on the axes, enabling real engineering design requirements to be displayed (for example, a plot of specific stiffness against specific strength). Beginning with a chart, both the engineering context for a material of interest, and the science underlying its properties, can be quickly and easily explored. The student can click through from a material on a chart to a record such as that in *Figure 2*, which starts with a description of the material and an image of a familiar object made from it – a way of conveying its use in industrial design. That is followed by a table of material properties, a list of typical uses, and, in a higher level of the software, design guidelines, technical notes and notes concerning its impact on the environment. As we discussed above, each property in a material record is linked to a science note *(Figure 5)* giving a definition of the attribute, a description of how it is measured and explanation of its origins. Finally, there is the link to the parallel database of processes.



Fatigue strength at 10^7 cycles

Definitions and measurement.
Drilling down: how do fatigue cracks start and propagate?
Further reading.

Definitions and measurement. Material subjected to repeated stress cycles may fail even when the peak stress is well below the tensile strength, or even below that for yield. Fatigue data are measured and presented as $\Delta\sigma - N_f$ curves, where $\Delta\sigma$ is the range over which the stress varies and N_f is the number of cycles to failure, as shown in Figure 1. Most tests use a sinusoidally-varying stress with an amplitude

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

and a mean

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

all defined on the figure. Fatigue data are usually reported for a specified R -value:

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

An R-value of -1 means that the mean stress is zero; an R-value of 0 means the stress cycles from 0 to σ_{max}. For many materials there exists a *fatigue* or *endurance limit*, σ_e (units: MPa). It is the stress amplitude σ_a, about zero mean stress, below which fracture does not occur, or occurs only after a very large number ($N_f > 10^7$) cycles.

We distinguish two regimes of fatigue loading. In *high-cycle fatigue* (meaning that the sample lasts for many cycles), the bulk of the sample is not stressed above its yield stress and so remains elastic. In *low-cycle fatigue,* failure happens sooner because σ_{max} is above the yield but not, of course above the tensile

Figure 1. Fatigue strength at 10^7 cycles, σ_e.

Figure 5: Part of the Science Note for ‘Fatigue strength’

We have found that the CES EduPack software provides a simple, highly visual and engaging, framework within which students can explore rich content – “drilling down” to the fundamental science and making a direct connection between this science and design applications. Such connections help to build a materials perspective and understanding and can be particularly valuable in developing an enthusiasm for the subject amongst first and second year students.

Supporting texts and resources

The computer-based tools of CES EduPack can only provide one component of a rounded introductory materials course. We have developed a series of supporting lectures and exercises that can help lecturers to build such a course. The choice of supporting textbook(s) will also be vital.

The CES EduPack software introduces materials fundamentals in a manner that complements any introductory materials text regardless of the approach (science or design-led) or the text from which it is taught. For example, Callister's "Materials Science and Engineering: an Introduction" (2), Budinski's "Engineering Materials" (3) or Askeland's "The Science and Engineering of Materials" (4), all of which take the science-led route, can be augmented and reinforced with software-based exercises to explore the world of materials.

We have developed the design-led approach in a number of texts, of which two are appropriate for first and second year teaching. A new text "Materials: engineering, science, processing and design" (5) introduces key methods and illustrates their application to the use of materials in mechanical, thermal, electro-magnetic and optical design. It offers a high degree of integration with CES EduPack, including exercises using the software. "Materials and Design" (6) addresses issues of industrial design, providing an introduction to materials for students of product design. "Materials Selection in Mechanical Design" (7) is a more advanced text, developing the methods to a higher level, one appropriate for third, fourth year and masters level teaching. All three have numerous exercises for which solution manuals are available.

Project-based teaching

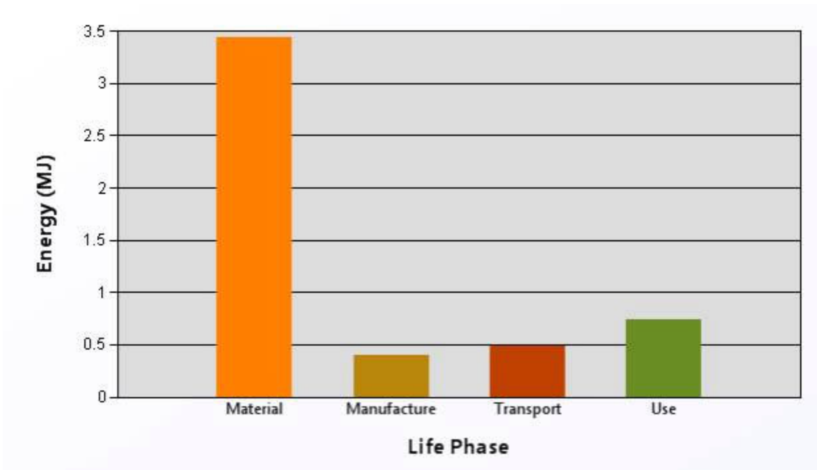
The CES EduPack provides a resource for project-based teaching. The projects that we use for first and second year students focus on analyzing material choice for familiar products, avoiding at this early stage the need for a detailed understanding of complex systems.

In the Bicycle Project, for example, students are first asked to select a component of a bicycle (frame, forks, saddle, spokes, brake-cable…) and a user group (e.g., children, shoppers, touring use, sprint, mountain biking…) for which the design is intended. They are then asked to formulate the requirements if the product is to meet the needs of that group and the objective appropriate to it (minimizing weight or cost, maximizing robustness…). These provide the inputs for the CES EduPack software, which delivers a ranked list of suitable candidates, datasheets for their properties, and suggested manufacturing routes.

Redesign to reduce the environmental impact of a product is a rich source of projects. The students must decide which phase of life (material production, product manufacture or product use) poses the greatest environmental problem, and then select appropriate materials to minimize this. The eco properties data provided with the CES EduPack database and an Eco Audit Tool *(Figure 6 is an abstract of the report generated by the eco audit tool)*, new for CES EduPack 2008, provide the resources to enable projects of this sort.

1 litre bottle of mineral water

Materials: 40g PET bottle, 1g PP cap, 1kg water



Phase	Energy (MJ)	Energy (%)
Material	3.442	67.88
Manufacture	0.402	7.92
Transport	0.487	9.60
Use	0.741	14.60
Total	5.071	100

Figure 6: Summary generated by the Eco Audit tool, identifying that the material phase is the dominant life phase for a bottle of mineral water

Summary

First and second year students need: a materials perspective, methods, tools and understanding to enable the rational selection and use of materials. Strong links with design, for example via a design-led teaching approach, can provide immediate integration with other engineering subjects. Whatever approach is adopted, the simplicity and visual impact of property charts offer valuable support, particularly within computer-based tools such as CES EduPack. Experience shows that students like such tools, which motivate them to explore materials for themselves.

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