Supporting Undergraduate Materials Science Teaching: Shackelford-based Courses and CES EduPack

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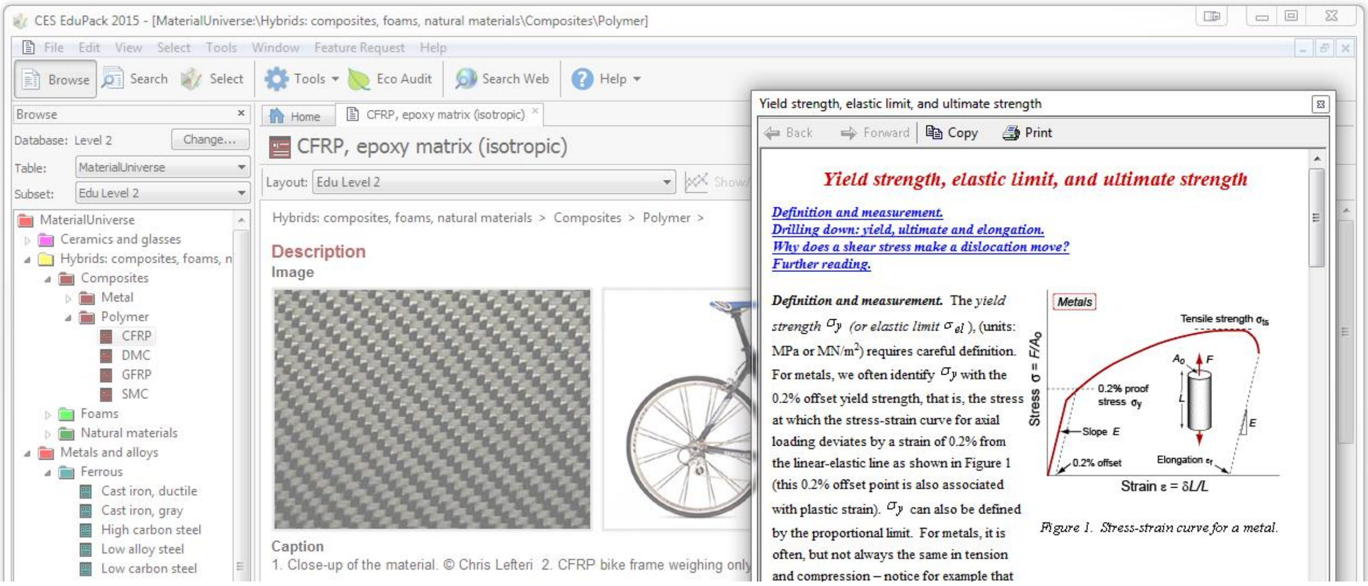


Introduction

Materials Science and Engineering can be taught without textbooks, however textbooks like those written by James Shackelford, Askeland and Fulay, William Callister, and so on can strengthen a course, significantly enhancing its structure and quality. *Introduction to Materials Science for Engineers, by James Shackelford* is one such text; using what is often called a science-led approach over a wide range of different materials classes. The CES EduPack is designed to complement and support teaching based around all the major textbooks for Materials, for both science-led and design-led approaches. In this paper we will discuss how courses based on Shackelford's textbook can use CES EduPack. The paper will show explicitly how the two resources can work together to provide an enhanced learning experience. The examples given here however, are also valid for most of the other leading textbooks in the field.

Shackelford, as we will refer to the textbook by this author, now in its 8th edition, is the primary text used in Materials Science in a large number of Universities. Building on the success of previous editions, this book continues to provide engineers with a strong understanding of the fundamentals as well as an overview of different material classes and their applications. The strength of the book comes from a balanced approach to Metals, Ceramics, Glasses, Polymers and composites and the engaging way in which it approaches the topic, with examples where materials have changed the world, mini biographies of materials scientists and engineers and case studies.

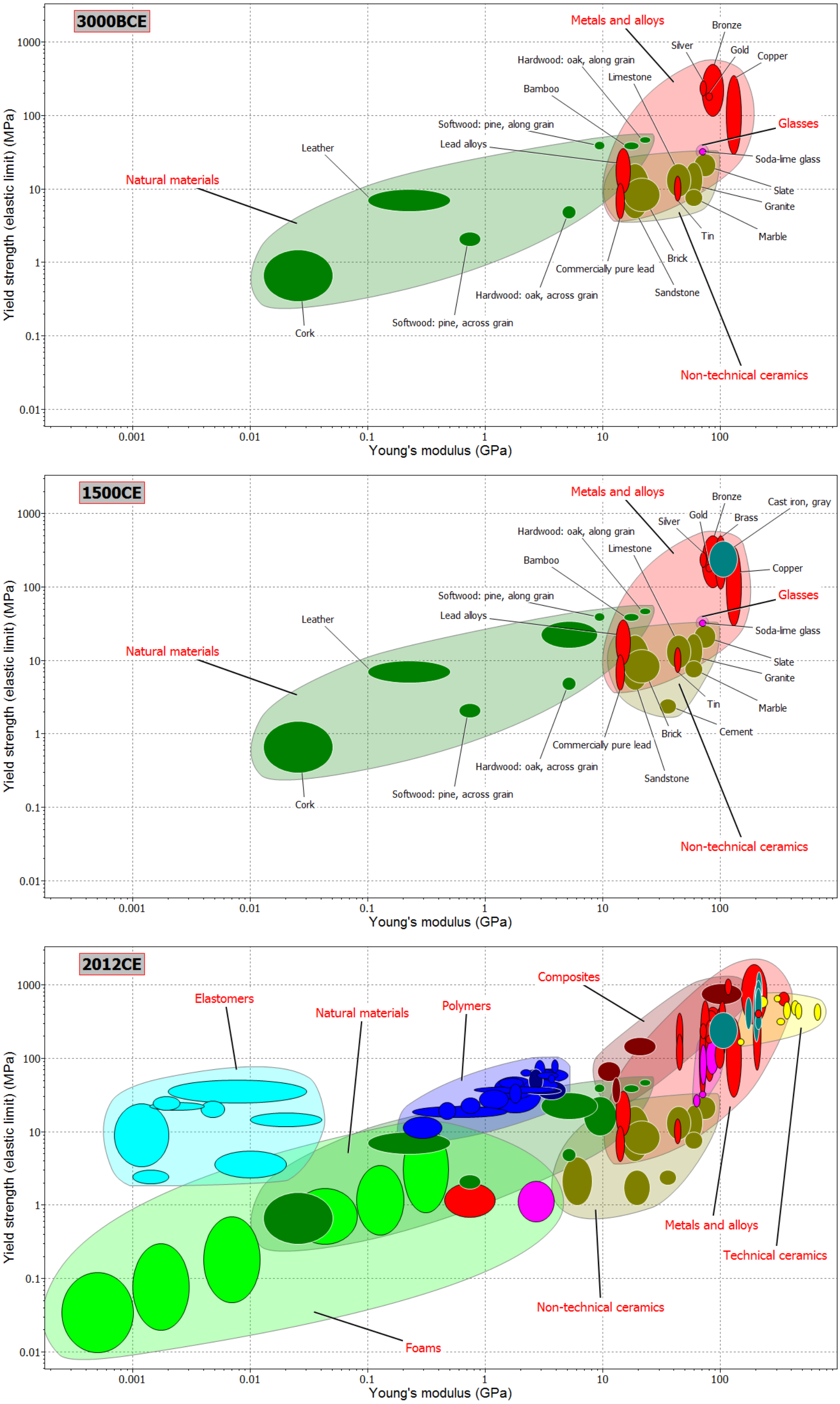


Figure 1. *The evolution of materials availability*

CES EduPack is a resource for supporting materials and manufacturing processes related courses across many engineering, science and design disciplines throughout all years of study. It has three levels with progressively increasing content: the simplest, designed for introductory materials teaching; the intermediate, for most 2nd to 4th year courses and the third for advanced undergraduate and Master's level teaching and project work. It is used at over 1000 Universities and Colleges worldwide and is developed year on year, in collaboration with the academics that use it around the world.

Complementing classical textbooks on materials science

At the heart of CES EduPack is a Materials and Processes Database containing records that cover thousands of engineering materials. There are three levels of the database, supporting teaching and learning from introductory courses to postgraduate levels. Levels 1 & 2 contain a limited number of material records, focused on introducing students to the key materials classes and the most important properties. Each material property in these records is linked to a so-called 'Science Note', which gives a brief explanation for the property, its definition, measurement and the underlying science. At the bottom of these explanations there are references to further reading on the topic. These include references to Shackelford and other textbooks – detailing the specific chapter in which the property is covered.

Books and software are obviously different. One advantage of a book is its longevity. It is a data format that will probably out-live any software around today! However, this is also its disadvantage. As the world of materials develops, texts like Shackelford have more and more to cover. While the problem of out-dated data can be solved by a new edition, the issue of which materials to cover in depth, and how to fit everything into 1000 pages, becomes more difficult. That is where software has an advantage. As long as the browsing and searching functions of a piece of software are easy enough to use, you can fit in (and update) a lot more data in an accessible way. CES EduPack Level 3 contains about 50 sets of property data on about 3900 materials. It also directly links to the ASM International Handbooks online for even more information, and specialist editions contain much more: in the Polymer Edition alone, a total of individual material records approaching 95000 is available for browsing, searching and selecting from.

Complementing Shackelford visually is something that both academics and their students may find engaging. The historical perspective in **Chapter 1** can take advantage of the "date first used" feature in CES EduPack that lets you plot the materials available to mankind at a certain time in history. Figure 1 shows the evolution of the number and type of materials availability throughout the history of mankind in a plot of yield strength versus Young's modulus. One can easily identify the shift from natural to man-made materials and the increasing population of the area in the plot over the years, from 3000BCE to the present. This ties in nicely with the very first section of Shackelford, where the book makes the inspirational point that the development of materials has defined Ages and shaped the world around us.

CES EduPack at the micro scale

Figures and data in Shackelford, such as those on atomic properties (Figures 3.4-3.6, Table 5.2 and Appendix 2) or materials properties (**Chapter 6** and Appendices 2 & 4) are, by necessity, short and rather dry. CES EduPack can support these sections, and others, by presenting data in an easy-to-find and easy-to-view way, via materials records with images of typical uses. The data can also be presented graphically, giving more context and helping visual learners to soak in the main points. Often the important thing is not to memorise a particular value, but to understand trends and relationships between properties. CES EduPack can therefore be used as a data resource to support and extend the 'Problems' section at the end of each chapter in Shackelford, and as a way for students to self-learn by exploring different materials and creating their own property charts. Receiving information in multiple and interactive formats can often help students retain knowledge more easily. Mini "Research" assignments can be set on topics in Shackelford and can be carried out by students using CES EduPack as an information resource. Students can copy and paste charts and datasheets into a homework report.

In the examples of Figures 3.4-3.6 in Shackelford, one possible illustration is a plot of atomic radius versus lattice parameter a (the unit cell edge length) in Figure 2. One can notice that, as expected, the volume of the unit cell is directly related to the atomic radius and that, for the same atomic radius, the unit cell volume increases from hexagonal close-packed (HCP) to body-centred cubic (BCC) to face-centred cubic (FCC).

Equation 6.9 of Shackelford, not derived in the book, can be verified simply by plotting

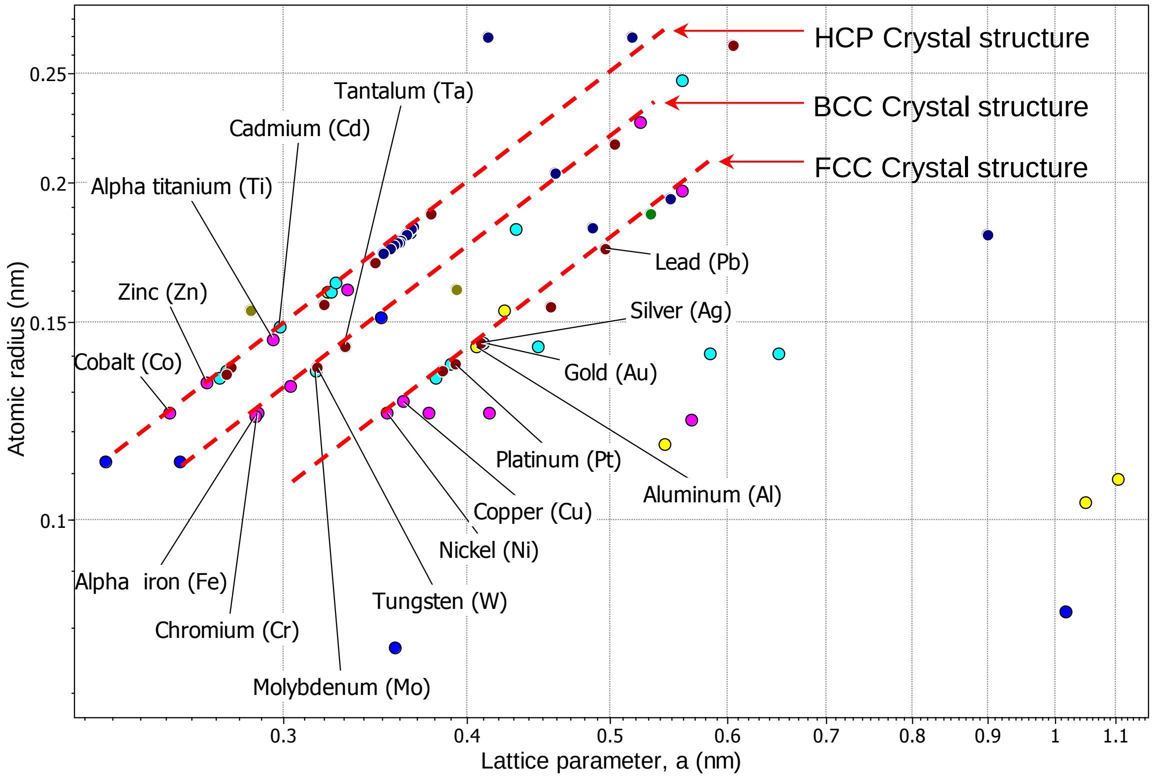


Figure 2. *Atomic radius versus lattice parameter for all the solid elements at room temperature.*

Young's modulus against the expression 2G(1+ν). The plot, shown in Figure 3, immediately shows a straight line relating one to the other for all engineering materials. Some materials deviate a little from this straight line: those that cannot be considered isotropic, like natural polymers and composites. Likewise, the Wiedemann-Franz law,

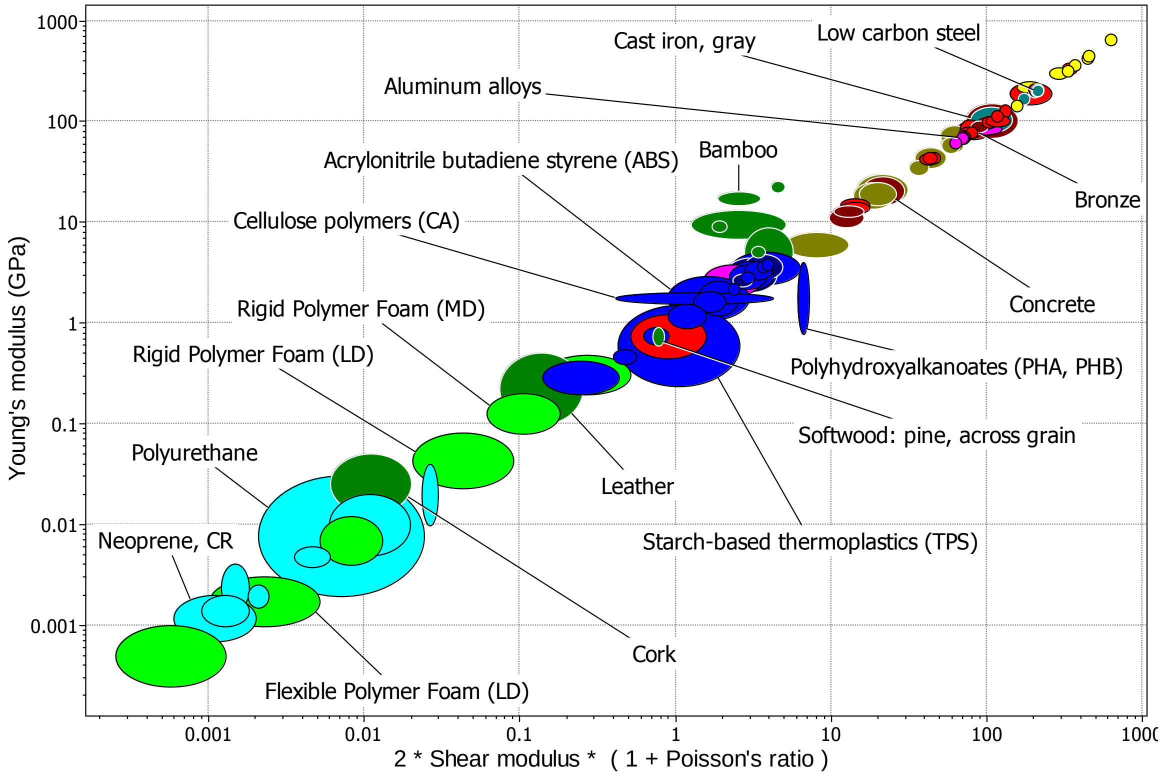


Figure 3. *The relationship that exists among elastic properties: Young's modulus, shear modulus and Poisson's ratio*

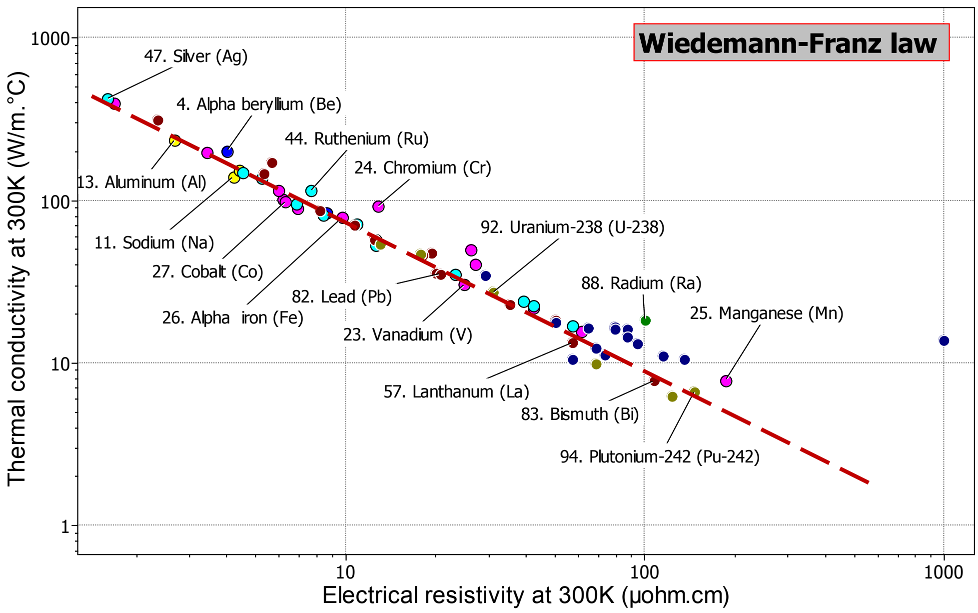
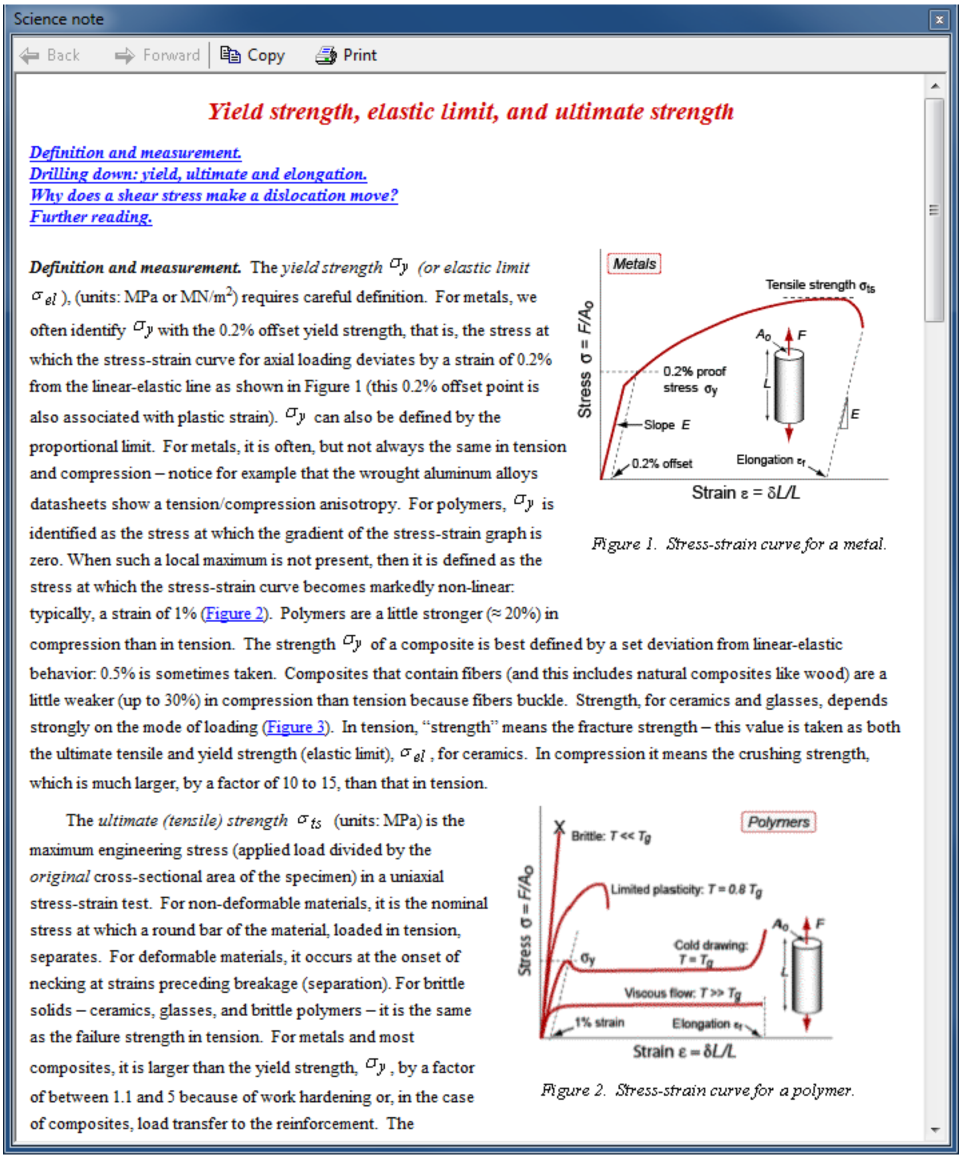


Figure 4. *The Wiedemann-Franz law plotted using the Elements data table in CES EduPack*

which ties together information covered in **Chapters 7** and **13**, can be plotted and checked graphically as in Figure 4.

From micro to macro: manipulating physical and mechanical properties

Chapter 6 on mechanical behaviour is devoted to stress-strain diagrams, elastic, plastic and viscoelastic deformation, hardness testing and creep. CES EduPack provides data for all materials in the database in all these dimensions, with the exception of creep. Science notes can be accessed by clicking on each of the properties in the records, to refresh students on the basic concepts and definitions of that property, or as part of guided self-learning (Figure 5). In the Aerospace Edition, it further provides all these properties as a function of temperature. Changing the temperature at which you want the properties to be displayed will automatically change their values, and you can plot them with temperature,


Science note

Back Forward Copy Print

Yield strength, elastic limit, and ultimate strength

Definition and measurement.
Drilling down: yield, ultimate and elongation.
Why does a shear stress make a dislocation move?
Further reading.

Definition and measurement. The *yield strength* σ_y *(or elastic limit* σ_{el}), (units: MPa or MN/m^2) requires careful definition. For metals, we often identify σ_y with the 0.2% offset yield strength, that is, the stress at which the stress-strain curve for axial loading deviates by a strain of 0.2% from the linear-elastic line as shown in Figure 1 (this 0.2% offset point is also associated with plastic strain). σ_y can also be defined by the proportional limit. For metals, it is often, but not always the same in tension and compression – notice for example that the wrought aluminum alloys datasheets show a tension/compression anisotropy. For polymers, σ_y is identified as the stress at which the gradient of the stress-strain graph is zero. When such a local maximum is not present, then it is defined as the stress at which the stress-strain curve becomes markedly non-linear: typically, a strain of 1% (Figure 2). Polymers are a little stronger (≈ 20%) in compression than in tension. The strength σ_y of a composite is best defined by a set deviation from linear-elastic behavior: 0.5% is sometimes taken. Composites that contain fibers (and this includes natural composites like wood) are a little weaker (up to 30%) in compression than tension because fibers buckle. Strength, for ceramics and glasses, depends strongly on the mode of loading (Figure 3). In tension, "strength" means the fracture strength – this value is taken as both the ultimate tensile and yield strength (elastic limit), σ_{el} , for ceramics. In compression it means the crushing strength, which is much larger, by a factor of 10 to 15, than that in tension.

Figure 1. Stress-strain curve for a metal.

The *ultimate (tensile) strength* σ_{ts} (units: MPa) is the maximum engineering stress (applied load divided by the *original* cross-sectional area of the specimen) in a uniaxial stress-strain test. For non-deformable materials, it is the nominal stress at which a round bar of the material, loaded in tension, separates. For deformable materials, it occurs at the onset of necking at strains preceding breakage (separation). For brittle solids – ceramics, glasses, and brittle polymers – it is the same as the failure strength in tension. For metals and most composites, it is larger than the yield strength, σ_y , by a factor of between 1.1 and 5 because of work hardening or, in the case of composites, load transfer to the reinforcement. The

Figure 2. Stress-strain curve for a polymer.

Figure 5. *Excerpt of the science note that pops up when you click on the "Yield strength" property in any record of the database*

as in Figure 6.

Shackelford's **chapter 8** on Failure is full of graphs and data of extreme importance to understand the mechanical behaviour of materials. CES EduPack can help enhance the understanding of the concepts with data. The explanation of fatigue and the S-N curves can be complemented by showing high-cycle fatigue curves for several materials. In level 3, CES EduPack can show these curves as ranges for different values of *R*. Figure 7 shows the same plot as Shackelford's Figure 8.21, for a different material, for the limited fatigue range in a log-log plot, for *R*=-1. The range denotes the statistical nature of fatigue. These plots are only available for metals, but all other material records have a fatigue strength at 10^7 cycles.

Phase diagrams are also an important topic for introductory materials science, presented in **chapter 9** of Shackelford. CES EduPack complements that at level 2 with a phase diagram for each alloy system, with a total of 15 binary and ternary phase diagrams. Figure 8 shows one of the most important material systems: that for stainless steels, involving Iron, Nickel and Chromium.

Chapter 10 part 4 goes in some depth into precipitation hardening, which can be depicted with CES EduPack for Aluminum alloys, as an example, in Figure 9. These types of plots help the students grasp immediately the consequences of heat treatments in mechanical properties. There is a whole lecture unit available from Granta Design's teaching resources website on manipulating properties, where a number of examples are given. This resource, (Lecture Unit 4:

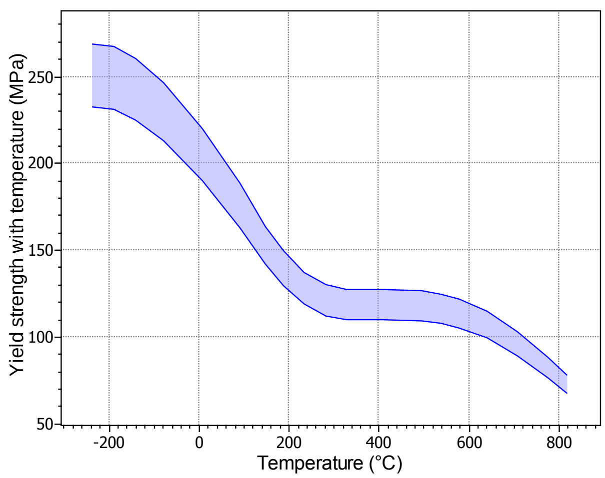


Figure 6. *Annealed austenitic stainless steel 301 yield strength varying with temperature*

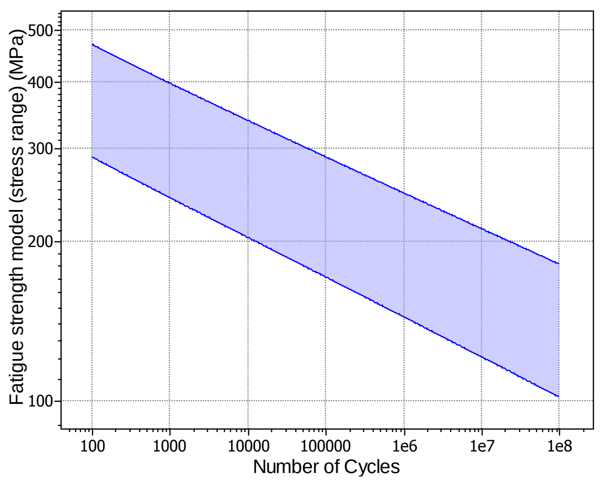


Figure 7. *High-cycle part of the S-N curve for Aluminum 7075-T6 for R=-1, on a log-log plot. The range expresses the statistical nature of fatigue*

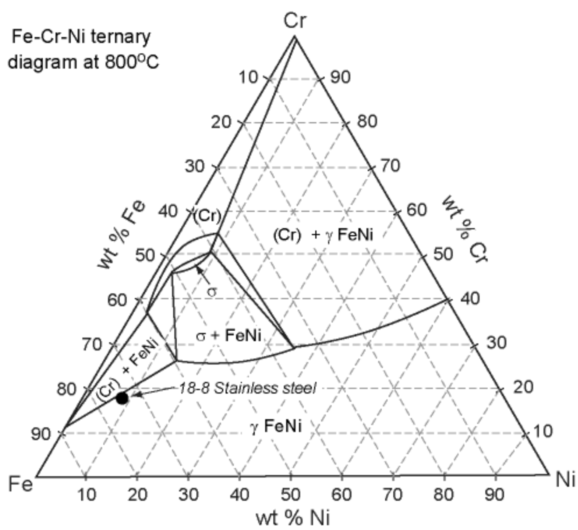


Figure 8. *A ternary phase diagram for the Fe-Cr-Ni system at 800ºC*

"Manipulating Properties: chemistry, microstructure, architecture") is dedicated to question and explain why materials behave mechanically like they do, and how their properties can be manipulated by heat treating and alloying, or by using additives in polymers or building composites.

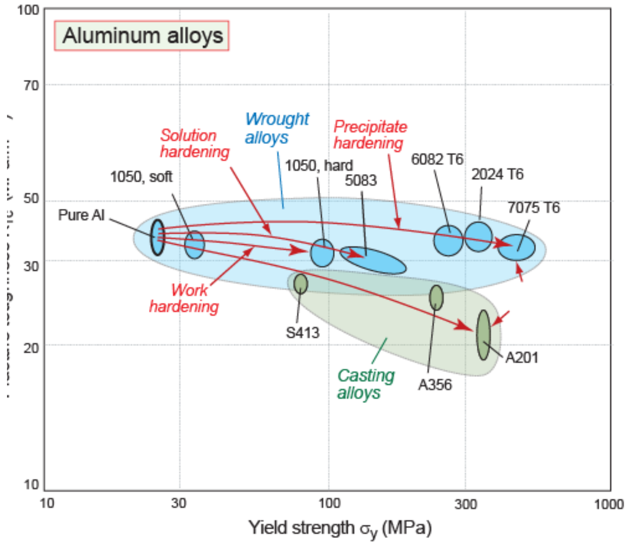


Figure 9. *The effects of various strengthening mechanisms in pure Aluminum and its alloys*

Chapters 9 and **10** dwell on phase transformations and microstructure by helping students understand both the equilibrium state and the role of kinetics. Mechanical properties are mentioned in passing, but the focus is on what is happening at the microscopic level. **Chapter 11** then starts by describing different material classes and how they are defined and named. These chapters can be supported by helping motivate the students to study the details they need to learn by showing how they affect material properties. Steels are particularly useful to explain the influence of alloying elements and the phenomena that develop during heat treatments.

Carbon content is one of the most influential factors on the mechanical properties of steels along with the way in which they are heat treated. The influence of carbon content on the properties of steel is shown in Figure 10, where the opposite effects in strength and ductility of carbon content are clearly depicted. The effects of heat treating can also be shown in a similar way. Figure 11 shows the influence of quench and temper parameters in the final average mechanical properties of an AISI 1080 high carbon steel.

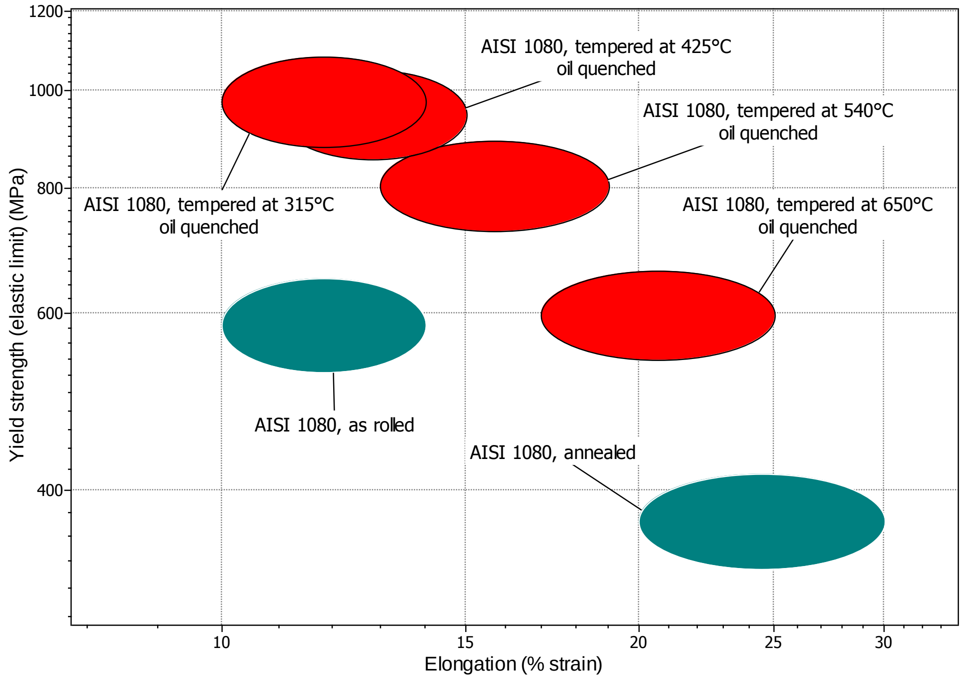


Figure 11. *The influence of Q&T parameters in the final mechanical properties of an AISI 1080 steel.*

At the macro scale: using materials

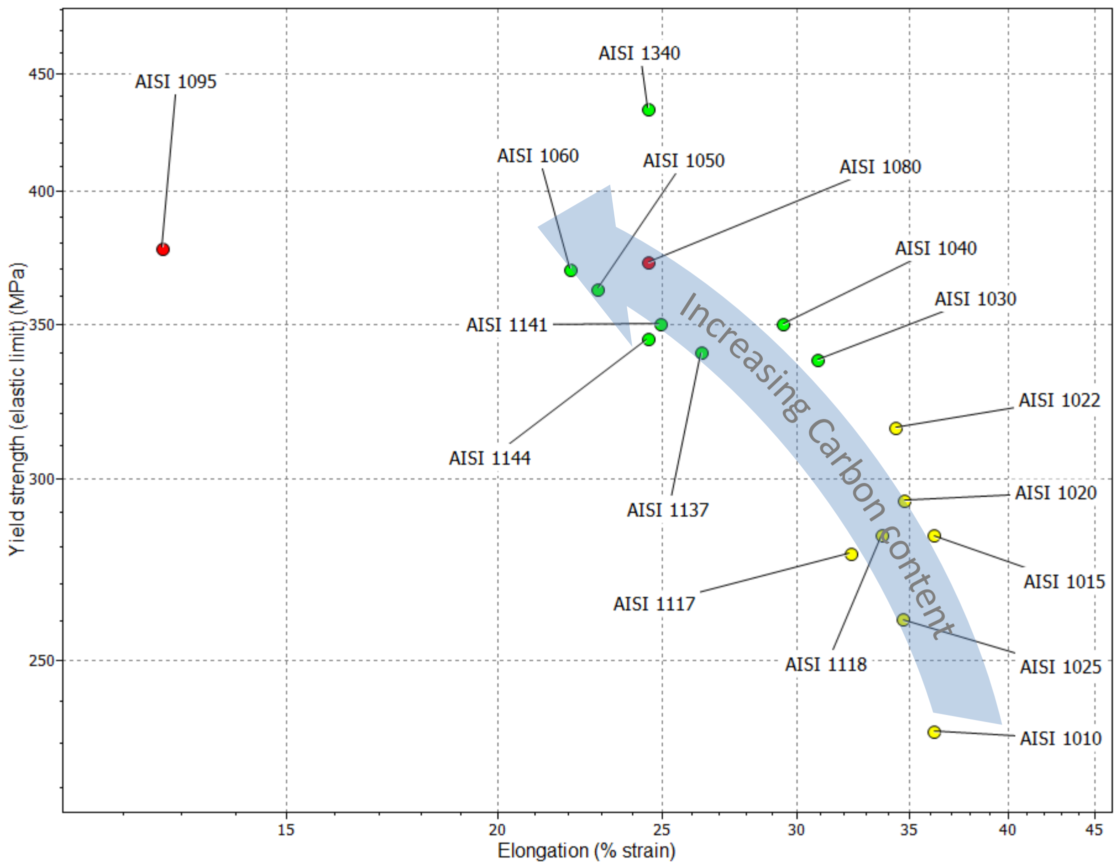


Figure 10. *The influence of carbon content and other alloying elements in the average mechanical properties of several annealed low carbon (in yellow), medium carbon (in green) and high carbon (in red) steels*

More than data

Chapters 11 and **12** in Shackelford discuss metals, ceramics, polymers and composites, how they are classified, what distinguishes them structurally, an overview of their properties and where they are used. A lack of space in the book means that this information is very brief for each material class. Students can delve into more depth on each material class in CES EduPack.

CES EduPack is a fully searchable database with a high visual impact. Finding materials for specific applications can be done by searching for a product and finding the material it is made of. If you're interested in finding the material that wetsuits are made from, just search for the word "wetsuit" and a record for Polychloroprene (more commonly known as Neoprene) will immediately appear. Figure 12 shows a screenshot of this record in level 1. All the level 1 and 2 material records have a picture of a product that somehow represents the use of that material.

Other information is needed to help Engineers use materials besides raw property data. This is covered in level 2 by the textual content of each record. A description of the material, a summary of its composition, design guidelines, technical notes and typical uses are all included. Figure 13 shows a screenshot from a level 2 record for Age-hardening wrought Aluminum alloys.

Polychloroprene (Neoprene, CR)

Layout: Edu Level 1 Show/Hide

Polymers and elastomers > Elastomers >

Description

Image

Caption

1. Close-up of a wetsuit showing the texture of the material. © Yoruno at en.wikipedia - (CC BY-SA 3.0) 2. Surfer in a polychloroprene wetsuit. © Johntex at en.wikipedia - (CC BY-SA 3.0)

The material

Polychloroprenes (Neoprene, CR) – the materials of wetsuits – are the leading non-tire synthetic rubbers. First synthesized in 1930, they are made by a condensation polymerization of the monomer 2-chloro –1,3 butadiene. The properties can by modified by copolymerization with sulfur, with other chloro-butadienes and by blending with other polymers to give a wide range of properties. Polychloroprenes are characterized by high chemical stability, resistance to water, oil, gasoline and UV radiation.

Composition (summary)

(CH2-CCl-CH2-CH2)n

General properties

Density	1.23e3	-	1.25e3	kg/m^3
Price	* 5.3	-	5.9	USD/kg

Mechanical properties

Young's modulus	7e-4	-	0.002	GPa
Yield strength (elastic limit)	3.4	-	24	MPa
Tensile strength	3.4	-	24	MPa
Elongation	100	-	800	% strain
Fatigue strength at 10^7 cycles	* 1.53	-	12	MPa
Fracture toughness	* 0.1	-	0.3	MPa.m^0.5

Thermal properties

Maximum service temperature	102	-	112	°C
Thermal conductor or insulator?	Good insulator			
Thermal conductivity	0.1	-	0.12	W/m.°C
Specific heat capacity	* 2e3	-	2.2e3	J/kg.°C
Thermal expansion coefficient	575	-	610	µstrain/°C

Electrical properties

Electrical conductor or insulator?	Good insulator

Optical properties

Transparency	Translucent

Eco properties

Embodied energy, primary production	* 61.2	-	67.6	MJ/kg
CO2 footprint, primary production	* 1.61	-	1.78	kg/kg
Recycle	✗			

Supporting information

Typical uses

Brake seals, diaphragms, hoses and o-rings, tracked-vehicle pads, footwear, wetsuits.

Links

ProcessUniverse

Figure 12. *A full record in CES EduPack at Level 1, showing material description, typical uses and an image. The records complement the material data presented in Shackelford*

Age-hardening wrought Al-alloys

Layout: Edu Level 2 | Show/Hide

Metals and alloys > Non-ferrous > Aluminum and alloys >

Description

Image



Caption

1. Close-up of a building cladding made of wrought aluminum alloy . © John Fernandez 2. Chassis of a personal computer. © Chris Lefteri 3. The 2000 and 7000 series age-hardening aluminum alloys are the backbone of the aerospace industry.

The material

The high-strength aluminum alloys rely on age-hardening: a sequence of heat treatment steps that causes the precipitation of a nano-scale dispersion of intermetallics that impede dislocation motion and impart strength. This can be as high as 700 MPa giving them a strength-to-weight ratio exceeding even that of the strongest steels. This record describes for the series of wrought Al alloys that rely on age-hardening requiring a solution heat treatment followed by quenching and ageing. This is recorded by adding TX to the series number, where X is a number between 0 and 8 that records the state of heat treatment. They are listed below using the IADS designations (see Technical notes for details).2000 series: Al with 2 to 6% Cu -- the oldest and most widely used aerospace series.6000 series: Al with up to 1.2% Mg and 1.3% Si -- medium strength extrusions and forgings.7000 series: Al with up to 8% Zn and 3% Mg -- the Hercules of aluminum alloys, used for high strength aircraft structures, forgings and sheet. Certain special alloys also contain silver. So this record, like that for the non-age hardening alloys, is broad, encompassing all of these.

Composition (summary)

2000 series: Al + 2 to 6% Cu + Fe, Mn, Zn and sometimes Zr
6000 series: Al + up to 1.2%Mg + 0.25% Zn + Si, Fe and Mn
7000 series: Al + 4 to 9 % Zn + 1 to 3% Mg + Si, Fe, Cu and occasionally Zr and Ag

General properties

Density	2.5e3	-	2.9e3	kg/m^3
Price	* 2.11	-	2.33	USD/kg
Date first used	1916			

Mechanical properties

Young's modulus	68	-	80	GPa
Shear modulus	25	-	28	GPa
Bulk modulus	64	-	70	GPa
Poisson's ratio	0.32	-	0.36	
Yield strength (elastic limit)	95	-	610	MPa
Tensile strength	180	-	620	MPa
Compressive strength	95	-	610	MPa
Elongation	1	-	20	% strain
Hardness - Vickers	60	-	160	HV
Fatigue strength at 10^7 cycles	57	-	210	MPa
Fracture toughness	21	-	35	MPa.m^0.5
Mechanical loss coefficient (tan delta)	1e-4	-	0.001	

Thermal properties

Melting point	495	-	640	°C
Maximum service temperature	120	-	200	°C
Minimum service temperature	-273			°C
Thermal conductor or insulator?	Good conductor			
Thermal conductivity	118	-	174	W/m.°C
Specific heat capacity	890	-	1.02e3	J/kg.°C
Thermal expansion coefficient	22	-	24	µstrain/°C

Electrical properties

Electrical conductor or insulator?	Good conductor			
Electrical resistivity	3.8	-	6	µohm.cm

Optical properties

Transparency	Opaque

Processability

Castability	4	-	5
Formability	3	-	4
Machinability	4	-	5
Weldability	3	-	4
Solder/brazability	2	-	3

Eco properties

Embodied energy, primary production	* 198	-	219	MJ/kg
CO2 footprint, primary production	* 12.2	-	13.4	kg/kg
Recycle	✓			

Figure 13. *Caption below*

Supporting information

Design guidelines

The age-hardening alloys have exceptional strength at low weight, but the origin of the strength -- age hardening -- imposes certain design constraints. At its simplest, age-hardening involves a three step heat treatment.

Step 1: the wrought alloy, as sheet, extrusion or forging, is solution heat treated -- held for about 2 hours at around 550 C (it depends on the alloys) to make the alloying elements (Cu, Zn, Mg, Si etc) dissolve.

Step 2: the material is quenched from the solution-treatment temperature, typically by dunking or spraying it with cold water. This traps the alloying elements in solution. Quenching is a savage treatment that can cause distortion and create internal stresses that may require correction, usually by rolling.

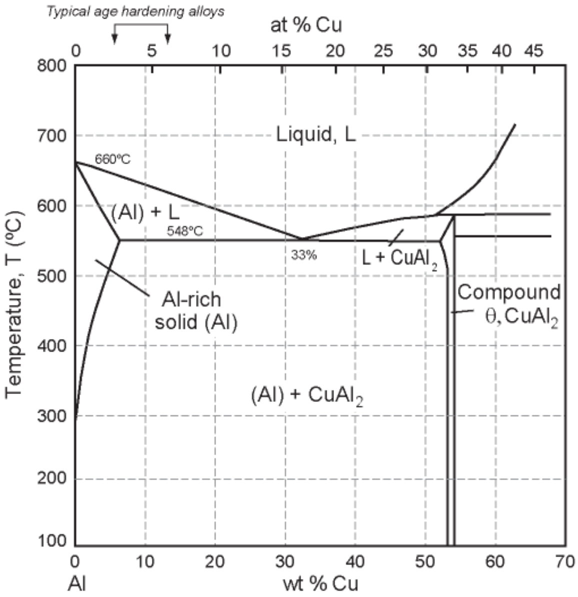
Step 3: the material is aged, meaning that it is heated to between 120 and 190 C for about 8 hours during which the alloying elements condense into nano-scale dispersions of intermetallics (CuAl, CuAl2, Mg2Si and the like). It is this dispersion that gives the strength.

The result is a material that, for its weight, has remarkably high strength and corrosion resistance. But if it is heated above the solution treatment temperature -- by welding, for example -- the strength is lost. This means that assembly requires fasteners such as rivets, usual in airframe construction, or adhesives. Some 6000 series alloys can be welded, but they are of medium rather than high strength.

Technical notes

Until 1970, designations of wrought aluminum alloys were a mess; in many countries, they were simply numbered in the order of their development. The International Alloy Designation System (IADS), now widely accepted, gives each wrought alloy a 4-digit number. The first digit indicates the major alloying element or elements. Thus the series 1xxx describe unalloyed aluminum; the 2xxx series contain copper as the major alloying element, and so forth. The third and fourth digits are significant in the 1xxx series but not in the others; in 1xxx series they describe the minimum purity of the aluminum; thus 1145 has a minimum purity of 99.45%; 1200 has a minimum purity of 99.00%. In all other series, the third and fourth digits are simply serial numbers; thus 5082 and 5083 are two distinct aluminum-magnesium alloys. The second digit has a curious function: it indicates a close relationship: thus 5352 is closely related to 5052 and 5252; and 7075 and 7475 differ only slightly in composition. To these serial numbers are added a suffix indicating the state of hardening or heat treatment. The suffix F means 'as fabricated'. Suffix O means 'annealed wrought products'. The suffix H means that the material is 'cold worked'. The suffix T means that it has been 'heat treated'. More information on designations and equivalent grades can be found in the Users section of the Granta Design website, www.grantadesign.com

Phase diagram



Phase diagram description

The 2000 series of wrought aluminum alloys are based on aluminum (Al) with 2.5 - 6% copper (Cu). This is the relevant part of the phase diagram.

Typical uses

2000 and 7000 series: aerospace structures, pressure vessels, ultralight land-based transport systems; sports equipment such as golf clubs and bicycles.

6000 series: cladding and roofing; medium strength extrusions, forgings and welded structures for general engineering and automotive such as connecting rods.

Links

Reference

ProcessUniverse

Producers

Values marked * are estimates.

Granta Design provides no warranty for the accuracy of this data

Figure 13. *(continued) A level 2 record for Age-hardening wrought Aluminum alloys, showing a description of the material, a summary of its composition, general, mechanical thermal, electrical and optical properties, processability and eco properties, supporting information and Links*

In level 3, a typical metal record starts with a standard designation, an EN name and UNS number and ends with typical uses, keywords, reference sources and standards with similar compositions. All the text is searchable, so a trade name, or a French or German standard for that particular alloy can easily be found.

Processing

Chapters 11 and **12** of Shackelford deal with materials processing in brief. CES EduPack provides a data-table of 230 manufacturing processes for shaping, joining and finishing materials. As this is a database it has the ability to link data from one area to another. This is particularly useful when you need to find out which materials can be processed in which ways. The Process data-table is linked to the materials data-table, so that every material record is linked to the processes that can be used to manufacture it, and every manufacturing process is linked back to the materials it can process. This link can be used when selecting the best material or process for a job.

High pressure die casting

Layout: Edu Level 2 All Processes ▾ Show/Hide

Description

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.

Process schematic

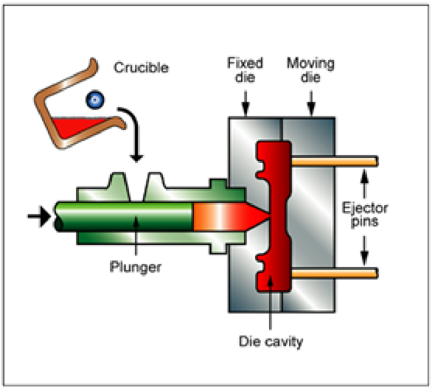


Figure caption

Pressure die casting

Shape

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

Physical attributes

Mass range	0.01	-	50	kg
Range of section thickness	0.5	-	12	mm
Tolerance	0.15	-	0.5	mm
Roughness	0.8	-	1.6	µm
Surface roughness (A=v. smooth)	A			

Process characteristics

Primary shaping processes	✓			
Discrete	✓			

Economic attributes

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

Cost modeling

Relative cost index (per unit)	* 44.2	-	165	
Parameters: Material Cost = 10USD/kg, Component Mass = 1kg, Batch Size = 1e3, Overhead Rate = 110USD/hr, Capital Write-off Time				
Capital cost	* 1.64e5	-	8.2e5	USD
Material utilization fraction	* 0.75	-	0.8	
Production rate (units)	* 2	-	200	/hr
Tooling cost	* 7.38e3	-	1.07e5	USD
Tool life (units)	* 2e4	-	1e6	

Links

Reference

MaterialUniverse

Values marked * are estimates.
Granta Design provides no warranty for the accuracy of this data

__Figure 14.__ Excerpt of a record for high pressure die casting in level 2. Further information is provided in a complete record, like design guide lines, technical notes, typical uses, economic and environmental issues.

Figure 14 shows an excerpt of a typical record for primary shaping at level 2 (that for die casting). The record contains information on the shapes that it can process, its physical and economic attributes, and the possibility of modelling the cost associated with it, through a number of parameters: material cost, component mass, batch size, overhead rate and capital write-off time. Further information is provided in a complete record, like design guidelines, technical notes, typical uses, economic and environmental issues. One

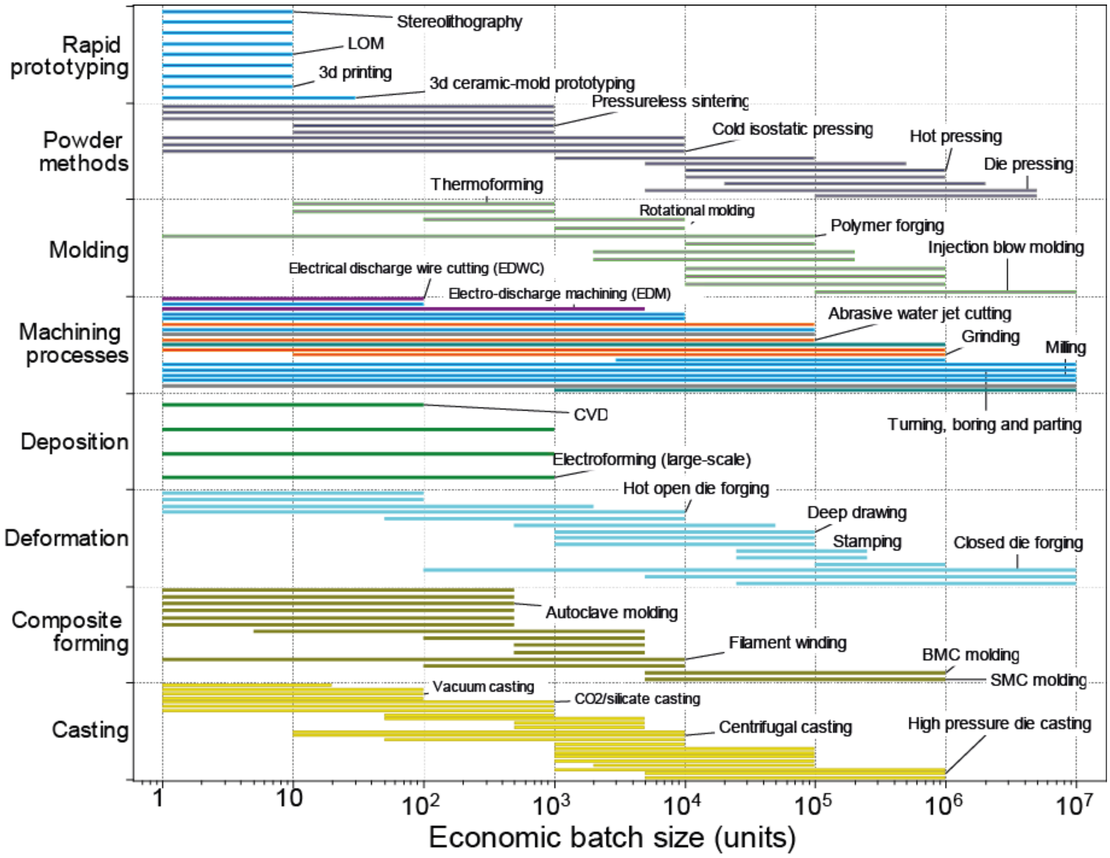


Figure 15. *Economic batch sizes for a number of shaping processes*

of the interesting features of this data-table is the economic batch size: the number of parts above which the process becomes economically viable. Figure 15 shows the economic batch size for a number of shaping processes. This information can be used to select the manufacturing process that is more suited for a specific production run.

Polymers and composites

Polymers and composites are dealt with in **chapter 12**. CES EduPack has numerous records for these materials. At level 3, it contains 800+ polymer records and 700+ composites with polymer, ceramic and metal matrices. The effect of fillers in polymers can be readily shown, as in Figure 16. Polymers with fillers can also be placed under the composites family. More important perhaps is CES EduPack capacity to build your own virtual composite with the ***Hybrid Synthesizer*** tool. This tool, present in some advanced editions, enables the user to build virtual foams, sandwich panels and composite materials; by specifying a number of parameters and the constituent materials. It then allows the user to compare these new virtual materials with the existing real materials in the database. CES EduPack automatically calculates the mechanical, thermal, electrical and physical properties of the new virtual composites and plots them alongside those of the existing materials. The models used to calculate these properties are all made explicit in the help menu of CES EduPack. Many involve simple rules like the rule of mixtures, others are more complex; but the graphical form in which they are transformed in CES EduPack plots make them come to life in a way that lets the student immediately understand their underlying principles. Figure 17 shows a virtual sandwich panel of Aluminum 7075-T6 faces and PVC foam core for varying thicknesses of both core and face sheets.

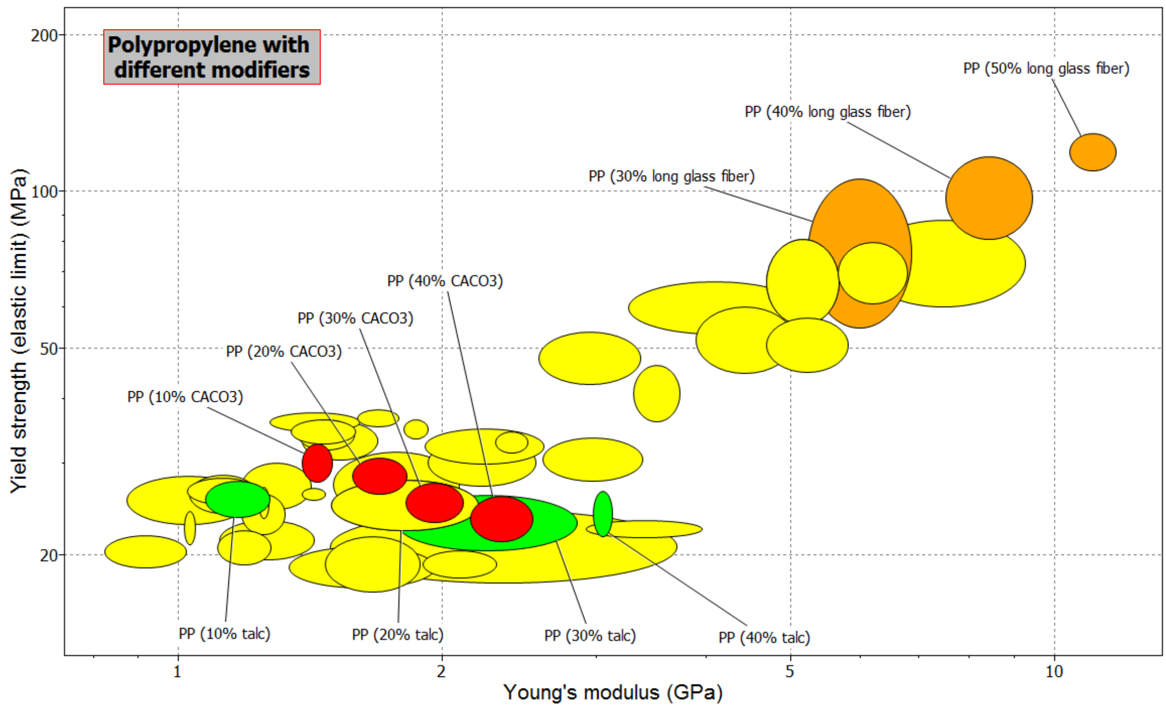


Figure 16. *The effect of fillers in PP-based polymers. All the bubbles represent PP copolymers and homopolymers with fillers and modifiers. Differently coloured bubbles show the evolution of mechanical properties with increasing amount of different fillers*

The plot effectively shows the advantage of using a sandwich panel instead of using a

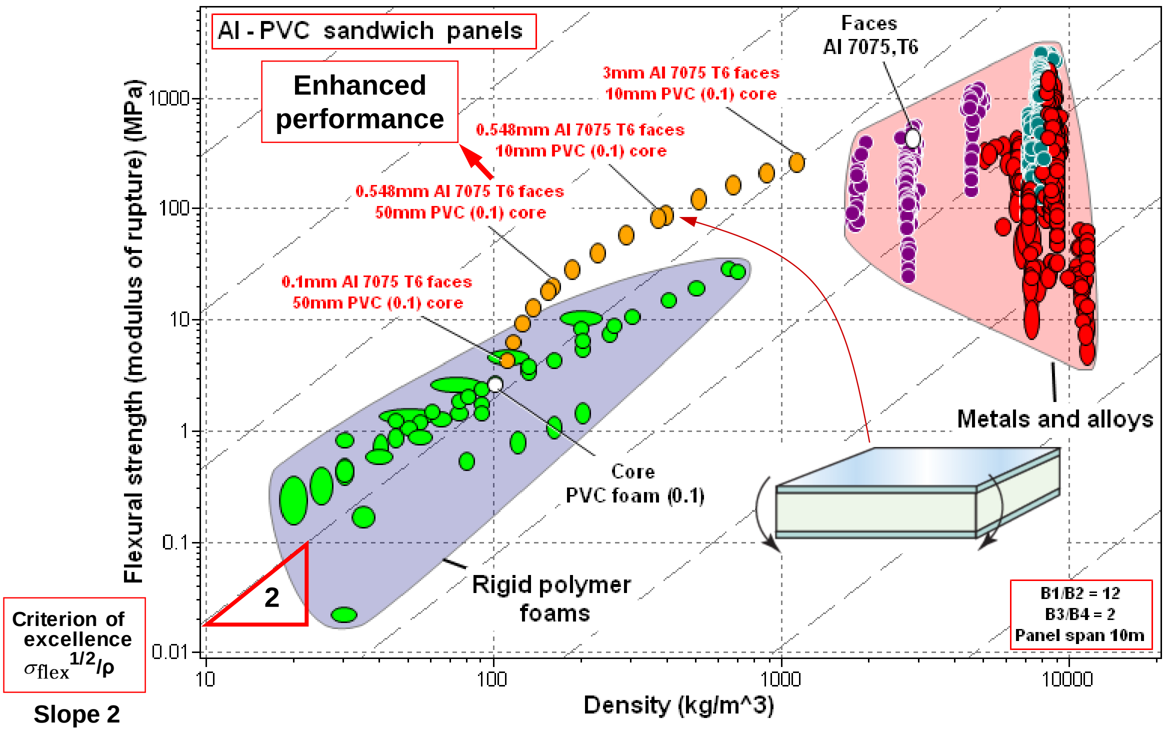


Figure 17. *The result of building a sandwich panel on the Hybrid Synthesizer tool in CES EduPack. The plot shows how a number of virtual sandwich panels of varying thickness of both core and face sheets can achieve better bending properties than the monolithic constituent materials alone*

monolithic material in terms of bending performance: the sandwich panel bridges the gap between both materials used. This enables the study of multiple sandwich panel configurations; but most of all, it fosters discussion of possible new composite materials without the need to physically build and test them. It provides an easy way of screening for composites that do the job. Naturally, this is a model, and the true properties of the composite have to be obtained by testing in a real life situation.

As well as using the Hybrid Synthesizer model, students studying **Chapter 12.2** of Shackelford can also use the charting facility in CES EduPack to explore for example the specific strengths of composites and compare them to natural materials and metals linking to **Table 12.8** (Figure 17).

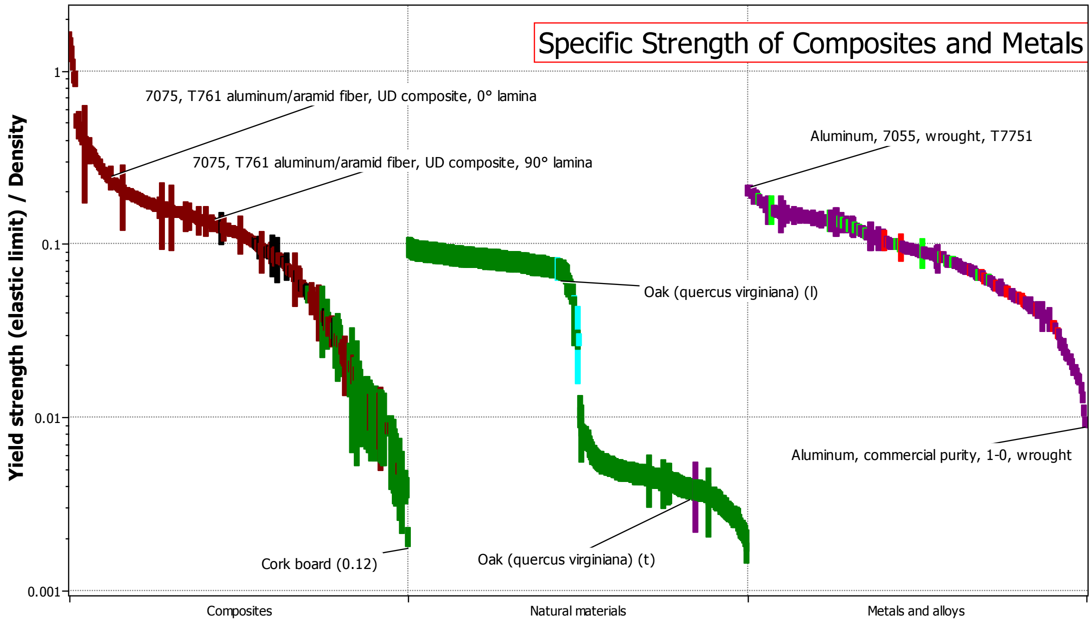


Figure 17. *Chart created using Level 3 of CES EduPack to illustrate the specific strengths of different materials classes*

Section 15.2 of Shackelford ends with the example of composites replacing metals. This materials substitution and product redesign task is exactly what many of Granta Design's commercial customers do with CES Selector the sister product to CES EduPack which is designed for speedy use by materials experts. Case studies from industry are available on the Granta Design website.

http://www.grantadesign.com/products/ces/casestudies.htm

Selection of Materials

Sections 15.1 to 15.3 of Shackelford focuses on selecting materials and giving case studies. The data needed to support decision making in choosing a material is illustrated and a method is outlined before a few case studies are provided. CES EduPack is able to supplement this by providing data on 4000 materials, selection tools and many more case studies. Lecture Units and exercises are also provided to help students learn the methodology. Other papers describe in detail how CES EduPack supports teaching on materials and process selection.(See references).

Materials and our Environment

Materials in use degrade over time depending on their environment. This is discussed as part of Materials in Engineering Design in **Chapter 15** part 4. CES EduPack can support the discussion by providing notes on how materials perform in 44 different chemicals and in different thermal and built environments. An overview of the mechanisms effecting durability is given as well as a where the problem occurs and which materials and coatings perform well in that environment. (Figure 18 shows this overview for water.)

Water (fresh)

Where found. Fresh water is ubiquitous: any object: exposure to rain, to washing or to high humidity acquires a film of water containing (unless distilled) dissolved oxygen and, usually, other impurities.

Industrial sectors. Petroleum, food processing, chemical engineering, engineering manufacture, construction, energy conversion, marine engineering, aerospace, bio-engineering.

The problem. Causes localized corrosion on iron and non-stainless steels.

Preferred materials and coatings.

Metals	Polymers and composites	Ceramics and glasses
Aluminum alloys Stainless steels Galvanized steel Copper alloys (pipe work and heating systems)	All polymers are corrosion free in fresh water, though some absorb up to 5%, causing swelling. PET HDPE GFRP	Glass Concrete Brick Porcelain

Inhibitors. Calcium bicarbonate (Steel, Cast Iron), polyphosphate (Cu, Zn, Al, Fe), calcium hydroxide (Cu, Zn, Fe), sodium silicate (Cu, Zn, Fe), sodium chromate (Cu, Zn, Pb, Fe), potassium dichromate (Mg), sodium nitrite (Monel), benzoic acid (Fe), calcium and zinc metaphosphates (Zn).

Underlying mechanisms. Aqueous corrosion, electro-chemical corrosion, differential aeration corrosion.

Figure 18. *Note from the durability section of material records in CES EduPack Level 2*

The environment is also a pressing concern for society which influences design. This is recognized in Shackelford and reflected in **chapter 15 part 4**, along with legislation that regulates the use of materials and recycling of materials. The chapter does not go into too much depth, but it does mention life cycle assessment of products and Design for Environment. CES EduPack goes a step further and actually helps students to model and analyse each phase of life of a product in terms of energy consumption, CO_2 emissions and cost. It leads the students in finding ways to reduce a product's environmental impact. This analysis is done within another built-in tool, the ***Eco-Audit Tool***. This tool enables a fast analysis in the design phase of a product, with sufficient accuracy to drive design decisions. It also enables direct comparison of different products. Figure 19 shows a comparison between a plastic bottle of water and a glass bottle of water in terms of energy consumed during the entire life cycle of the bottle. This enables a fruitful discussion in class about the impact that each phase of life has in the entire life cycle, the ways in which one can decrease this impact, and what implications this can potentially have in the other phases of life. Clicking on the columns in the chart gives suggestions of how to reduce the environmental impact and the materials and process selection tools can be used to optimise the Material and Manufacturing phases.

Table 15.9 in **Chapter 15.4** of Shackelford lists Major Environmental legislation in the United States. The CES EduPack Sustainable Development Edition was designed to enable students to do project work to assess the sustainability of a technological development. One aspect of this assessment is to understand legislation that would impact the development. The software has a database of global legislation affecting materials and products and their use. The students can search by topic and country. Hazardous materials, hazardous materials production processes and the creation of air pollution are also discussed in this section. Students using CES EduPack can take these concerns into account in their designs by using data on NOx and SOx production, whether a material complies with European Restriction on Hazardous Substances (RoHS) legislation and whether a material is toxic. Hazards in the production process are described in the notes for the material, for instance Beryllium Alloys contain a warning. Even when regulations are outside one's home country, the global nature of the modern economy can make them important. For example, while no US legislation currently restricts lead in solder, the European RoHS and Japanese legislation does. Companies that wish to sell the same product globally have to take these into account.

Lastly in this section of the book, recycling of different material classes is described and the great example of legislation driving materials design in solders. Students wishing to

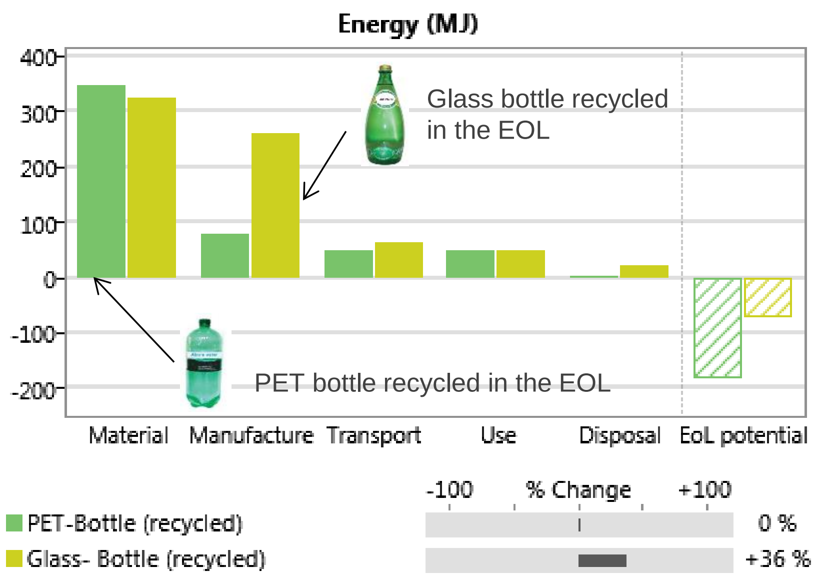


Figure 19. *Eco-audit for a comparison of two distinct bottles of water: one of plastic and another of glass. The scenario for this comparison is the following: 100 bottles of water, filled In France, transported for 550 km to the UK, refrigerated for two days and drunk*

understand end of life options in more detail can find data on whether a material is recyclable, the percentage of recyclable material in current supply, the Energy and Carbon footprint associated with recycling and also information about downcycling, combustion and so on in CES EduPack.

A visual take on materials and manufacturing processes

Charts of material properties like the ones shown in Figure 1 or Figure 3 or any other Figures with bubbles were obtained using CES EduPack. Another way of highlighting separate material families is to produce a bar chart like the one in Figure 20, where each material family is isolated to better appreciate their ranges of properties. A custom subset of materials can also be plotted: this is how Figures 9, 10 and 11 were created. This allows to isolate a set of materials from the whole database and to plot only what is needed. Labelling the plots is also very easily done, like the year in the top left corner of each of the plots in Figure 1. Every material record in a plot can also be labelled, just by clicking on the material and dragging the label to any place in the plot. The material families can be similarly labelled. All the plots can be copied and pasted to a word processor to produce reports and assignments.

Other Materials Science textbooks with links in CES EduPack

In the Science Notes, of which an excerpt was shown in Figure 5, links are also provided for further reading. These textbooks include, besides Shackelford, widely known titles from Ashby, Budinski, Askeland and Callister, with the respective chapter(s) of each where the relevant topic is discussed in detail.

Granta Design's teaching resource website offers a number of complementing resources that can help in the teaching of materials science; supplementing any textbooks used. Lecture Units 3 (The Elements) and 4 (Manipulating Properties) are particularly useful but many more are also available on the website. White papers like this one, together with case studies, exercises, project files, posters and charts can also be downloaded from Granta Design's teaching resource website, to further complement CES EduPack and the textbooks.

Further adaptation to – and support for – teaching needs

The needs of a course for engineers working in aerospace design differ from those of one for the design of civil structures or for product design. A benefit of software is the ability to customize it, ensuring that the materials information to which the student has access is relevant to the specifics of the subject being studied. Thus a course on materials science may be strengthened by a database on the elements, spanning the Periodic Table and providing crystallographic data, data on cohesion and physical properties. Aerospace engineering requires access to data for light alloys and composites, and perhaps for materials that meet US military specifications (MMPDS for metals and CMH-17 for

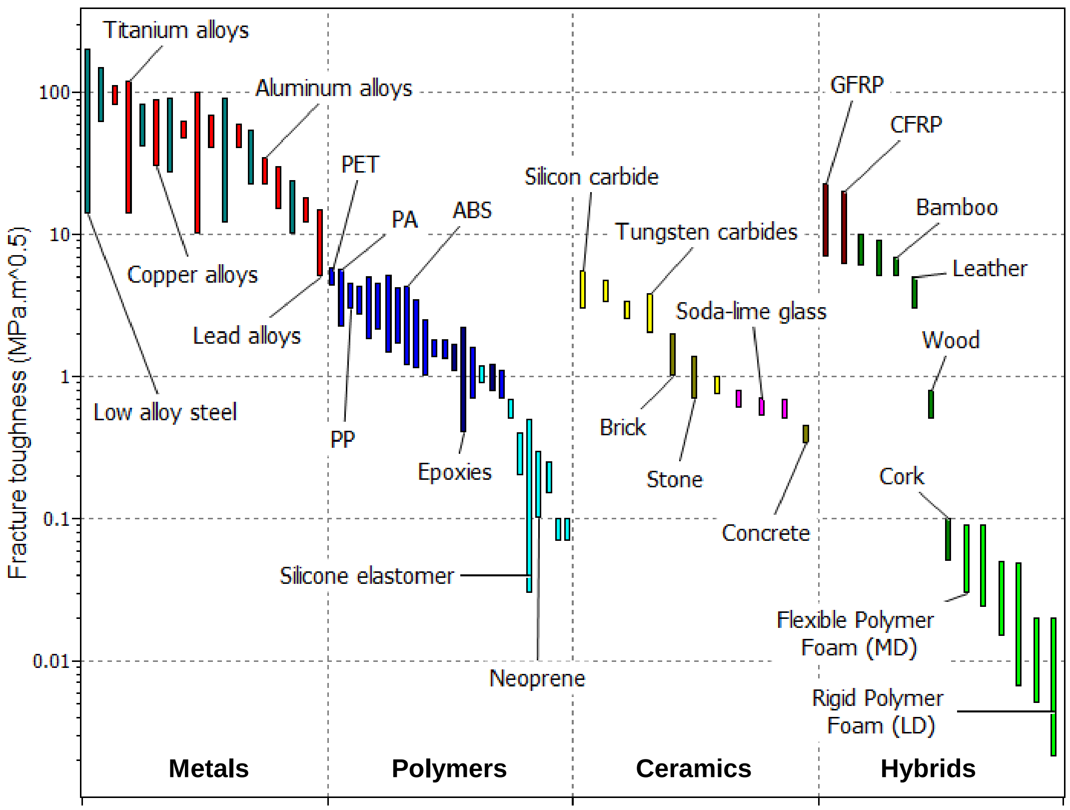


Figure 20. *Fracture toughness for each of the material families in CES EduPack, level 1*

composites). A course for civil engineers requires data for cement, concrete, structural grades of steel, aluminum 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 or ASTM standards. All of these data sets (summarized in Table 1. CES

EduPack Editions for education) exist and can be provided with the basic CES EduPack system allowing easy adaptation both to the level of the course and its subject matter.

Table 1. CES EduPack Editions for education

Edition	Courses	Databases
Standard	General & Mech. Eng., Chemical Eng., Materials and Manufacturing	Materials & Processes (Levels 1-3) + Elements
Aerospace	Aerospace Eng. Motorsports Eng.	Materials & Processes (Levels 1&2) +Level 3 Aero+ Elements+ MMPDS+ CMH17
Architecture	Architecture	Architecture + Structural Sections
Bio Engineering	Bio, Medical Engineering	Levels 1&2 Bio Materials + Elements
Design	Industrial and Product Design	Materials & Processes (Levels 1&2) + Elements
Eco-Design	Eco Design, Sustainable Eng.—or any course integrating these	Materials & Processes (Levels 1&2) + Level 3 Eco Design + Elements + CAMPUS
Low Carbon Power	Sustainability and energy	Materials & Processes (Levels 1-2) + Level 3 Low Carbon Power (also Nuclear Power Energy Storage Systs) + Elements
Polymer	Polymer Science and Eng., Advanced Industrial Design	Materials & Processes (Levels 1&2) +Level 3 (enhanced)+ Elements+ CAMPUS+ Prospector (formerly IDES)
Sustainability & the Built Environment	Civil Engineering, Structures, Built Environment, advanced use in Architecture	Materials & Processes (Levels 1&2) + Level 3 Eco Design + Architecture + Structural Sections+ Elements
Sustainable Development Edition	Eco Design, Sustainable Eng. Sustainable Development—or any course integrating these	Materials & Processes (Levels 1&2) + Level 3 Sustainable Development + Elements

Conclusions

Shackelford and the CES EduPack have different but complementary strengths and can be used together to great effect. Shackelford's depth on the scientific aspects of materials and in particular material-structure-property relationships (and control through heat treatment) is very useful for Materials scientists and engineers that are interested in this level of understanding. CES EduPack is a very visual, interactive way of supplementing the student's knowledge on a Shackelford-based course with more connection to the use of materials and properties that make them useful. It is also a great way to introduce sustainability as a factor in design.

Mini research tasks and basic selection projects using the CES EduPack can be set to promote self-learning. Instructors that use the CES EduPack are given access to online teaching resources including suggested projects with worked solutions, PowerPoint presentations from Professor Mike Ashby and shared resources and case studies generated by other CES EduPack users. You can find out more below.

Assignment Ideas

1. Pick an alloy system described in **section 11.1**. Find the same alloy in CES EduPack Level 2. Read about it in both resources. Now pick a typical use from the list in the CES EduPack record. Describe why you think this alloy is suited to that application, start with the properties that make it useful and then dig down to explain why this material has those properties. (Remember that you can click on the science notes that describe the origins of the properties in the CES EduPack. Re-reading **Chapters 9 and 10** in Shackelford may also help.)
2. Tables 15.1 and 15.2 in Shackelford list the Tensile Strength and Elongation of Tool Steels. Create a chart of these two properties using CES EduPack at level 3. Choose Tool Steels in the **Select from** field. Describe the overall trend in properties. Explore how the properties vary depending on whether the steel is hot or cold worked. Describe why you think the temperature matters. **Chapter 10** will help. Pick a Tool Steel in CES EduPack. One of the attributes in the record is Condition. Read the field and describe in detail what treatment processes your steel has been through and why. If necessary, remember you can click on the attributes note (and click at the bottom of the note for the science note on this topic).
3. Investment casting of metals is described in **Chapter 11** followed by a section on Additive Manufacturing and Laser Engineered Net Shaping (LENS). Using those descriptions and by searching for Investment Casting and LENS in CES EduPack compare the two processes in terms of economics, the shapes that can be achieved and the quality of resulting parts. (The cost model at Levels 2 & 3 of CES EduPack will be useful.)

Reference textbooks

Shackelford, J., (2015) “Introduction to Materials Science for Engineers”, 8th Edition, Pearson, Upper Saddle River, NJ, USA. ISBN-13: 9780133826654.

Callister, W. D. Jr. and Rethwisch, D. (2010) Materials Science and Engineering, an Introduction. 8th Edition, John Wiley and Sons, NY, USA.
ISBN 978-0-470-50586-1

Budinski K.G. and Budinsky M.K. (2009), Engineering Materials, Properties and Selection, 9th Edition, Prentice Hall, London, UK.
ISBN 978-0136109501

Ashby M.F., Shercliff, H. and Cebon, D. (2009) Materials: Engineering, Science, Processing and Design, 2nd Edition, Butterworth Heinemann, Oxford, UK. ISBN 978-0073398143.

Ashby, M.F. (2012) Materials and the Environment – eco-informed material choice, 2nd Butterworth Heinemann, Oxford, UK. ISBN 978-0-12-385971-6.

Fulay, P., Wright, W., Askeland, D.R. (2011), The Science and Engineering of Materials, 6th Edition, Wadsworth, California. USA.
ISBN 978-0495668022

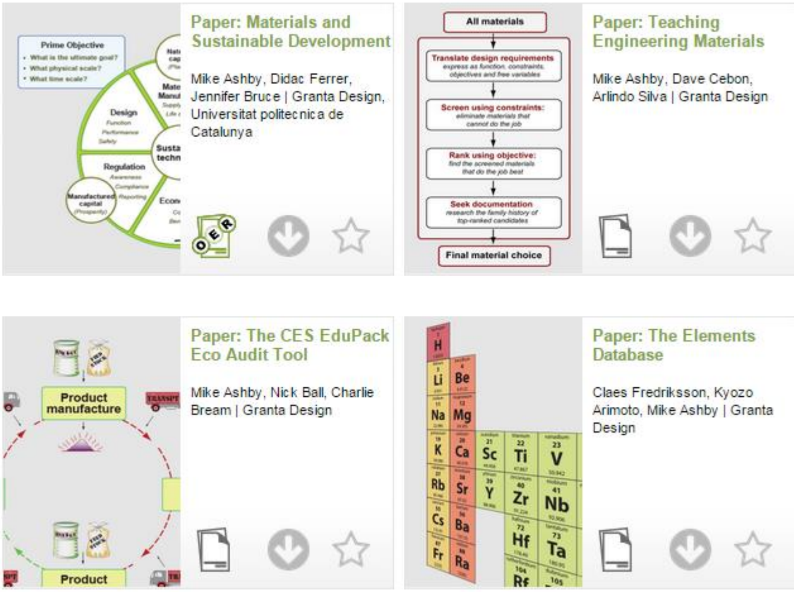
Ashby, M.F.; D. Cebon, D; Silva, A. “Paper: Teaching Engineering Materials” Granta Design Ltd 2012 www.teachingresources.grantadesign.com/Type/Papers/PAPTEMEN12

Other resources from Granta

(all references are available from www.teachingresources.grantadesign.com)

Or follow the hyperlinks below.

30 White papers



90 Lecture Units