New Approaches to Materials Education for Students of Engineering

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Abstract

A novel approach to the teaching of materials to engineering students is outlined. It starts from the overview of the "world" of materials made possible by material property charts, and develops both an understanding of material properties and skills in selecting materials and processes to meet design specifications. It is supported by extensive computer-based methods and tools, and is well adapted both for elementary and for advanced courses.

1. Why do we teach engineering students about materials?

Materials science is a discipline, like any other branch of science. There are powerful arguments for the approaches to teaching of any one of these: the scientific method, the rigour, the ability to apply logical thought and reasoned experimentation to physical problems in the broadest sense. And the subject of materials *is* a broad one, drawing together understanding from physics, from chemistry, from mathematics and – these days – from computer science [1-11]. But while the study of materials bridges these "pure" disciplines, it is, in the end, an applied science. Engineering schools include and value its teaching because engineers *make* things, and they make them out of materials.

The teaching of materials today is still coloured by its more recent history, in which the physicist and chemist played a great part. The starting point (taking the physicist's view) is Schroedinger's equation; the reasoning leads on to concepts of atomic bonding, to the geometry of molecular and crystal structures, to crystal defects and the glassy state, to alloy theory and phase stability, the kinetics of phase transformations, the mechanisms of plasticity and fracture … and so on, gradually moving up through the length-scales from the atomistic through the microscopic to the macroscopic. This understanding is the foundation on which the subject rests, and for that reason there is a reluctance to approach it in other ways. But it is a path that creates a difficulty: the information the engineer really needs to perform his or her role as a *maker* of things comes only at the end or not at all.

Alternative approaches are possible. One is to start at the other extreme: a birds-eye view of the "world" of materials, mapping their properties, giving from the start some ability to navigate in this new environment and apply materials information during the engineering design process. It is then possible to focus-in progressively, exposing a gradually increasing level of detail. This is not to reject the underlying underpinning of physics and chemistry;

these can be developed as the details requiring them come into focus. The motive, rather, is to give the students tools that they can use immediately in their role as engineer, refining these tools as the course advances.

Briefly put, this is the thinking behind the approach we have developed over the last 15 years at Cambridge. The objective: to provide engineering students, in a limited number of class hours, with the *understanding*, the *methods* and the *tools* to make educated decisions about the choice of materials and processes. We have found it to be effective in engaging the interest of students, increasing enrollment in material courses, and stimulating interaction with students and colleagues in mechanics, thermodynamics, structures, electrical engineering, manufacturing and design. The approach, described in a little more detail below, makes maximum use of computer-assisted methods, further stimulating student engagement and enabling project work that can be set by the instructor or self-generated by the student.

2 A brief outline of the approach

The starting point is the "world" of materials. Figure 1 shows the material families: *polymers, metals, ceramics, glasses, natural materials*, and the *composites* that can be synthesised by combining these. Figure 2 expands this structure, suggesting a hierarchical organisation of the population. Each family embraces classes, sub-classes and members; in Figure 2, the family of metals is expanded to show the class of aluminum alloys and the sub-class of 6000-series aluminum alloys, containing many members (e.g. Al-6061). A member is characterised by a set of attributes – its "property profile" – indicated on the right of the figure. A structure such as this has the merit that it is easily understood, can be limited initially to the ten or so "commodity" classes in each family (thus about 60 materials in all) that, collectively, account for about 98% of all material usage. The structure can be expanded further (and deepened) as the student progresses.

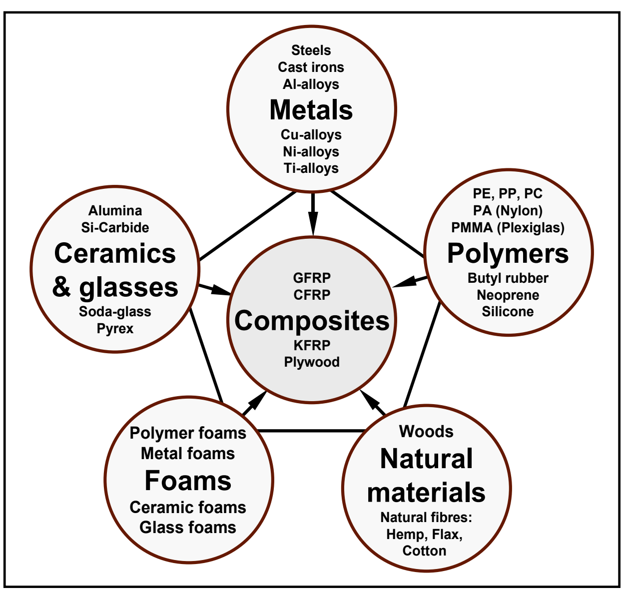


Figure 1 The world of materials

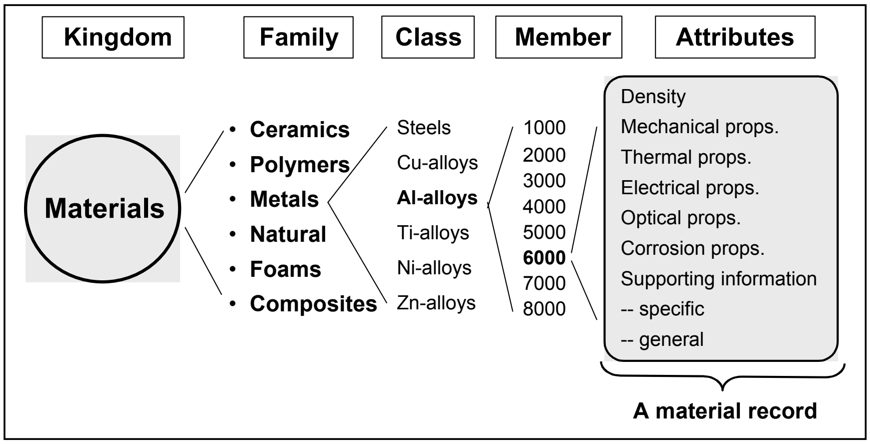
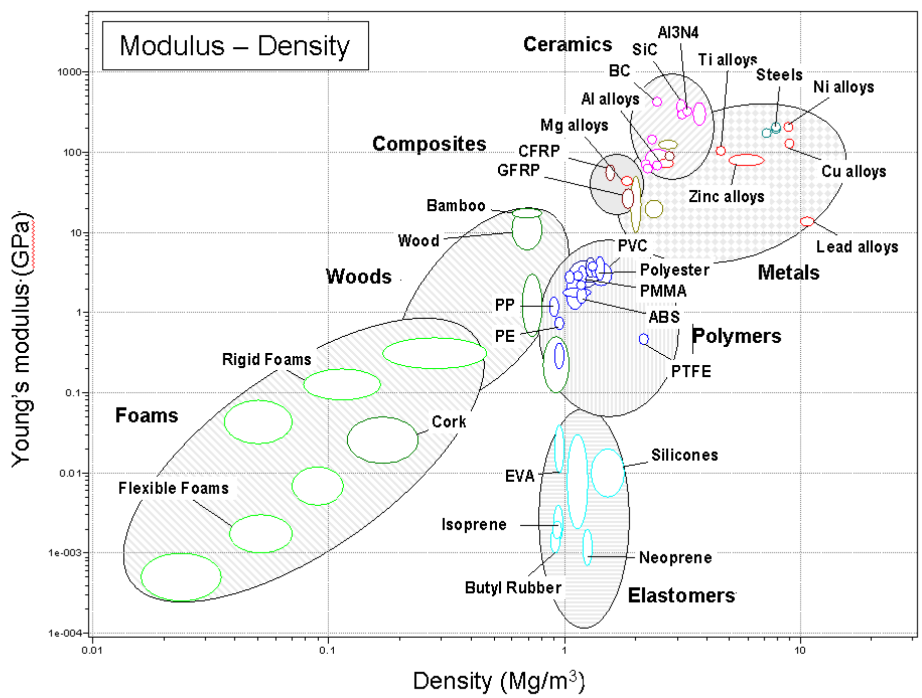


Figure 2. A hierarchical classification of materials, ending with a record.

From this emerges a helpful concept: that of the "material property chart", of which Figures 3, 4 and 5 are examples. Each is a map, so to speak, of one slice through material-property space. Figure 3 plots *stiffness*, measured by Young's modulus, against *weight*, measured by density. The large balloons enclose the members of the families: metals, polymers, ceramics and so on. Each occupies a characteristic area of the map; *all* metals lie in the "metals" balloon , none outside it.



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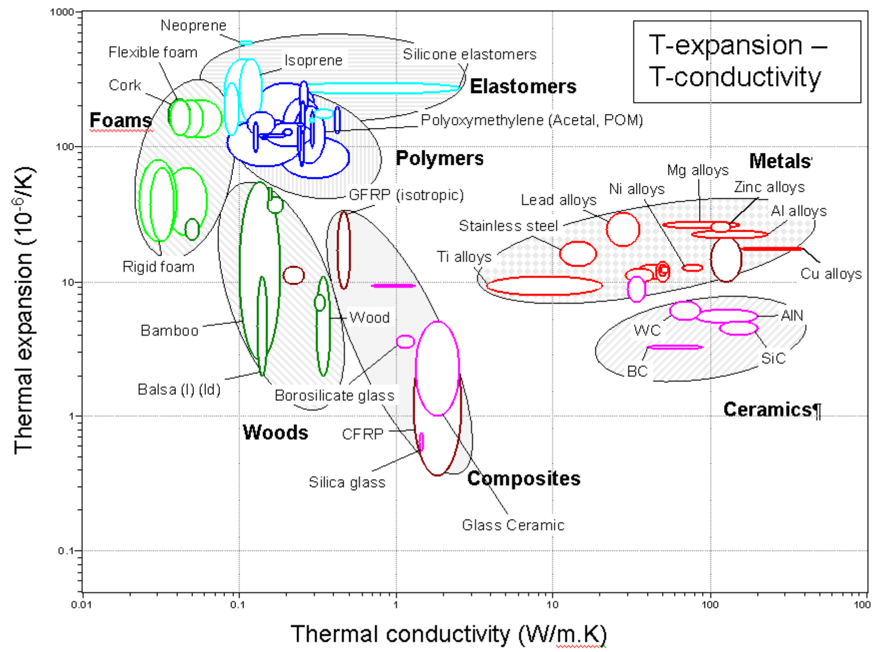


Figure 4. A chart of thermal conductivity and thermal expansion for materials created using the CES4 software with the Level 1 database

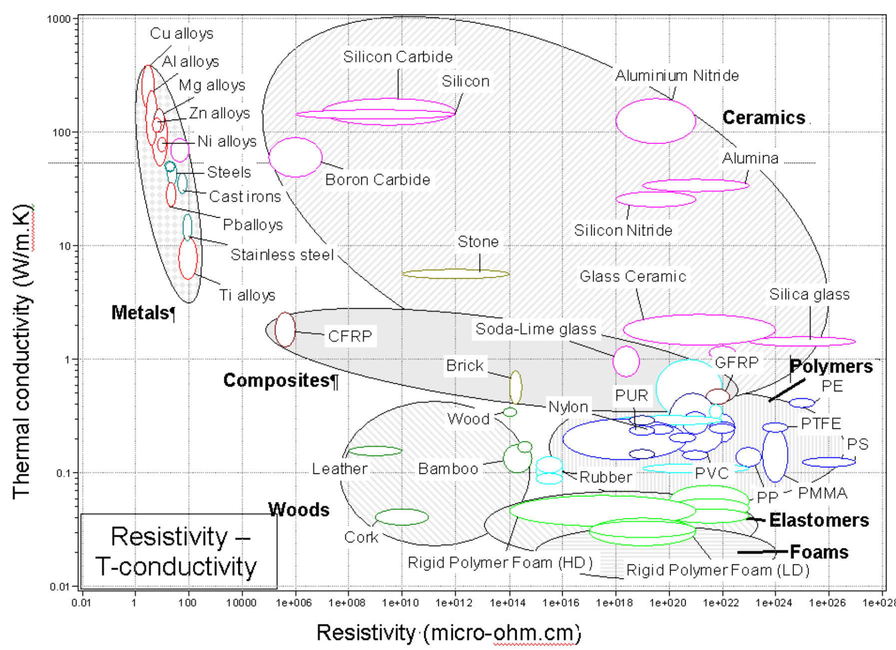


Figure 5. A chart of electrical resistivity and thermal conductivity materials created using the CES4 software with the Level 1 database

Within each balloon are the material classes, and if the resolution were sufficient, the individual members would come into focus. Figure 4 shows a pair of thermal properties, conductivity and expansion coefficient, mapped in a similar way. Again, each class occupies a characteristic area of the map. Electrical properties can be mapped in a similar way: Figure 5 shows the electrical resistivity and the thermal conductivity. The chart makes it clear that, for metals at least, the two are closely correlated. Hand-drawn versions of these charts are available for all the usual material properties*.

Already the student has something useful for engineering design. A design requires a material that is light and stiff – Figure 3 guides the choice. A material with low thermal expansion or expansion that matches another material? Figure 4 suggests answers. A material that conducts heat well but is an electrical insulator? Figure 5 provides candidates. The charts put material properties in perspective: metals are 20 to 100 times stiffer than polymers and conduct heat 100 times faster. Elastomers have enormous expansion coefficients but are excellent electrical insulators. This "order of magnitude" familiarity is useful; much engineering design, even today, is intuitive, but the intuition is informed by just this sort of familiarity.

The charts lead naturally to another set of questions. Why do the members of each material class cluster in the way they do? What determines where the clusters lie on the charts? Why are some material properties so obviously correlated? 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 behaviour. The materials texts cited as references [1] – [6] provide this information.

Student interest is stimulated by encouragement to use these charts to explore the materials world. But as understanding progresses, more detail is needed. It is here that software can help, allowing the student to create charts with any desired combination of properties, to zoom in on any chosen part to increase resolution, and to access records for the attributes of individual materials. Figures 3, 4 and 5 were created using one such software package [12] specifically designed for education. It is described next.

3. The content and use of the educational software.

The CES educational software is an information platform for materials and processes. It draws on three levels of data and methods, simple at the start but progressing to a professional-level materials selection system for advanced students and postgraduate training. Level 1 contains limited data for 66 of the most widely used materials, drawn from the six families of Figure 1. Each record, of which Figure 6 is an example, starts with a brief description of the material and its history, illustrated with an image of a familiar product in which it is used. Numeric data follow for the most basic mechanical, thermal, electrical and optical properties. A material record ends with a list of its common applications. Manufacturing processes for shaping, joining and finishing, 65 of them in all, are treated in a similar, simple way: a description, a schematic illustrating how the process works, a brief list

* The charts can be copied from the text "Materials Selection in Mechanical Design", listed as reference [10] in the text, or downloaded from www.grantadesign.com without restriction of copyright.

of attributes and applications (see Figure 7). The Level 1 system allows the student to explore materials and processes without being overwhelmed by detail.

Polypropylene (PP) (CH2-CH(CH3))n

Polypropylene, PP, first produced commercially in 1958, is the younger brother of polyethylene - a very similar molecule with similar price, processing methods and application. Like PE it is produced in very large quantities (more than 30 million tons per year in 2000), growing at nearly 10% per year, and like PE its molecule-lengths and side-branches can be tailored by clever catalysis, giving precise control of impact strength, and of the properties that influence molding and drawing. In its pure form polypropylene is flammable and degrades in sunlight. Fire retardants make it slow to burn and stabilizers give it extreme stability, both to UV radiation and to fresh and salt water and most aqueous solutions.

General properties

Density	0.89	-	0.91	Mg/m^3
Price	0.601	-	0.878	GBP/kg
Energy content	76	-	84	MJ/kg

Mechanical properties

Young's Modulus	0.896	-	1.55	GPa
Elastic Limit	20.7	-	37.2	MPa
Tensile Strength	27.6	-	41.4	MPa
Elongation	100	-	600	%
Hardness - Vickers	6.2	-	11.2	HV
Endurance Limit	11	-	16.6	MPa
Fracture Toughness	3	-	4.5	$MPa.m^{1/2}$

Thermal properties

Melting point	423	-	448	K
Maximum Service Temperature	356	-	380	K
Thermal Expansion	122	-	180	µstrain/K
Thermal Conductivity	0.113	-	0.167	W/m.K
Specific Heat	1870	-	1960	J/kg.K

Electrical properties

Conductor or insulator?	Good insulator			
Resistivity	3.3e+022	-	3e+023	µohm.cm
Dielectric Constant	2.2	-	2.3	
Power Factor	5e-004	-	7e-004	
Breakdown Potential	22.7	-	24.6	MV/m

Optical properties

Transparent or opaque?	Translucent

Typical uses.

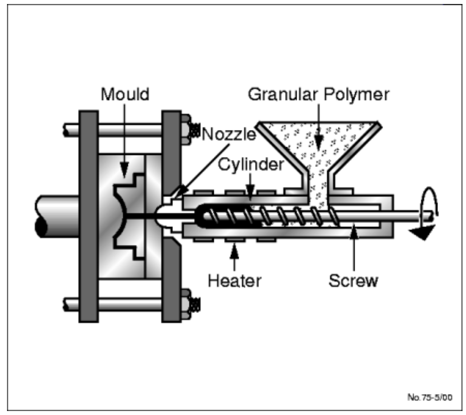
Ropes, general polymer engineering, automobile air ducting, parcel shelving and air-cleaners, garden furniture, washing machine tank, wet-cell battery cases, pipes and pipe fittings, beer bottle crates, chair shells, capacitor dielectrics, cable insulation, kitchen kettles, car bumpers, shatter proof glasses, crates, suitcases, artificial turf, thermal underwear.

Figure 6. An example of a Level 1 material record.

Injection molding

No other process has changed product design more than injection molding. Injection molded products appear in every sector of product design: consumer products, business, industrial, computers, communication, medical and research products, toys, cosmetic packaging and sports equipment. The most common equipment for molding thermoplastics is the reciprocating screw machine, shown schematically in the figure. Polymer granules are fed into a spiral press where they mix and soften to a dough-like consistency that can be forced through one or more channels ('sprues') into the die. The polymer solidifies under pressure and the component is then ejected.

Thermoplastics, thermosets and elastomers can all be injection molded. Co-injection allows molding of components with different materials, colors and features. Injection foam molding allows economical production of large molded components by using inert gas or chemical blowing agents to make components that have a solid skin and a cellular inner structure.



Physical Attributes

Mass range	0.01	-	25	kg
Range of section thickness	0.4	-	6.3	mm
Tolerance	0.1	-	1	mm
Roughness	0.2	-	1.6	µm
Surface roughness (A=v. smooth)	A			

Economic Attributes

Economic batch size (units)	1e+004	-	1e+006
Relative tooling cost	very high		
Relative equipment cost	high		
Labor intensity	low		

Shapes

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

Typical uses

Extremely varied. Housings, containers, covers, knobs, tool handles, plumbing fittings, lenses.

Figure 7. An example of a Level 1 process record.

Level 2 retains this format, expanding the range of attributes for which data are listed, and adding information on design, on technical details and on possible environmental concerns. It allows more ambitious exercises and projects, still without smothering the student with information. The final, third level, develops this yet further with substantially expanded lists of properties and a much larger number of data records, providing a tool with which the student is already familiar, but now capable of professional-level selection exercises and projects (currently 2940 materials, 207 processes).

All three levels are managed by the same search and selection engine, so although the complexity and power increase, the interface remains familiar. Records can be retrieved by a number of simple search methods. More challenging (and stimulating) is the range of tools for selection to meet a set of engineering design requirements. The aim here is *not* that of producing "Nintendo-engineers", able to click a mouse while following a set procedure. It is rather to develop systematic methods that engender understanding and encourage creative thinking. A selection exercise starts with an analysis of the design requirements: What is the function of the component? What constraints must it meet? What objectives influence the choice (maximising performance, perhaps, or minimising cost)? What freedom of choice exists – choice of material, of dimensions, of shape? The selection tool allows the user to eliminate materials that fail to meet the constraints and to rank the candidates that remain by their ability to meet the objective. Trade-off methods allow compromises to be reached between conflicting objectives (performance versus cost, for instance).

As an aid to instructors teaching a course on this subject, a comprehensive set of PowerPoint presentations with additional notes for instructors [13], case studies [14] and problem sets are available, providing the material for lectures and classes. These dovetail with the texts [10, 11] in which the selection methods are developed in full.

The progression through the three levels provides the students with the knowledge and confidence to select materials for mechanical, thermo-mechanical and electro-mechanical design, as well as processes for forming, joining and surface treating the materials. It provides a tool that they take with them when they leave the university and start a professional career.

4. Further adaptation to student needs.

The needs of a course for engineers working in aerospace design differs from those of one for the design of civil structures or for product design. A benefit of computer-aided teaching is the ability to customise it, arranging that the materials to which the student has access are those relevant to the subject. Thus a course on aerospace engineering requires access to data for light alloys and composites, and perhaps for materials that meet US military specifications (MIL-HDBK 5 for metals and MIL-HDBK 17 for composites). A course for civil engineers requires data for cement, concrete, structural grades of steel, aluminium and wood, and for structural sections made from these. One on product design might benefit from access to a large amount of grade-specific polymer data that meets ISO standards. All of these datasets exist. State of the art educational software such as the CES system [12] allow easy adaptation both to the level of the course and its subject matter. The software includes a toolkit which enables instructors to adapt the databases to their own specific requirements. It allows the databases to be copied, edited, expanded or augmented with completely new, user-created databases. This opens up the possibility of projects of an advanced nature, creating information systems to support other design activities.

5. Closing note

The number and variety of materials available today is increasing at a rate faster than at any previous time. The next generation of engineers – the ones we are educating now – will need the ability to use materials of all sorts (conventional as well as advanced) in ways that meet more demanding technical, environmental, economic and aesthetic requirements than ever before. Forward-looking engineering education aims to provide the student with *understanding*, with *methods* to apply the understanding, and with *tools* to facilitate this application; examples of the last is a facility with FE, solid modeling and other CAD software. The aims of materials teaching should, in our view, be the same. This paper describes our approach to realizing these.

Acknowledgements

(i) The ideas, methods and tools described here have evolved over the past 15 years. Numerous colleagues in many countries have (sometimes unknowingly) stimulated or contributed to this evolution. Among these we would particularly like to recognise Prof. Yves Bréchet (Grenoble, France), Profs. Ken Wallace, Norman Fleck and Chris Calladine and Drs. John Clarkson and Hugh Shercliff (Cambridge, UK), Prof Dave Embury (McMaster, Canada) and, above all, the staff of Granta Design, Cambridge.

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Biographical Information

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