Appendix C

Material and process selection charts

C.1 Introduction

The charts in this booklet summarize *material properties* and *process attributes*. Each chart appears on a single page with a brief commentary about its use on the facing page. Background and data sources can be found in the appendix to Chapter 13, pp. 313–333.

The material charts map the areas of property space occupied by each material class. They can be used in two ways:

(a) to retrieve approximate values for material properties
(b) to select materials which have prescribed property profiles

The collection of process charts, similarly, can be used as a data source or as a selection tool. Sequential application of several charts allows several design goals to be met simultaneously. More advanced methods are described in the book cited above.

The best way to tackle selection problems is to work directly on the appropriate charts. Permission is given to copy charts for this purpose. Normal copyright restrictions apply to reproduction for other purposes.

It is not possible to give charts which plot all the possible combinations: there are too many. Those presented here are the most commonly useful. Any other can be created easily using the CMS2 (1995) or CES (1999) software.

1.1 Cautions

The data on the charts and in the tables are approximate: they typify each class of material (stainless steels, or polyethylenes, for instance) or processes (sand casting, or injection moulding, for example), but within each class there is considerable variation. They are adequate for the broad comparisons required for conceptual design, and, often, for the rough calculations of embodiment design. **They are not appropriate for detailed design calculations**. For these, it is essential to seek accurate data from handbooks and the data sheets provided by material suppliers. The charts help in narrowing the choice of candidate materials to a sensible short list, but not in providing numbers for final accurate analysis.

Every effort has been made to ensure the accuracy of the data shown on the charts. No guarantee can, however, be given that the data are error-free, or that new data may not supersede those given here. The charts are an aid to creative thinking, not a source of numerical data for precise analysis.

1.2 Material classes, class members and properties

The materials of mechanical and structural engineering fall into nine broad classes listed in Table 1.1.

Within each class, the Materials Selection Charts show data for a representative set of materials, chosen both to span the full range of behaviour for that class, and to include the most widely used members of it. In this way the envelope for a class (heavy lines) encloses data not only for the materials listed on Table 1.2 (next two pages) but for virtually all other members of the class as well.

As far as possible, the same materials appear on all the charts. There are exceptions. Invar is only interesting because of its low thermal expansion: it appears on the thermal expansion charts (10 and 11) but on no others. Mn–Cu alloys have high internal damping: they are shown on the loss-coefficient chart (8) but not elsewhere. And there are others. But, broadly, the material and classes which appear on one chart appear on them all.

Table 1.1 Material classes

Engineering alloys	(metals and their alloys)
Engineering polymers	(thermoplastics and thermosets)
Engineering ceramics	('fine' ceramics)
Engineering composites	(GFRP, KFRP and CFRP)
Porous ceramics	(brick, cement, concrete, stone)
Glasses	(silicate glasses)
Woods	(common structural timbers)
Elastomers	(natural and artificial rubbers)
Foams	(foamed polymers)

Table 1.2 Members of each material class

Class	*Members*	*Short name*
Engineering alloys (The metals and alloys of engineering)	Aluminium alloys	Al Alloys
	Beryllium alloys	Be Alloys
	Cast irons	Cast iron
	Copper alloys	Cu Alloys
	Lead alloys	Lead Alloys
	Magnesium alloys	Mg Alloys
	Molybdenum alloys	Mo Alloys
	Nickel alloys	Ni Alloys
	Steels	Steels
	Tin alloys	Tin Alloys
	Titanium alloys	Ti Alloys
	Tungsten alloys	W Alloys
	Zinc alloys	Zn Alloys
Engineering polymers (The thermoplastics and thermosets of engineering)	Epoxies	EP
	Melamines	MEL
	Polycarbonate	PC
	Polyesters	PEST
	Polyethylene, high density	HDPE
	Polyethylene, low density	LDPE
	Polyformaldehyde	PF
	Polymethylmethacrylate	PMMA
	Polypropylene	PP
	Polytetrafluorethylene	PTFE
	Polyvinylchloride	PVC

Table 1.2 *(continued)*

Engineering ceramics (Fine ceramics capable of load-bearing applications)	Alumina	Al_2O_3
	Beryllia	BeO
	Diamond	Diamond
	Germanium	Ge
	Magnesium	MgO
	Silicon	Si
	Sialons	Sialons
	Silicon carbide	SiC
	Silicon nitride	Si_3N_4
	Zirconia	ZrO_2
Engineering composites (The composites of engineering practice A distinction is drawn between the properties of a ply–'uniply'–and of a laminate 'laminates')	Carbon fibre reinforced polymer	CFRP
	Glass fibre reinforced polymer	GFRP
	Kevlar fibre reinforced polymer	KFRP
Porous ceramics (Traditional ceramics cements, rocks and minerals)	Brick	Brick
	Cement	Cement
	Common rocks	Rocks
	Concrete	Concrete
	Porcelain	Pcln
	Pottery	Pot
Glasses (Silicate glass and silica itself)	Borosilicate glass	B-glass
	Soda glass	Na-glass
	Silica	SiO_2
Woods (Separate envelopes describe properties parallel to the grain and normal to it, and wood products)	Ash	Ash
	Balsa	Balsa
	Fir	Fir
	Oak	Oak
	Pine	Pine
	Wood products (ply, etc)	Wood products
Elastomers (Natural and artificial rubbers)	Natural rubber	Rubber
	Hard butyl rubber	Hard butyl
	Polyurethane	PU
	Silicone rubber	Silicone
	Soft Butyl rubber	Soft butyl
Polymer foams (Foamed polymers of engineering)	These include:	
	Cork	Cork
	Polyester	PEST
	Polystyrene	PS
	Polyurethane	PU
Special materials (Materials included on one or a few charts only, because of their special characteristics)	Beryllium–copper alloys	BeCu
	Invar	Invar
	WC–Co Cermets	WC–Co
	Mn–Cu alloys	Mn–Cu Alloys

You will not find specific materials listed on the charts. The aluminium alloy 7075 in the T6 condition (for instance) is contained in the property envelopes for *Al-alloys*; the Nylon 66 in those for *nylons*. The charts are designed for the broad, early stages of materials selection, not for retrieving the precise values of material properties needed in the later, detailed design, stage.

The Material Selection Charts which follow display, for the nine classes of materials, the properties listed in Table 1.3.

The charts let you pick off the subset of materials with a property within a specified range: materials with modulus E between 100 and 200 GPa for instance; or materials with a thermal conductivity above 100 W/mK.

More usually, performance is maximized by selecting the subset of materials with the greatest value of a grouping of material properties. A light, stiff beam is best made of a material with a high value of $E^{1/2}/\rho$; safe pressure vessels are best made of a material with a high value of $K_{Ic}^{1/2}/\sigma_f$, and so on. Table 1.4 lists some of these performance-maximizing groups or 'material indices'. The charts are designed to display these, and to allow you to pick off the subset of materials which maximize them. Details of the method, with worked examples, are given in Chapters 5 and 6.

Multiple criteria can be used. You can pick off the subset of materials with both high $E^{1/2}/\rho$ *and* high E (good for light, stiff beams) from Chart 1; that with high σ_f^3/E^2 and high E (good materials for pivots) from Chart 4. Throughout, the goal is to identify from the charts a *subset* of materials, not a single material. Finding the best material for a given application involves many considerations, many of them (like availability, appearance and feel) not easily quantifiable. The charts do not give you the final choice — that requires the use of your judgement and experience. Their power is that they guide you quickly and efficiently to a subset of materials worth considering; and they make sure that you do not overlook a promising candidate.

1.4 Process classes and class members

A *process* is a method of shaping, finishing or joining a material. *Sand casting*, *injection moulding*, *polishing* and *fusion welding* are all processes. The choice, for a given component, depends on the material of which it is to be made, on its size, shape and precision, and on how many are required.

The manufacturing processes of engineering fall into nine broad classes:

Table 1.3 Material properties shown on the charts

Property	*Symbol*	*Units*
Relative cost	C_m	(–)
Density	ρ	(Mg/m^3)
Young's modulus	E	(GPa)
Strength	σ_f	(MPa)
Fracture toughness	K_{Ic}	(MPam$^{1/2}$)
Toughness	G_{Ic}	(J/m^2)
Damping coefficient	η	(–)
Thermal conductivity	λ	(W/mK)
Thermal diffusivity	a	(m^2/s)
Volume specific heat	$C_{P\rho}$	(J/m^{3}K)
Thermal expansion coefficient	a	(1/K)
Thermal shock resistance	ΔT	(K)
Strength at temperature	$\sigma(T)$	(MPa)
Specific wear rate	W/AP	(1/MPa)

Table 1.4 Examples of material-indices

Function	*Index*
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m \rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m \rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m \rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E_\rho}$
Thermal insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_m \rho}$

(ρ = density; E = Young's modulus; σ_y = elastic limit; C_m = cost/kg; λ = thermal conductivity; κ = electrical conductivity; C_p = specific heat)

Table 1.5 Process classes

Casting	(sand, gravity, pressure, die, etc.)
Pressure moulding	(direct, transfer, injection, etc.)
Deformation processes	(rolling, forging, drawing, etc.)
Powder methods	(slip cast, sinter, hot press, hip)
Special methods	(CVD, electroform, lay up, etc.)
Machining	(cut, turn, drill, mill, grind, etc.)
Heat treatment	(quench, temper, solution treat, age, etc.)
Joining	(bolt, rivet, weld, braze, adhesives)
Finish	(polish, plate, anodize, paint)

Each process is characterized by a set of *attributes*: the materials it can handle, the shapes it can make and their precision, complexity and size. Process Selection Charts map the attributes, showing the ranges of size, shape, material, precision and surface finish of which each class of process is capable. The procedure does not lead to a final choice of process. Instead, it identifies a subset of processes which have the potential to meet the design requirements. More specialized sources must then be consulted to determine which of these is the most economical.

C.2 THE MATERIALS SELECTION CHARTS

Chart 1: Young's modulus, *E* against density, ρ

This chart guides selection of materials for light, stiff, components. The contours show the longitudinal wave speed in m/s; natural vibration frequencies are proportional to this quantity. The guide lines show the loci of points for which

(a) $E/\rho = C$ (minimum weight design of stiff ties; minimum deflection in centrifugal loading, etc.)
(b) $E^{1/2}/\rho = C$ (minimum weight design of stiff beams, shafts and columns)
(c) $E^{1/3}/\rho = C$ (minimum weight design of stiff plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest stiffness-to-weight ratio lie towards the upper left-hand corner.

Other moduli are obtained approximately from E using

(a) $\nu = 1/3$; $G = 3/8E$; $K \approx E$ (metals, ceramics, glasses and glassy polymers)
or (b) $\nu \approx 1/2$; $G \approx 1/3E$; $K \approx 10E$ (elastomers, rubbery polymers)

where ν is Poisson's ratio, G the shear modulus and K the bulk modulus.

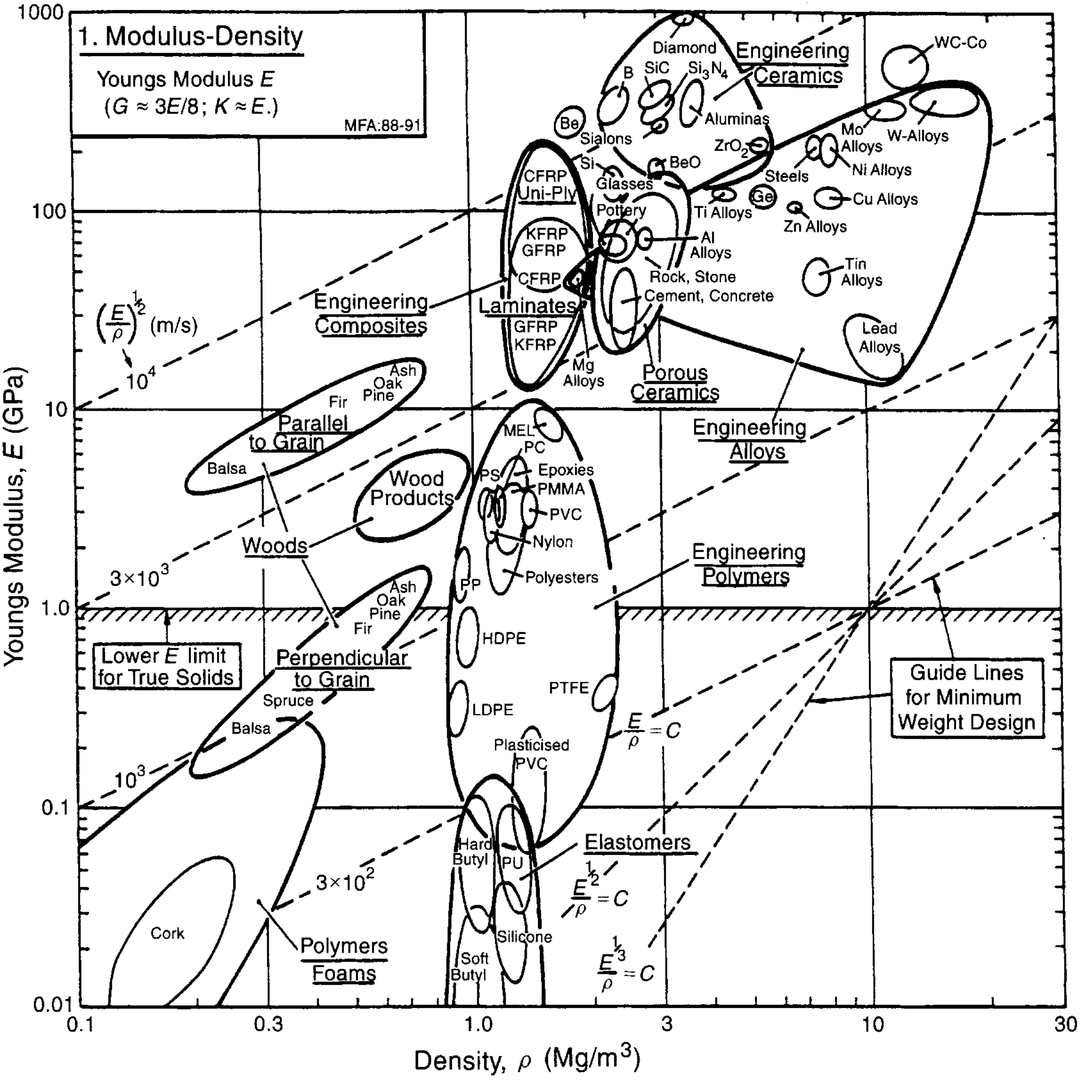

1. Modulus-Density
Youngs Modulus E
($G \approx 3E/8$; $K \approx E$.)
MFA:88-91
Youngs Modulus, E (GPa)
Density, ρ (Mg/m^3)
1000
100
10
1.0
0.1
0.01
0.1
0.3
1.0
3
10
30
$\left(\frac{E}{\rho}\right)^{\frac{1}{2}}$ (m/s)
10^4
3×10^3
10^3
3×10^2
Diamond
B
SiC
Si_3N_4
Engineering Ceramics
Aluminas
Be
Sialons
ZrO_2
Si
BeO
Glasses
Pottery
WC-Co
Mo Alloys
W-Alloys
Ni Alloys
Steels
Ge
Cu Alloys
Ti Alloys
Zn Alloys
Al Alloys
Tin Alloys
Rock, Stone
Cement, Concrete
Lead Alloys
CFRP Uni-Ply
KFRP
GFRP
CFRP
Laminates
GFRP
KFRP
Engineering Composites
Mg Alloys
Porous Ceramics
Engineering Alloys
Ash
Oak
Pine
Fir
Parallel to Grain
Balsa
Wood Products
Woods
MEL
PC
PS
Epoxies
PMMA
PVC
Nylon
Polyesters
Engineering Polymers
PP
HDPE
PTFE
LDPE
Ash
Oak
Pine
Fir
Perpendicular to Grain
Lower E limit for True Solids
Spruce
Balsa
Plasticised PVC
$\frac{E}{\rho} = C$
Guide Lines for Minimum Weight Design
Hard Butyl
PU
Elastomers
$\frac{E^{\frac{1}{2}}}{\rho} = C$
Silicone
Cork
Polymers Foams
Soft Butyl
$\frac{E^{\frac{1}{3}}}{\rho} = C$

Chart 2: Strength, σ_f, against density, ρ

The ‘strength’ for metals is the 0.2% offset yield strength. For polymers, it is the stress at which the stress–strain curve becomes markedly non-linear — typically, a strain of about 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The chart guides selection of materials for light, strong, components. The guide lines show the loci of points for which:

(a) $\sigma_f/\rho = C$ (minimum weight design of strong ties; maximum rotational velocity of discs)
(b) $\sigma_f^{2/3}/\rho = C$ (minimum weight design of strong beams and shafts)
(c) $\sigma_f^{1/2}/\rho = C$ (minimum weight design of strong plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest strength-to-weight ratio lie towards the upper left corner.

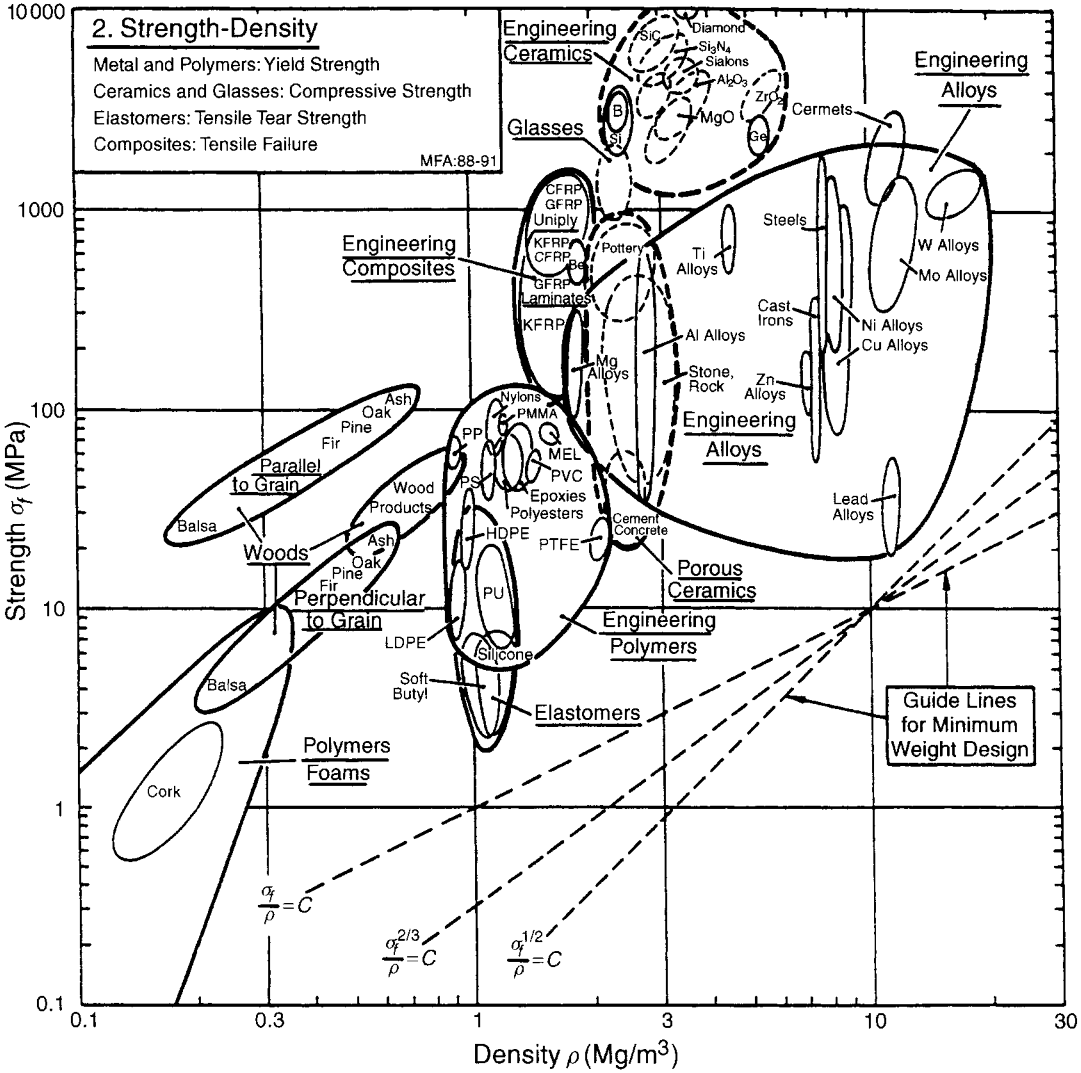

2. Strength-Density
Metal and Polymers: Yield Strength
Ceramics and Glasses: Compressive Strength
Elastomers: Tensile Tear Strength
Composites: Tensile Failure
MFA:88-91
Engineering Ceramics
SiC
Diamond
Si_3N_4
Sialons
Al_2O_3
ZrO_2
B
MgO
Si
Ge
Glasses
Cermets
Engineering Alloys
CFRP
GFRP
Uniply
KFRP
CFRP
Be
GFRP
Laminates
KFRP
Engineering Composites
Pottery
Ti Alloys
Steels
W Alloys
Mo Alloys
Cast Irons
Ni Alloys
Cu Alloys
Al Alloys
Mg Alloys
Stone, Rock
Zn Alloys
Engineering Alloys
Ash
Oak
Pine
Fir
Parallel to Grain
Balsa
Woods
Wood Products
Nylons
PMMA
PP
MEL
PVC
PS
Epoxies
Polyesters
HDPE
PTFE
Cement
Concrete
Porous Ceramics
Lead Alloys
Ash
Oak
Pine
Fir
Perpendicular to Grain
PU
LDPE
Silicone
Engineering Polymers
Balsa
Soft Butyl
Elastomers
Guide Lines for Minimum Weight Design
Polymers Foams
Cork
$\frac{\sigma_f}{\rho}=C$
$\frac{\sigma_f^{2/3}}{\rho}=C$
$\frac{\sigma_f^{1/2}}{\rho}=C$
Strength σ_f (MPa)
10000
1000
100
10
1
0.1
Density ρ (Mg/m^3)
0.1
0.3
1
3
10
30

Chart 3: Fracture toughness, K_{Ic}, against density, ρ

Linear-elastic fracture mechanics describes the behaviour of cracked, brittle solids. It breaks down when the fracture toughness is large and the section is small; then J-integral methods should be used. The data shown here are adequate for the rough calculations of conceptual design and as a way of ranking materials. The chart guides selection of materials for light, fracture-resistant components. The guide lines show the loci of points for which:

(a) $K_{Ic}^{4/3}/\rho = C$ (minimum weight design of brittle ties, maximum rotational velocity of brittle discs, etc.)
$K_{Ic}/\rho = C$
(b) $K_{Ic}^{4/5}/\rho = C$ (minimum weight design of brittle beams and shafts)
$K_{Ic}^{2/3}/\rho = C$
(c) $K_{Ic}^{2/3}/\rho = C$ (minimum weight design of brittle plates)
$K_{Ic}^{1/2}/\rho = C$

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest toughness-to-weight ratio lie towards the upper left corner.

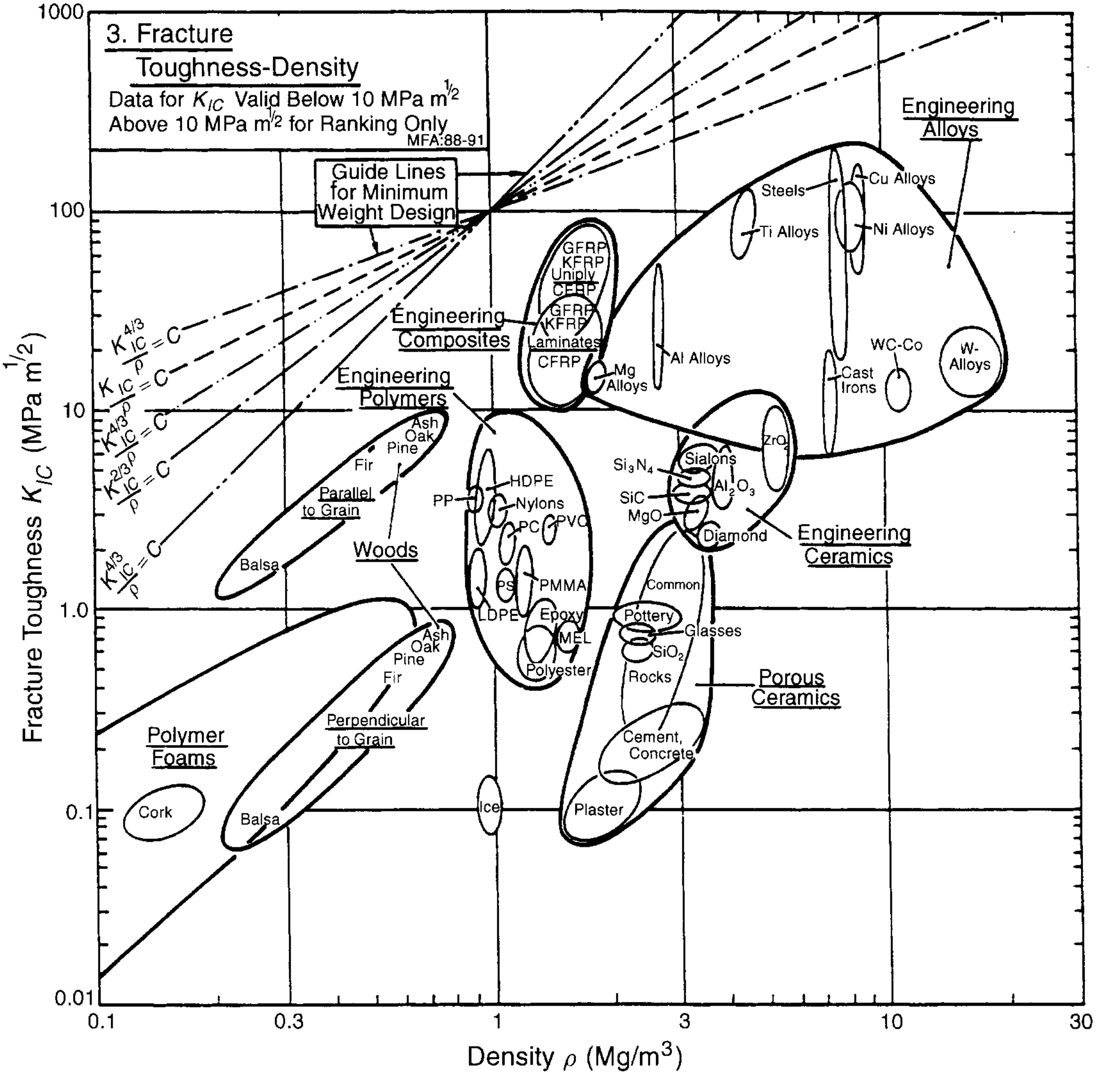

3. Fracture Toughness-Density
Data for K_{IC} Valid Below 10 MPa $m^{1/2}$
Above 10 MPa $m^{1/2}$ for Ranking Only
MFA:88-91
Guide Lines for Minimum Weight Design
$\frac{K_{IC}^{4/3}}{\rho} = C$
$\frac{K_{IC}}{\rho} = C$
$\frac{K_{IC}^{4/3}}{\rho} = C$
$\frac{K_{IC}^{2/3}}{\rho} = C$
$\frac{K_{IC}^{4/3}}{\rho} = C$
Engineering Alloys
Steels
Cu Alloys
Ti Alloys
Ni Alloys
GFRP
KFRP
Uniply
CFRP
GFRP
KFRP
Laminates
CFRP
Engineering Composites
Mg Alloys
Al Alloys
WC-Co
W-Alloys
Cast Irons
Engineering Polymers
Ash
Oak
Pine
Fir
Parallel to Grain
Balsa
Woods
PP
HDPE
Nylons
PC
PVC
PS
PMMA
LDPE
Epoxy
MEL
Polyester
Si$_3$N$_4$
SiC
MgO
Sialons
ZrO$_2$
Al$_2$O$_3$
Diamond
Engineering Ceramics
Common
Pottery
Glasses
SiO$_2$
Rocks
Porous Ceramics
Cement, Concrete
Plaster
Ice
Polymer Foams
Cork
Ash
Oak
Pine
Fir
Perpendicular to Grain
Balsa
1000
100
10
1.0
0.1
0.01
Fracture Toughness K_{IC} (MPa $m^{1/2}$)
0.1
0.3
1
3
10
30
Density ρ (Mg/m^3)

Chart 4: Young's modulus, *E*, against strength, σ_f

The chart for elastic design. The contours show the failure strain, σ_f/E. The 'strength' for metals is the 0.2% offset yield strength. For polymers, it is the 1% yield strength. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The chart has numerous applications among them: the selection of materials for springs, elastic hinges, pivots and elastic bearings, and for yield-before-buckling design. The guide lines show three of these; they are the loci of points for which:

(a) $\sigma_f/E = C$ (elastic hinges)

(b) $\sigma_f^2/E = C$ (springs, elastic energy storage per unit volume)

(c) $\sigma_f^{3/2}/E = C$ (selection for elastic constants such as knife edges; elastic diaphragms, compression seals)

The value of the constant C increases as the lines are displaced downward and to the right.

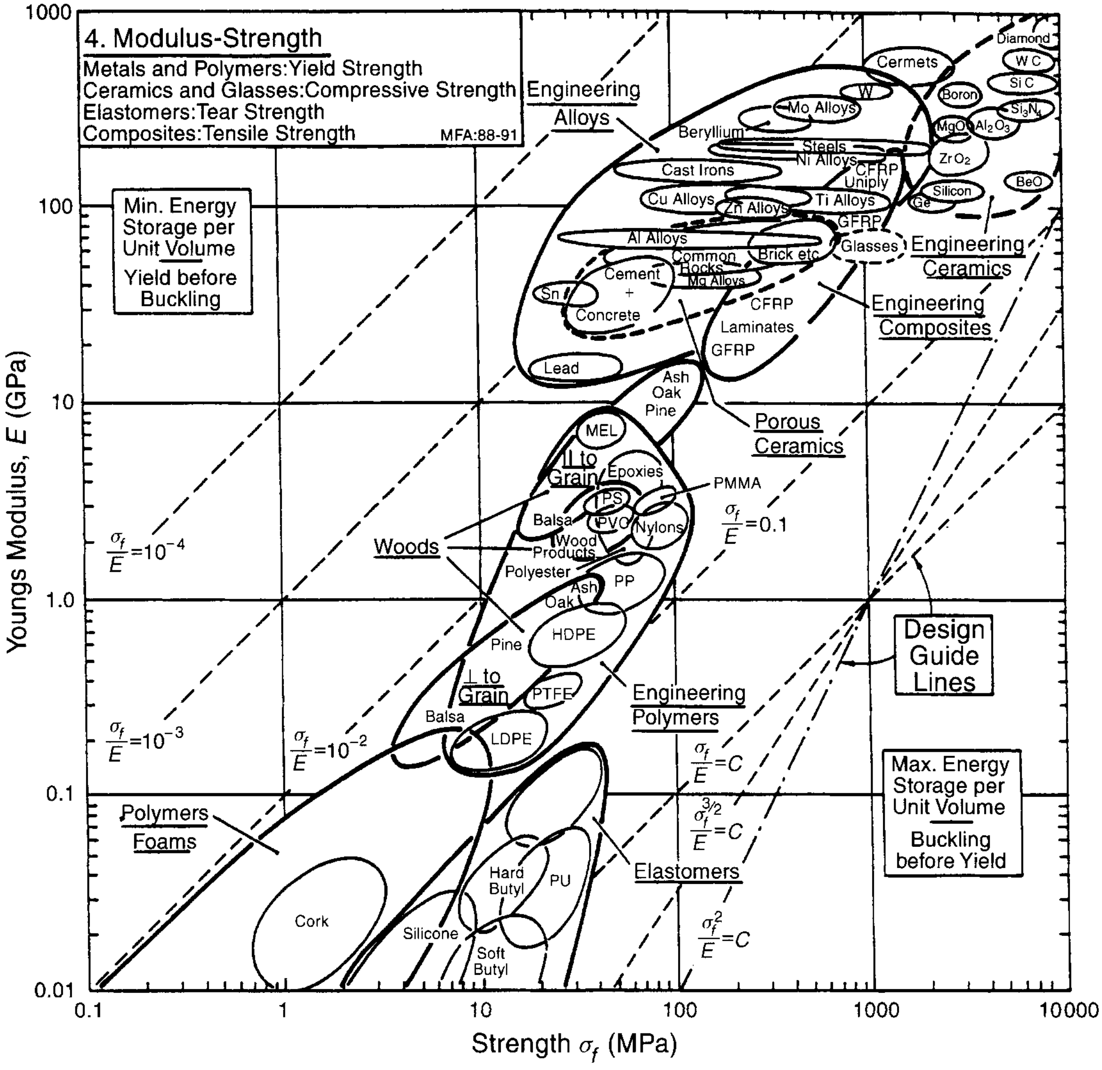

4. Modulus-Strength
Metals and Polymers:Yield Strength
Ceramics and Glasses:Compressive Strength
Elastomers:Tear Strength
Composites:Tensile Strength
MFA:88-91
Min. Energy Storage per Unit Volume
Yield before Buckling
Max. Energy Storage per Unit Volume
Buckling before Yield
Design Guide Lines
$\frac{\sigma_f}{E}=10^{-4}$
$\frac{\sigma_f}{E}=10^{-3}$
$\frac{\sigma_f}{E}=10^{-2}$
$\frac{\sigma_f}{E}=0.1$
$\frac{\sigma_f}{E}=C$
$\frac{\sigma_f^{3/2}}{E}=C$
$\frac{\sigma_f^2}{E}=C$
Engineering Alloys
Engineering Ceramics
Engineering Composites
Porous Ceramics
Engineering Polymers
Woods
Polymers Foams
Elastomers
Diamond
W C
Si C
Si$_3$N$_4$
Cermets
Boron
W
Mo Alloys
Beryllium
MgO
Al$_2$O$_3$
Steels
Ni Alloys
ZrO$_2$
CFRP Uniply
Cast Irons
BeO
Silicon
Ge
Cu Alloys
Zn Alloys
Ti Alloys
GFRP
Al Alloys
Glasses
Common Rocks
Brick etc
Mg Alloys
Cement + Concrete
Sn
CFRP Laminates
GFRP
Lead
Ash Oak Pine
MEL
∥ to Grain
Epoxies
PS
PMMA
Balsa
PVC
Nylons
Wood Products
Polyester
Ash Oak
PP
HDPE
Pine
⊥ to Grain
PTFE
Balsa
LDPE
Hard Butyl
PU
Cork
Silicone
Soft Butyl
Youngs Modulus, E (GPa)
1000
100
10
1.0
0.1
0.01
Strength σ_f (MPa)
0.1
1
10
100
1000
10000

Chart 5: Specific modulus, E/ρ, against specific strength, σ_f/ρ

The chart for specific stiffness and strength. The contours show the yield strain, σ_f/E. The qualifications on strength given for Charts 2 and 4 apply here also. The chart finds application in minimum weight design of ties and springs, and in the design of rotating components to maximize rotational speed or energy storage, etc. The guide lines show the loci of points for which

(a) $\sigma_f^2/E\rho = C$ (ties, springs of minimum weight; maximum rotational velocity of discs)
(b) $\sigma_f^{3/2}/E_\rho^{1/2} = C$
(c) $\sigma_f/E = C$ (elastic hinge design)

The value of the constant C increases as the lines are displaced downwards and to the right.

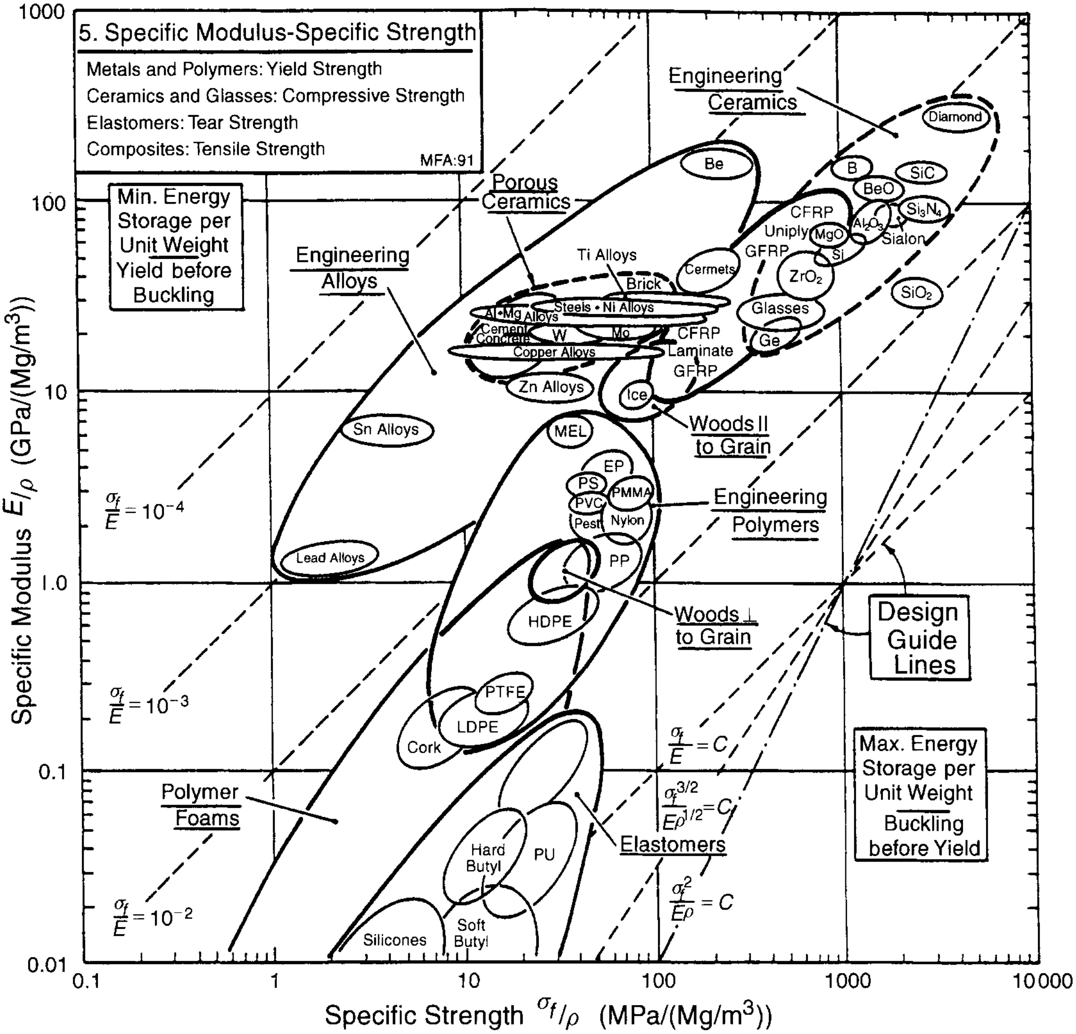

5. Specific Modulus-Specific Strength
Metals and Polymers: Yield Strength
Ceramics and Glasses: Compressive Strength
Elastomers: Tear Strength
Composites: Tensile Strength
MFA:91
Min. Energy Storage per Unit Weight Yield before Buckling
Max. Energy Storage per Unit Weight Buckling before Yield
Design Guide Lines
Engineering Ceramics
Porous Ceramics
Engineering Alloys
Engineering Polymers
Polymer Foams
Elastomers
Woods ll to Grain
Woods ⊥ to Grain
Diamond
B
SiC
BeO
Si3N4
Al2O3
Sialon
CFRP Uniply
MgO
Si
GFRP
ZrO2
SiO2
Glasses
Ge
Be
Cermets
Ti Alloys
Brick
Al•Mg Alloys
Steels • Ni Alloys
Cement Concrete
W
Mo
Copper Alloys
CFRP Laminate GFRP
Zn Alloys
Ice
Sn Alloys
Lead Alloys
MEL
EP
PS
PMMA
PVC
Pest
Nylon
PP
HDPE
PTFE
LDPE
Cork
Hard Butyl
PU
Soft Butyl
Silicones
$\frac{\sigma_f}{E} = 10^{-4}$
$\frac{\sigma_f}{E} = 10^{-3}$
$\frac{\sigma_f}{E} = 10^{-2}$
$\frac{\sigma_f}{E} = C$
$\frac{\sigma_f^{3/2}}{E\rho^{1/2}} = C$
$\frac{\sigma_f^2}{E\rho} = C$
Specific Modulus E/ρ (GPa/(Mg/m^3))
Specific Strength σ_f/ρ (MPa/(Mg/m^3))
1000
100
10
1.0
0.1
0.01
0.1
1
10
100
1000
10000

Chart 6: Fracture toughness, K_{Ic}, against Young's modulus, E

The chart displays both the fracture toughness, K_{Ic}, and (as contours) the toughness, $G_{Ic} \approx K_{Ic}^2/E$; and it allows criteria for stress and displacement-limited failure criteria (K_{Ic} and K_{Ic}/E) to be compared. The guide lines show the loci of points for which

(a) $K_{Ic}^2/E = C$ (lines of constant toughness, G_c; energy-limited failure)
(b) $K_{Ic}/E = C$ (guideline for displacement-limited brittle failure)

The values of the constant C increases as the lines are displaced upwards and to the left. Tough materials lie towards the upper left corner, brittle materials towards the bottom right.

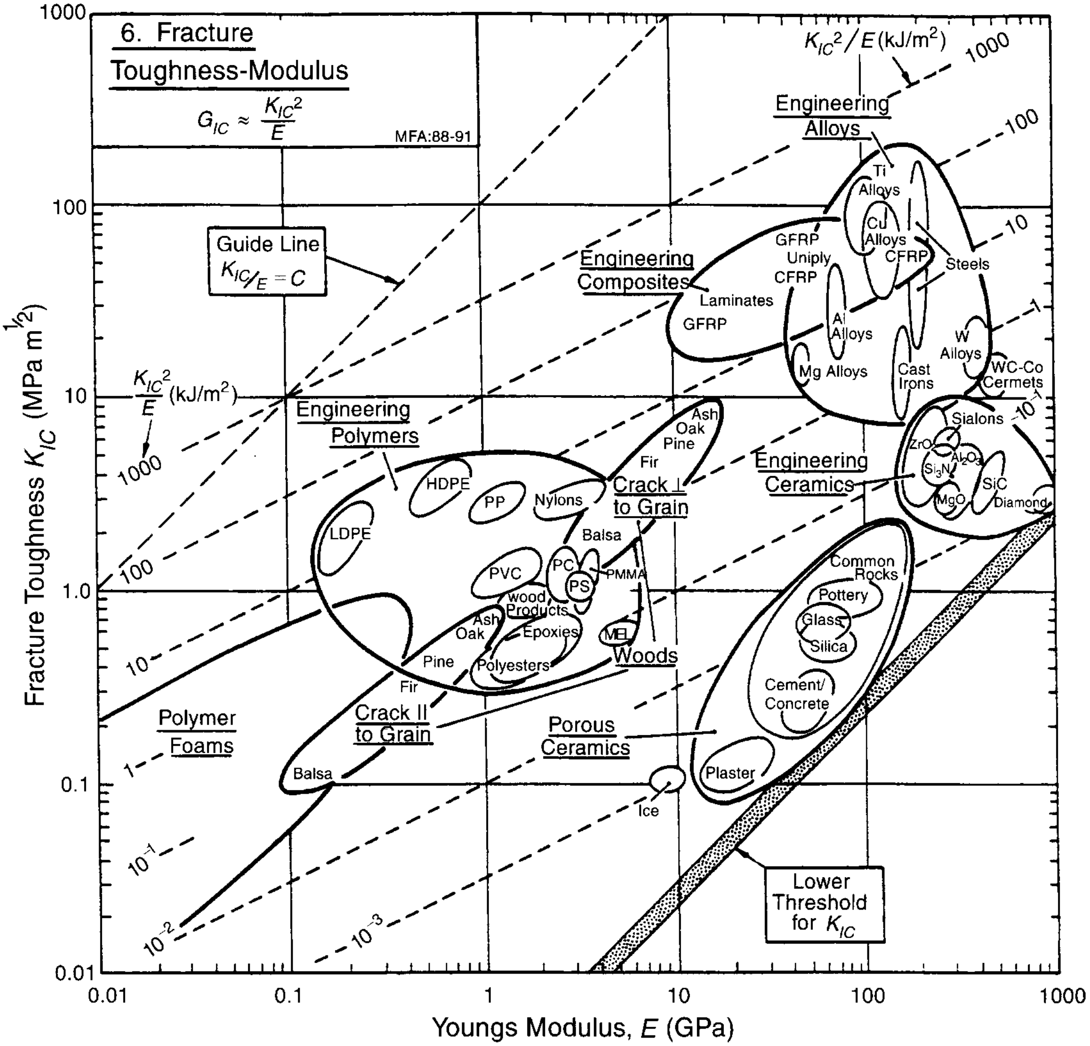

6. Fracture
Toughness-Modulus
$G_{IC} \approx \frac{K_{IC}^2}{E}$
MFA:88-91
K_{IC}^2/E (kJ/m^2)
1000
100
10
1
10^{-1}
Guide Line
$K_{IC}/E = C$
$\frac{K_{IC}^2}{E}$ (kJ/m^2)
1000
100
10
1
10^{-1}
10^{-2}
10^{-3}
Engineering
Alloys
Ti Alloys
Cu Alloys
CFRP
Steels
GFRP Uniply CFRP
Engineering
Composites
Laminates
GFRP
Al Alloys
Mg Alloys
Cast Irons
W Alloys
WC-Co Cermets
Engineering
Polymers
HDPE
PP
Nylons
LDPE
PVC
PC
PS
PMMA
wood Products
Epoxies
MEL
Polyesters
Ash
Oak
Pine
Fir
Balsa
Crack ⊥
to Grain
Woods
Crack ll
to Grain
Engineering
Ceramics
Sialons
ZrO$_2$
Al$_2$O$_3$
Si$_3$N$_4$
SiC
MgO
Diamond
Common Rocks
Pottery
Glass
Silica
Cement/ Concrete
Plaster
Porous
Ceramics
Ice
Polymer
Foams
Lower Threshold for K_{IC}
Fracture Toughness K_{IC} (MPa m$^{1/2}$)
1000
100
10
1.0
0.1
0.01
Youngs Modulus, E (GPa)
0.01
0.1
1
10
100
1000

Chart 7: Fracture toughness, K_{Ic}, against strength, σ_f

The chart for safe design against fracture. The contours show the process-zone diameter, given approximately by $K_{Ic}^2/\pi\sigma_f^2$. The qualifications on 'strength' given for Charts 2 and 4 apply here also. The chart guides selection of materials to meet yield-before-break design criteria, in assessing plastic or process-zone sizes, and in designing samples for valid fracture toughness testing. The guide lines show the loci of points for which

(a) $K_{Ic}/\sigma_f = C$ (yield-before-break)
(b) $K_{Ic}^2/\sigma_f = C$ (leak-before-break)

The value of the constant C increases as the lines are displaced upward and to the left.

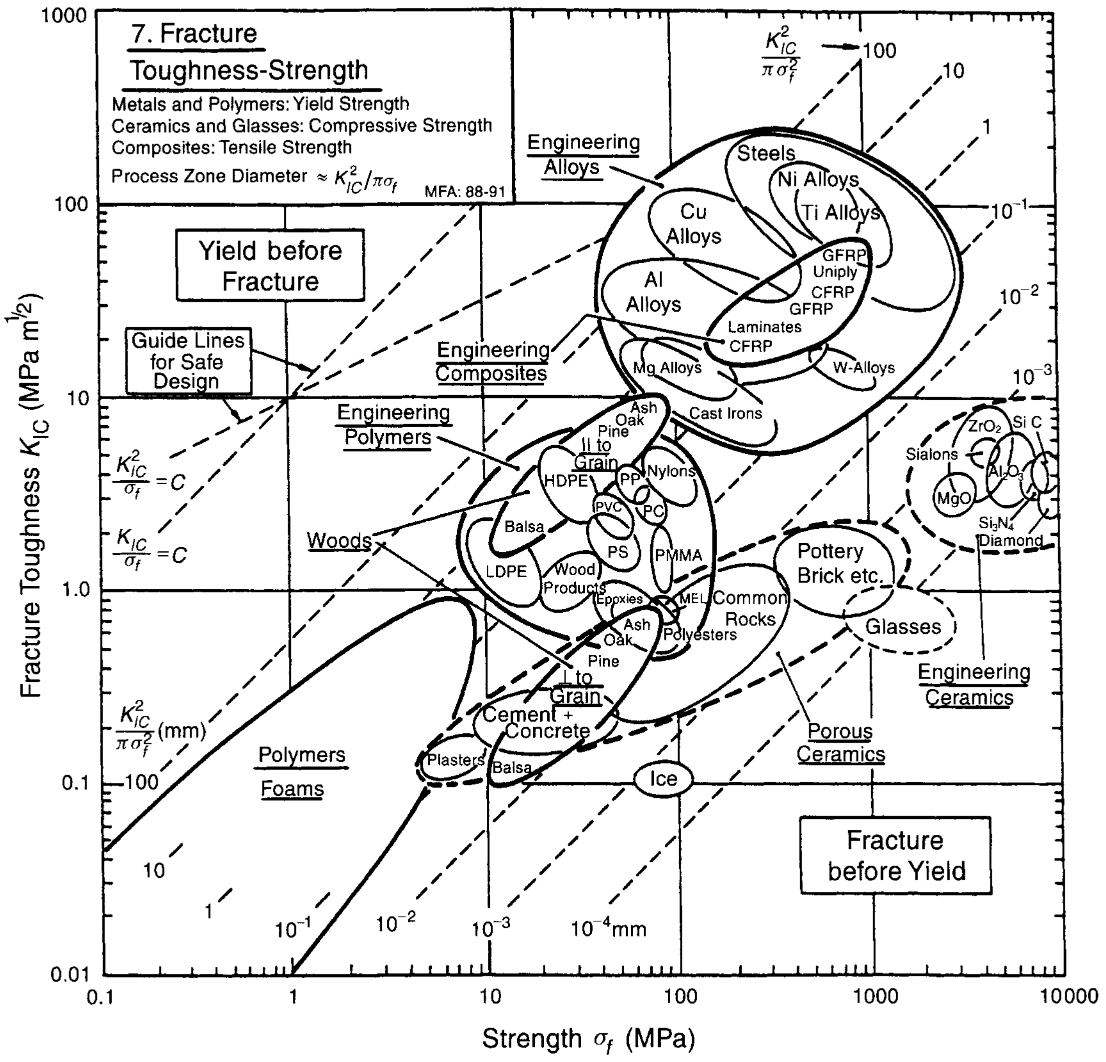

7. Fracture Toughness-Strength
Metals and Polymers: Yield Strength
Ceramics and Glasses: Compressive Strength
Composites: Tensile Strength
Process Zone Diameter ≈ $K_{IC}^2/\pi\sigma_f$
MFA: 88-91
Yield before Fracture
Fracture before Yield
Guide Lines for Safe Design
$\frac{K_{IC}^2}{\sigma_f} = C$
$\frac{K_{IC}}{\sigma_f} = C$
$\frac{K_{IC}^2}{\pi\sigma_f^2}$ (mm)
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}mm
Engineering Alloys
Steels
Ni Alloys
Ti Alloys
Cu Alloys
Al Alloys
GFRP Uniply
CFRP
GFRP
Laminates CFRP
Mg Alloys
W-Alloys
Cast Irons
Engineering Composites
Engineering Polymers
Ash
Oak
Pine
II to Grain
HDPE
PP
Nylons
PVC
PC
Balsa
PS
PMMA
LDPE
Wood Products
Epoxies
MEL
Polyesters
Woods
⊥ to Grain
Common Rocks
Pottery Brick etc.
Glasses
Sialons
ZrO₂
Si C
Al₂O₃
MgO
Si₃N₄
Diamond
Engineering Ceramics
Porous Ceramics
Cement + Concrete
Plasters
Ice
Polymers Foams
Fracture Toughness K_{IC} (MPa $m^{1/2}$)
1000
100
10
1.0
0.1
0.01
Strength σ_f (MPa)
0.1
1
10
100
1000
10000

Chart 8: Loss coefficient, η, against Young's modulus, E

The chart gives guidance in selecting material for low damping (springs, vibrating reeds, etc.) and for high damping (vibration-mitigating systems). The guide line shows the loci of points for which

(a) $\eta E = C$ (rule-of-thumb for estimating damping in polymers)

The value of the constant C increases as the line is displaced upward and to the right.

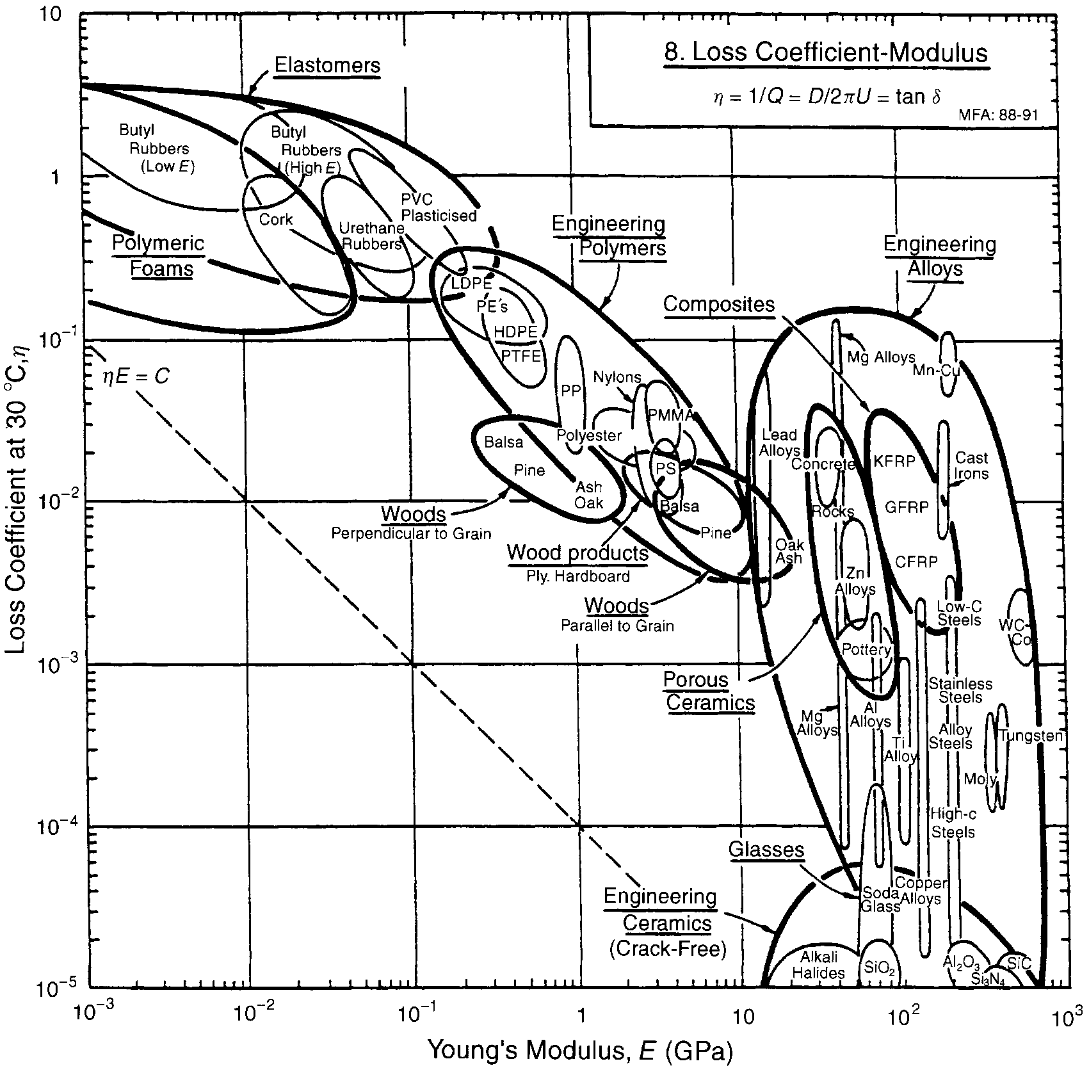

8. Loss Coefficient-Modulus
$\eta = 1/Q = D/2\pi U = \tan\delta$
MFA: 88-91
Elastomers
Butyl Rubbers (Low E)
Butyl Rubbers (High E)
Cork
Urethane Rubbers
PVC Plasticised
Polymeric Foams
Engineering Polymers
LDPE
PE's
HDPE
PTFE
PP
Nylons
PMMA
Polyester
PS
Balsa
Pine
Ash Oak
Woods Perpendicular to Grain
Wood products Ply. Hardboard
Balsa
Pine
Oak Ash
Woods Parallel to Grain
$\eta E = C$
Composites
Engineering Alloys
Mg Alloys
Mn-Cu
Lead Alloys
Concrete
KFRP
Cast Irons
Rocks
GFRP
CFRP
Zn Alloys
Low-C Steels
WC-Co
Pottery
Porous Ceramics
Stainless Steels
Mg Alloys
Al Alloys
Ti Alloy
Alloy Steels
Tungsten
Moly
High-c Steels
Glasses
Soda Glass
Copper Alloys
Engineering Ceramics (Crack-Free)
Alkali Halides
SiO_2
Al_2O_3
Si_3N_4
SiC
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Loss Coefficient at 30 °C, η
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Young's Modulus, E (GPa)

Chart 9: Thermal conductivity, λ, against thermal diffusivity, *a*

The chart guides in selecting materials for thermal insulation, for use as heat sinks and so forth, both when heat flow is steady, (λ) and when it is transient ($a = \lambda/\rho C_p$ where ρ is the density and C_p the specific heat). Contours show values of the volumetric specific heat, $\rho C_p = \lambda/a$ (J/m^{3}K). The guide lines show the loci of points for which

(a) $\lambda/a = C$ (constant volumetric specific heat)
(b) $\lambda/a^{1/2} = C$ (efficient insulation; thermal energy storage)

The value of constant C increases towards the upper left.

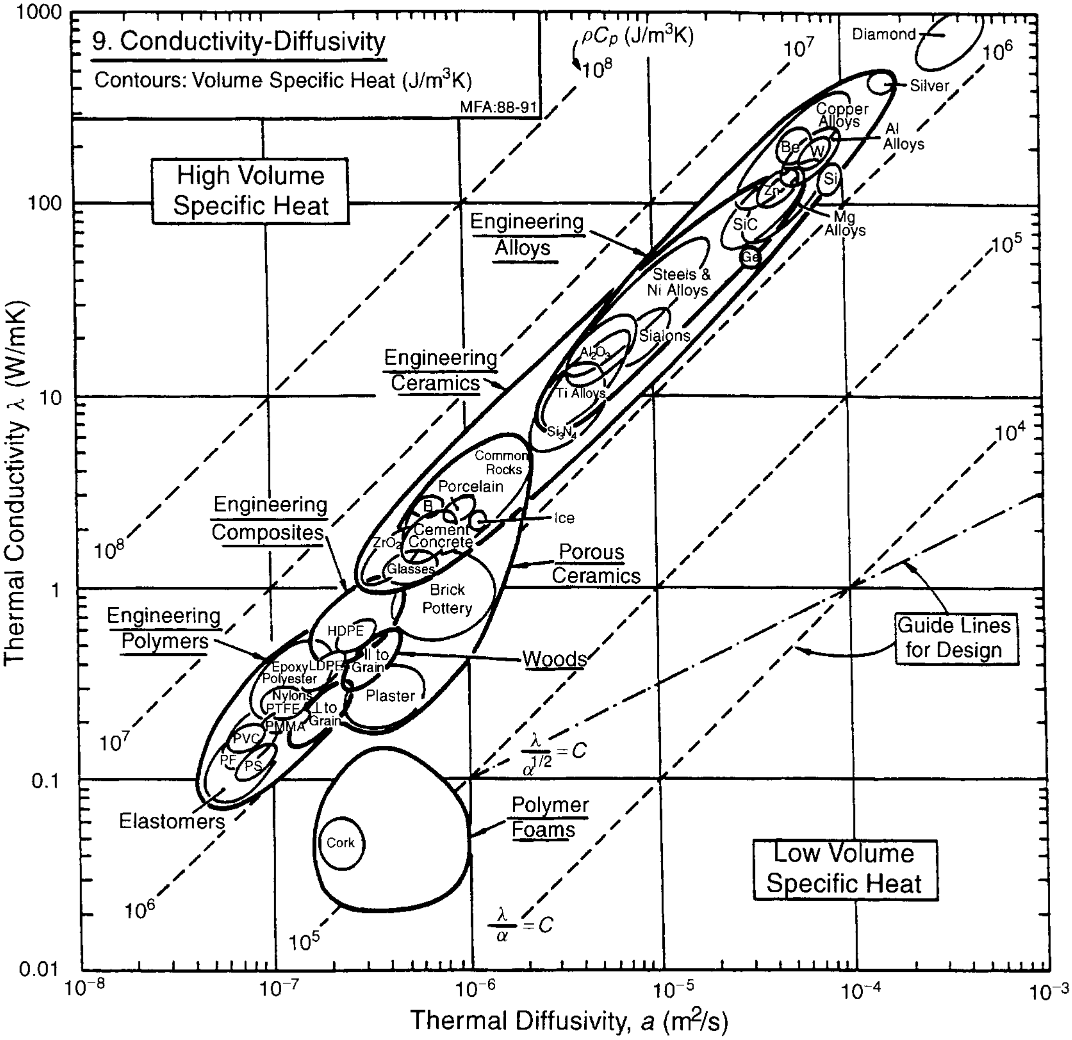

9. Conductivity-Diffusivity
Contours: Volume Specific Heat (J/m³K)
MFA:88-91
ρCp (J/m³K)
10⁸
10⁷
10⁶
10⁵
10⁴
High Volume Specific Heat
Low Volume Specific Heat
Diamond
Silver
Copper Alloys
Al Alloys
Be
W
Si
Zn
Mg Alloys
SiC
Ge
Engineering Alloys
Steels & Ni Alloys
Sialons
Al₂O₃
Ti Alloys
Si₃N₄
Engineering Ceramics
Common Rocks
Porcelain
B
Ice
Cement
ZrO₂
Concrete
Glasses
Engineering Composites
Porous Ceramics
Brick Pottery
HDPE
Engineering Polymers
Epoxy
LDPE
Polyester
ll to Grain
Woods
Nylons
PTFE
⊥ to Grain
Plaster
PMMA
PVC
PF
PS
Elastomers
Guide Lines for Design
λ/α^{1/2} = C
λ/α = C
Cork
Polymer Foams
Thermal Conductivity λ (W/mK)
1000
100
10
1
0.1
0.01
Thermal Diffusivity, a (m²/s)
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³

Chart 10: T-Expansion coefficient, α, against T-conductivity, λ

The chart for assessing thermal distortion. The contours show value of the ratio λ/α (W/m). Materials with a large value of this design index show small thermal distortion. They define the guide line

(a) $\lambda/\alpha = C$ (minimization of thermal distortion)

The value of the constant C increases towards the bottom right.

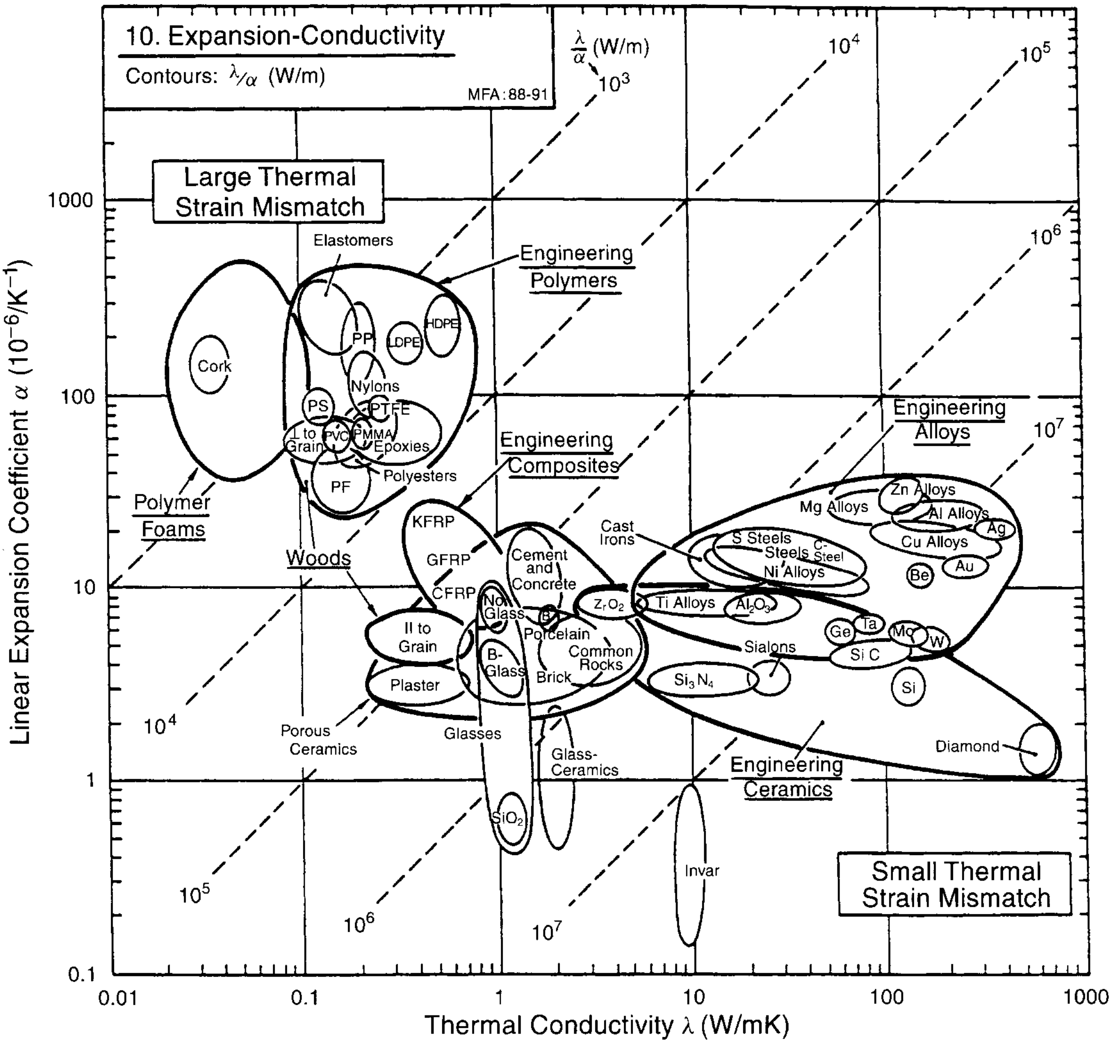

10. Expansion-Conductivity
Contours: λ/α (W/m)
MFA:88-91
λ/α (W/m)
10³
10⁴
10⁵
10⁶
10⁷
Large Thermal Strain Mismatch
Small Thermal Strain Mismatch
Elastomers
Engineering Polymers
Cork
PP
LDPE
HDPE
Nylons
PS
PTFE
⊥ to Grain
PVC
PMMA
Epoxies
Polyesters
PF
Polymer Foams
Woods
Engineering Composites
KFRP
GFRP
CFRP
Cement and Concrete
Cast Irons
Engineering Alloys
Zn Alloys
Mg Alloys
Al Alloys
Ag
Cu Alloys
Au
Be
S Steels
C-Steel
Steels
Ni Alloys
Ti Alloys
ZrO₂
Al₂O₃
Ge
Ta
Mo
W
Si C
Sialons
Si₃N₄
Si
Diamond
II to Grain
Plaster
Na Glass
B
Porcelain
Common Rocks
B-Glass
Brick
Porous Ceramics
Glasses
Glass-Ceramics
SiO₂
Invar
Engineering Ceramics
Linear Expansion Coefficient α (10⁻⁶/K⁻¹)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
Thermal Conductivity λ (W/mK)

Chart 11: Linear thermal expansion, α, against Young's modulus, *E*

The chart guides in selecting materials when thermal stress is important. The contours show the thermal stress generated, per °C temperature change, in a constrained sample. They define the guide line

$$\alpha E = C\,\text{MPa/K (constant thermal stress per K)}$$

The value of the constant C increases towards the upper right.

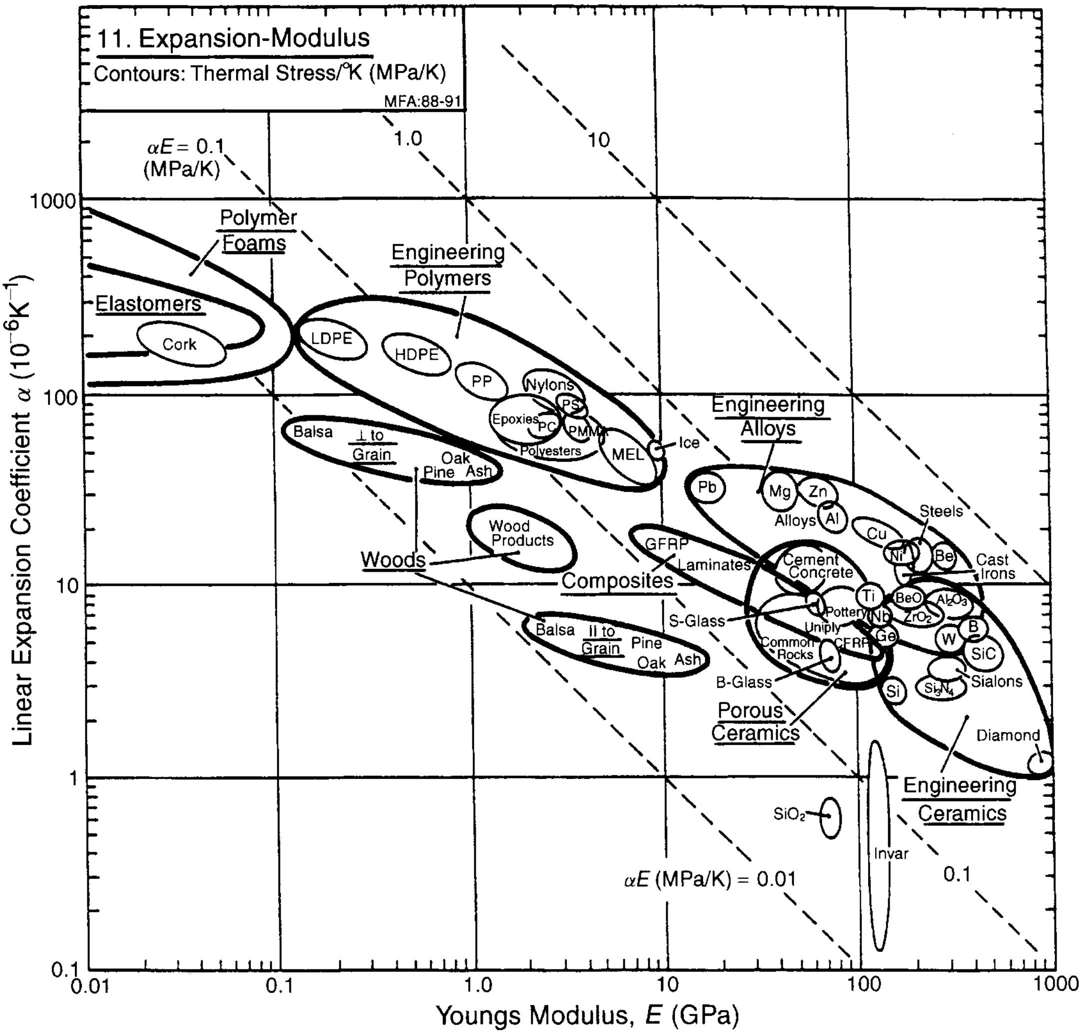

11. Expansion-Modulus
Contours: Thermal Stress/°K (MPa/K)
MFA:88-91
αE = 0.1 (MPa/K)
1.0
10
αE (MPa/K) = 0.01
0.1
Polymer Foams
Elastomers
Cork
Engineering Polymers
LDPE
HDPE
PP
Nylons
PS
Epoxies
PC
PMMA
Polyesters
MEL
Ice
Balsa ⊥ to Grain
Oak
Pine
Ash
Wood Products
Woods
Composites
GFRP
Laminates
S-Glass
Uniply
CFRP
B-Glass
Balsa II to Grain
Pine
Oak
Ash
Engineering Alloys
Pb
Mg
Zn
Alloys
Al
Cu
Steels
Ni
Be
Cast Irons
Cement Concrete
Pottery
Ti
Nb
Ge
Common Rocks
Porous Ceramics
BeO
Al₂O₃
ZrO₂
B
W
SiC
Si
Si₃N₄
Sialons
Diamond
Engineering Ceramics
SiO₂
Invar
Linear Expansion Coefficient α (10⁻⁶K⁻¹)
0.1
1
10
100
1000
Youngs Modulus, E (GPa)
0.01
0.1
1.0
10
100
1000

Chart 12: Normalized strength, σ_t/E, against linear expansion coeff., α

The chart guides in selecting materials to resist damage in a sudden change of temperature ΔT. The contours show values of the thermal shock parameter

$$B\Delta T = \frac{\sigma_t}{\alpha E}$$

in °C. Here σ_t is the tensile failure strength (the yield strength of ductile materials, the fracture strength of those which are brittle), E is Young's modulus and B is a factor which allows for constraint and for heat-transfer considerations:

$$B = 1/A \quad \text{(axial constraint)}$$

$$B = (1-\nu)/A \quad \text{(biaxial constraint)}$$

$$B = (1-2\nu)/A \quad \text{(triaxial constraint)}$$

with

$$A = \frac{th/\lambda}{1 + th/\lambda}$$

Here ν is Poisson's ratio, t a typical sample dimension, h is the heat-transfer coefficient at the sample surface and λ is its thermal conductivity. The contours define the guide line

$$B\Delta T = C \quad \text{(thermal shock resistance)}$$

The value of the constant C increases towards the top left.

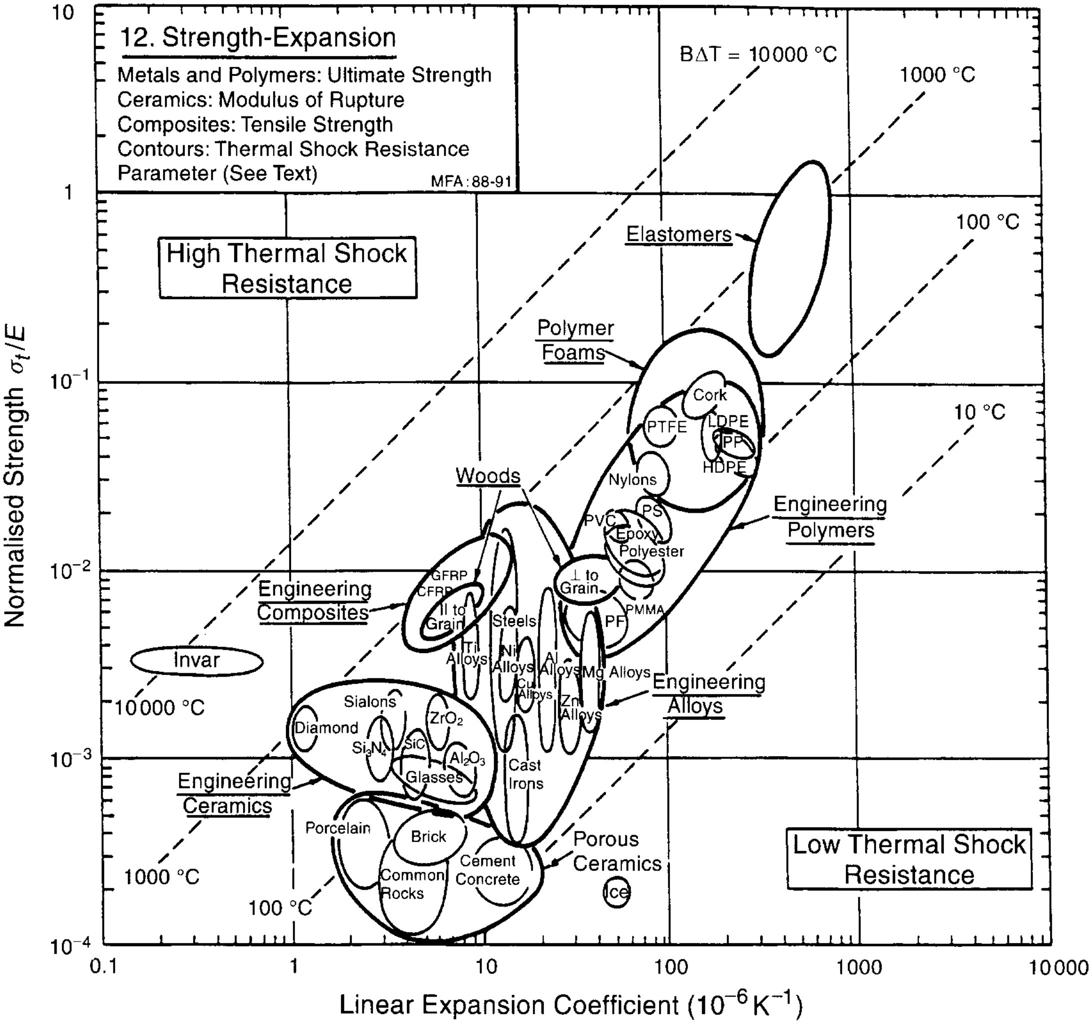

12. Strength-Expansion
Metals and Polymers: Ultimate Strength
Ceramics: Modulus of Rupture
Composites: Tensile Strength
Contours: Thermal Shock Resistance
Parameter (See Text)
MFA:88-91
BΔT = 10000 °C
1000 °C
100 °C
10 °C
10000 °C
1000 °C
100 °C
High Thermal Shock Resistance
Low Thermal Shock Resistance
Elastomers
Polymer Foams
Cork
PTFE
LDPE
PP
HDPE
Nylons
PS
PVC
Epoxy
Polyester
Engineering Polymers
Woods
⊥ to Grain
II to Grain
GFRP
CFRP
Engineering Composites
PMMA
PF
Steels
Ti Alloys
Ni Alloys
Al Alloys
Cu Alloys
Mg Alloys
Zn Alloys
Engineering Alloys
Invar
Sialons
Diamond
ZrO2
Si3N4
SiC
Al2O3
Glasses
Cast Irons
Engineering Ceramics
Porcelain
Brick
Cement
Concrete
Common Rocks
Porous Ceramics
Ice
Normalised Strength σf/E
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
0.1
1
10
100
1000
10000
Linear Expansion Coefficient (10⁻⁶ K⁻¹)

Chart 13: Strength-at-temperature, $\sigma(T)$, against temperature, T

Materials tend to show a strength which is almost independent of temperature up to a given temperature (the 'onset-of-creep' temperature); above this temperature the strength falls, often steeply. The lozenges show this behaviour (see inset at the bottom right). The 'strength' here is a short-term yield strength, corresponding to 1 hour of loading. For long loading times (10 000 hours for instance), the strengths are lower.

This chart gives an overview of high temperature strength, giving guidance in making an initial choice. Design against creep and creep-fracture requires further information and techniques.

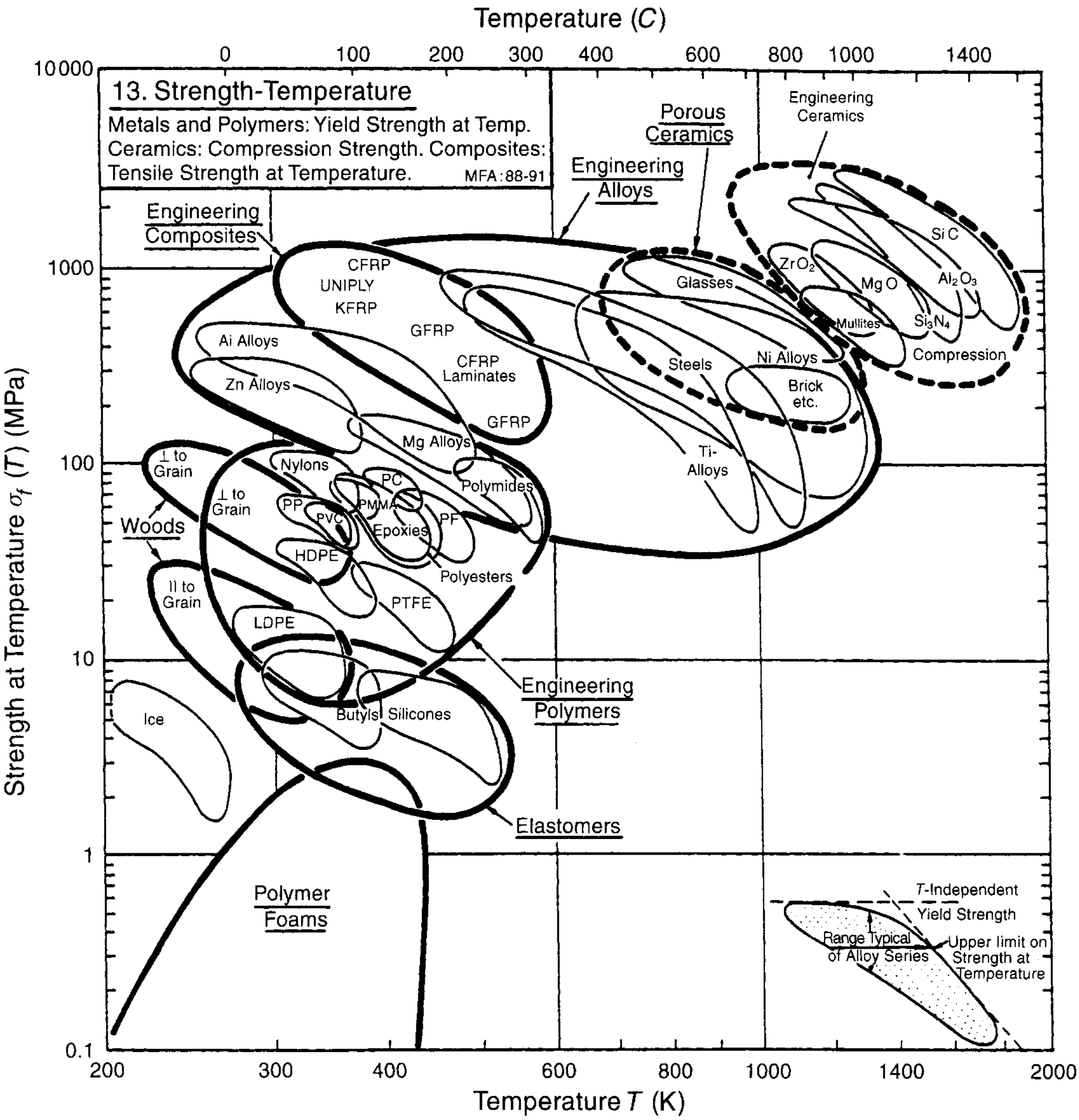

Temperature (C)
0
100
200
300
400
600
800
1000
1400
13. Strength-Temperature
Metals and Polymers: Yield Strength at Temp.
Ceramics: Compression Strength. Composites:
Tensile Strength at Temperature.
MFA:88-91
Engineering Composites
Engineering Alloys
Porous Ceramics
Engineering Ceramics
CFRP
UNIPLY
KFRP
GFRP
CFRP Laminates
GFRP
Ai Alloys
Zn Alloys
Mg Alloys
Glasses
Steels
Ni Alloys
Brick etc.
Ti-Alloys
ZrO2
MgO
SiC
Al2O3
Mullites
Si3N4
Compression
⊥ to Grain
⊥ to Grain
Woods
II to Grain
Nylons
PC
PP
PVC
PMMA
Epoxies
PF
Polymides
HDPE
Polyesters
PTFE
LDPE
Butyls
Silicones
Engineering Polymers
Elastomers
Ice
Polymer Foams
T-Independent
Yield Strength
Range Typical of Alloy Series
Upper limit on Strength at Temperature
Strength at Temperature σf (T) (MPa)
10000
1000
100
10
1
0.1
200
300
400
600
800
1000
1400
2000
Temperature T (K)

Chart 14: Young's modulus, *E*, against relative cost, $C_R\rho$

The chart guides selection of materials for cheap, stiff, components (material cost only). The relative cost C_R is calculated by taking that for mild steel reinforcing-rods as unity; thus

$$C_R = \frac{\text{Cost per unit weight of material}}{\text{Cost per unit weight of mild steel}}$$

The guide lines show the loci of points for which

(a) $E/C_R\rho = C$ (minimum cost design of stiff ties, etc.)
(b) $E^{1/2}/C_R\rho = C$ (minimum cost design of stiff beams and columns)
(c) $E^{1/3}/C_R\rho = C$ (minimum cost design of stiff plates)

The value of the constant C increases as the lines are displayed upwards and to the left. Materials offering the greatest stiffness per unit cost lie towards the upper left corner. Other moduli are obtained approximately from E by

(a) $\nu = 1/3$; $G = 3/8E$; $K \approx E$ (metals, ceramics, glasses and glassy polymers)
or (b) $\nu \approx 1/2$; $G \approx 1/3E$; $K \approx 10E$ (elastomers, rubbery polymers)

where ν is Poisson's ratio, G the shear modulus and K the bulk modulus.

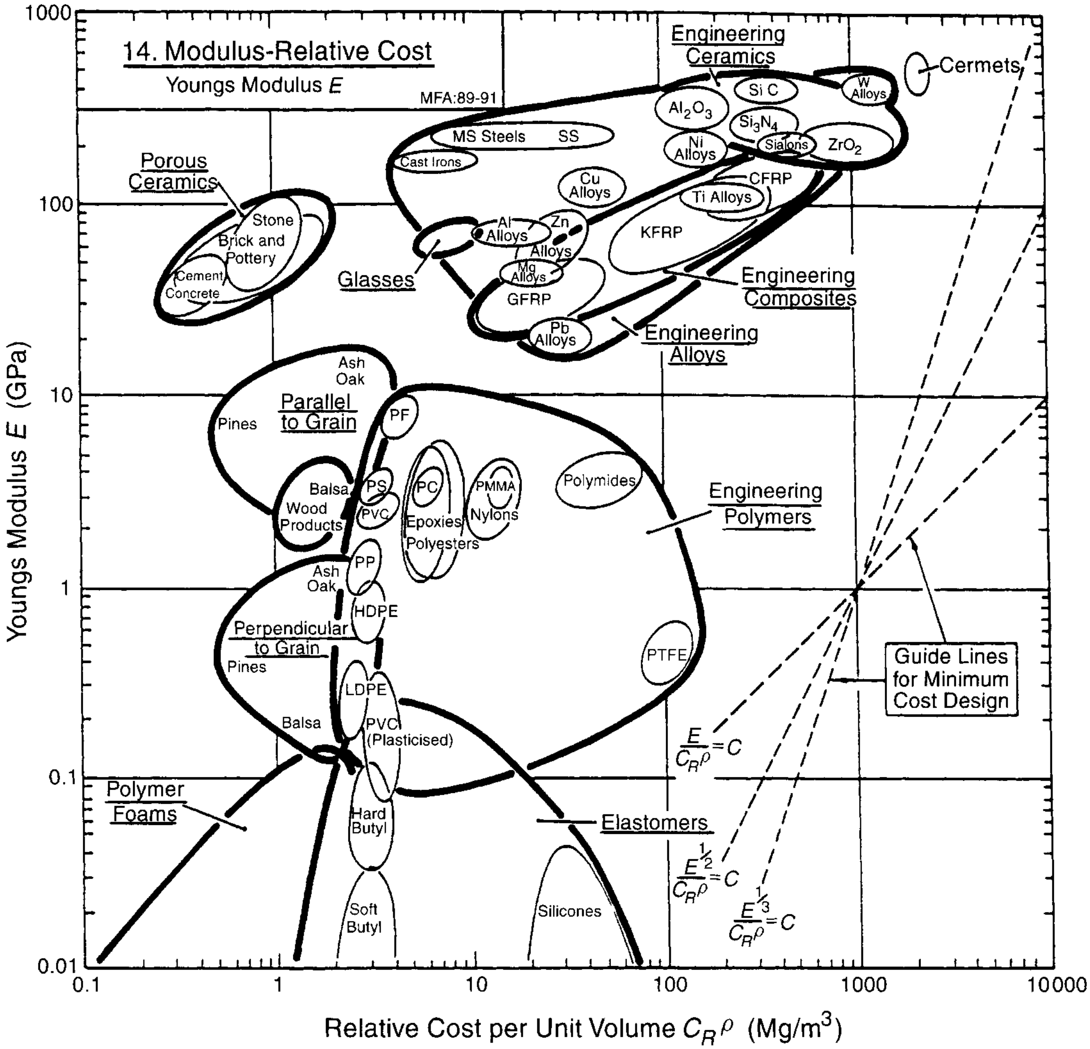

14. Modulus-Relative Cost
Youngs Modulus E
MFA:89-91
Engineering Ceramics
Cermets
W Alloys
Si C
Al_2O_3
Si_3N_4
Sialons
ZrO_2
Ni Alloys
MS Steels
SS
Cast Irons
Porous Ceramics
Stone
Brick and Pottery
Cement
Concrete
Cu Alloys
CFRP
Ti Alloys
Al Alloys
Zn Alloys
Mg Alloys
KFRP
GFRP
Glasses
Engineering Composites
Pb Alloys
Engineering Alloys
Ash
Oak
Pines
Parallel to Grain
PF
Balsa
Wood Products
PS
PVC
PC
PMMA
Epoxies
Nylons
Polyesters
Polymides
Engineering Polymers
Ash
Oak
PP
HDPE
Perpendicular to Grain
Pines
PTFE
LDPE
Balsa
PVC (Plasticised)
Guide Lines for Minimum Cost Design
$\frac{E}{C_R\rho} = C$
Polymer Foams
Hard Butyl
Elastomers
$\frac{E^{1/2}}{C_R\rho} = C$
$\frac{E^{1/3}}{C_R\rho} = C$
Soft Butyl
Silicones
1000
100
10
1
0.1
0.01
Youngs Modulus E (GPa)
0.1
1
10
100
1000
10000
Relative Cost per Unit Volume $C_R\rho$ (Mg/m^3)

Chart 15: Strength, σ_f, against relative cost, $C_R\rho$

The chart guides selection of materials for cheap strong, components (material cost only). The 'strength' for metals is the 0.2% offset yield strength. For polymers, it is the stress at which the stress–strain curve becomes markedly non-linear — typically, a strain of about 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The relative cost C_R is calculated by taking that for mild steel reinforcing-rods as unity; thus

$$C_R = \frac{\text{cost per unit weight of material}}{\text{cost per unit weight of mild steel}}$$

The guide lines show the loci of points for which

(a) $\sigma_f/C_R\rho = C$ (minimum cost design of strong ties, rotating discs, etc.)

(b) $\sigma_f^{2/3}/C_R\rho = C$ (minimum cost design of strong beams and shafts)

(c) $\sigma_f^{1/2}/C_R\rho = C$ (minimum cost design of strong plates)

The value of the constants C increase as the lines are displaced upwards and to the left. Materials offering the greatest strength per unit cost lie towards the upper left corner.

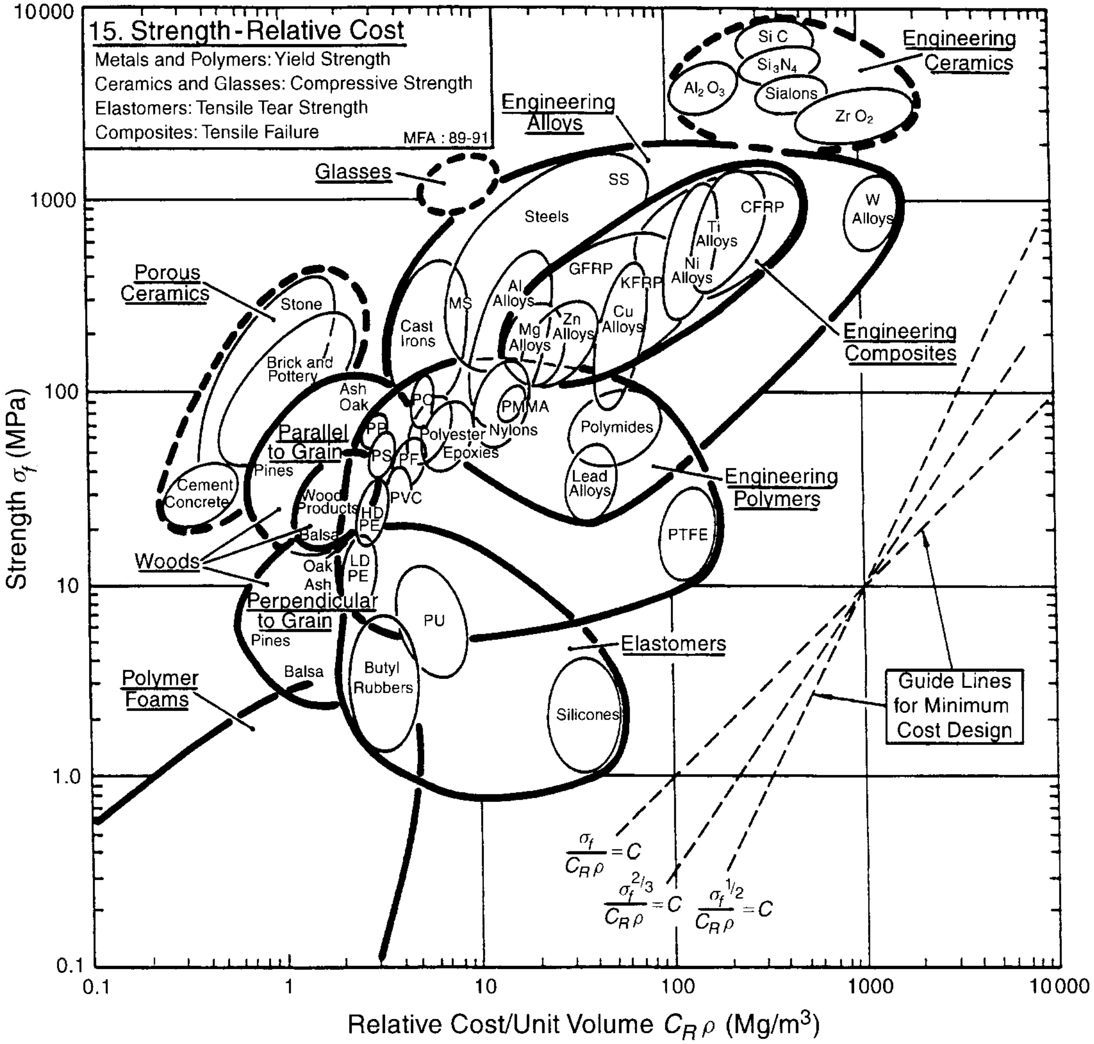

15. Strength-Relative Cost
Metals and Polymers: Yield Strength
Ceramics and Glasses: Compressive Strength
Elastomers: Tensile Tear Strength
Composites: Tensile Failure
MFA : 89-91
Engineering Ceramics
Si C
Si_3N_4
Al_2O_3
Sialons
Zr O_2
Engineering Alloys
Glasses
SS
Steels
CFRP
W Alloys
Ti Alloys
Ni Alloys
GFRP
KFRP
Porous Ceramics
Stone
Brick and Pottery
Cast Irons
MS
Al Alloys
Mg Alloys
Zn Alloys
Cu Alloys
Engineering Composites
Ash Oak
PC
PMMA
Parallel to Grain
Pines
PP
PS
PF
Polyester
Epoxies
Nylons
Polymides
Cement Concrete
Wood Products
Balsa
HD PE
PVC
Lead Alloys
Engineering Polymers
PTFE
Woods
Oak Ash
LD PE
Perpendicular to Grain
Pines
PU
Elastomers
Polymer Foams
Balsa
Butyl Rubbers
Silicones
Guide Lines for Minimum Cost Design
$\frac{\sigma_f}{C_R \rho} = C$
$\frac{\sigma_f^{2/3}}{C_R \rho} = C$
$\frac{\sigma_f^{1/2}}{C_R \rho} = C$
Strength σ_f (MPa)
10000
1000
100
10
1.0
0.1
0.1
1
10
100
1000
10000
Relative Cost/Unit Volume $C_R \rho$ (Mg/m^3)

Chart 16: Dry wear rate against maximum bearing pressure, $P_{\max}$

The wear rate is defined as

$$W = \frac{\text{volume removed from contact surface}}{\text{distance slid}}$$

Archard's law, broadly describing wear rates at sliding velocities below 1 m/s, states that

$$W = k_a A_n P$$

where A_n is the nominal contact area, P the bearing pressure (force per unit area) at the sliding surfaces and k_a is Archard's wear-rate constant. At low bearing pressures k_a is a true constant, but as the maximum bearing pressure is approached it rises steeply. The chart shows Archard's constant,

$$k_a = \frac{W}{A_n P}$$

plotted against the hardness H of the material. In any one class of materials, high hardness correlates with low k_a.

Materials which have low k_a have low wear rates at a given bearing pressure, P. Efficient bearings, in terms of size or weight, will be loaded to a safe fraction of their maximum bearing pressure, which is proportional to hardness. For these, materials with low values of the product $k_a H$ are best. The diagonal lines show values of $k_a H$.

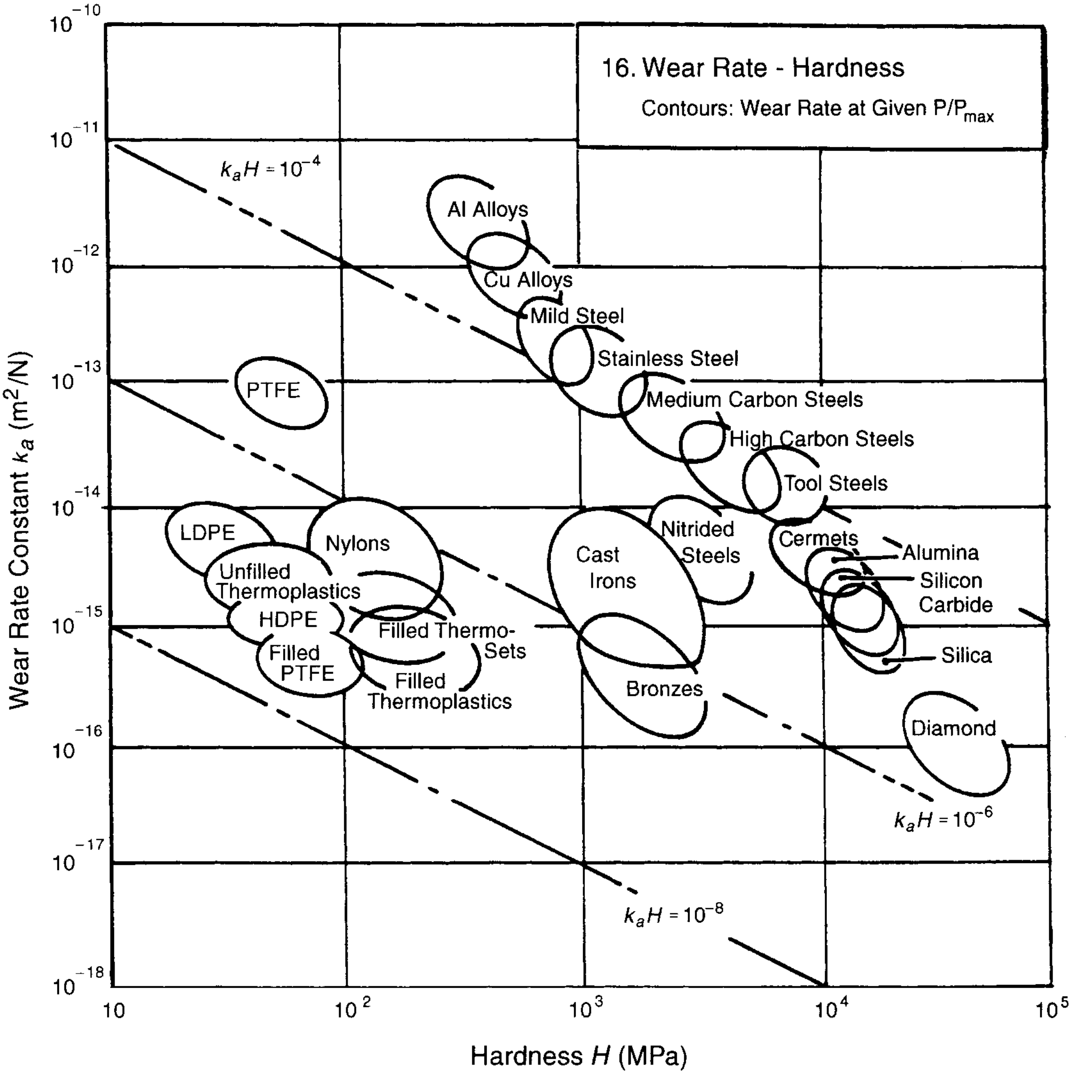

16. Wear Rate - Hardness
Contours: Wear Rate at Given P/P$_{max}$
$k_aH = 10^{-4}$
$k_aH = 10^{-6}$
$k_aH = 10^{-8}$
Al Alloys
Cu Alloys
Mild Steel
Stainless Steel
Medium Carbon Steels
High Carbon Steels
Tool Steels
PTFE
LDPE
Nylons
Unfilled Thermoplastics
HDPE
Filled PTFE
Filled Thermo-Sets
Filled Thermoplastics
Cast Irons
Nitrided Steels
Bronzes
Cermets
Alumina
Silicon Carbide
Silica
Diamond
Wear Rate Constant k_a (m^2/N)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10
10^2
10^3
10^4
10^5
Hardness H (MPa)

Chart 17: Young's modulus, *E*, against energy content, $q\rho$

The chart guides selection of materials for stiff, energy-economic components. The energy content per m^3, $q\rho$, is the energy content per kg, q, multiplied by the density ρ. The guide-lines show the loci of points for which

(a) $E/q\rho = C$ (minimum energy design of stiff ties; minimum deflection in centrifugal loading etc.)
(b) $E^{1/2}/q\rho = C$ (minimum energy design of stiff beams, shafts and columns)
(c) $E^{1/3}/q\rho = C$ (minimum energy design of stiff plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest stiffness per energy content lie towards the upper left corner.

Other moduli are obtained approximately from E using

(a) $\nu = 1/3$; $G = 3/8E$; $K \approx E$ (metals, ceramics, glasses and glassy polymers)
or (b) $\nu \approx 1/2$; $G \approx 1/3E$; $K \approx 10E$ (elastomers, rubbery polymers)

where ν is Poisson's ratio, G the shear modulus and K the bulk modulus.

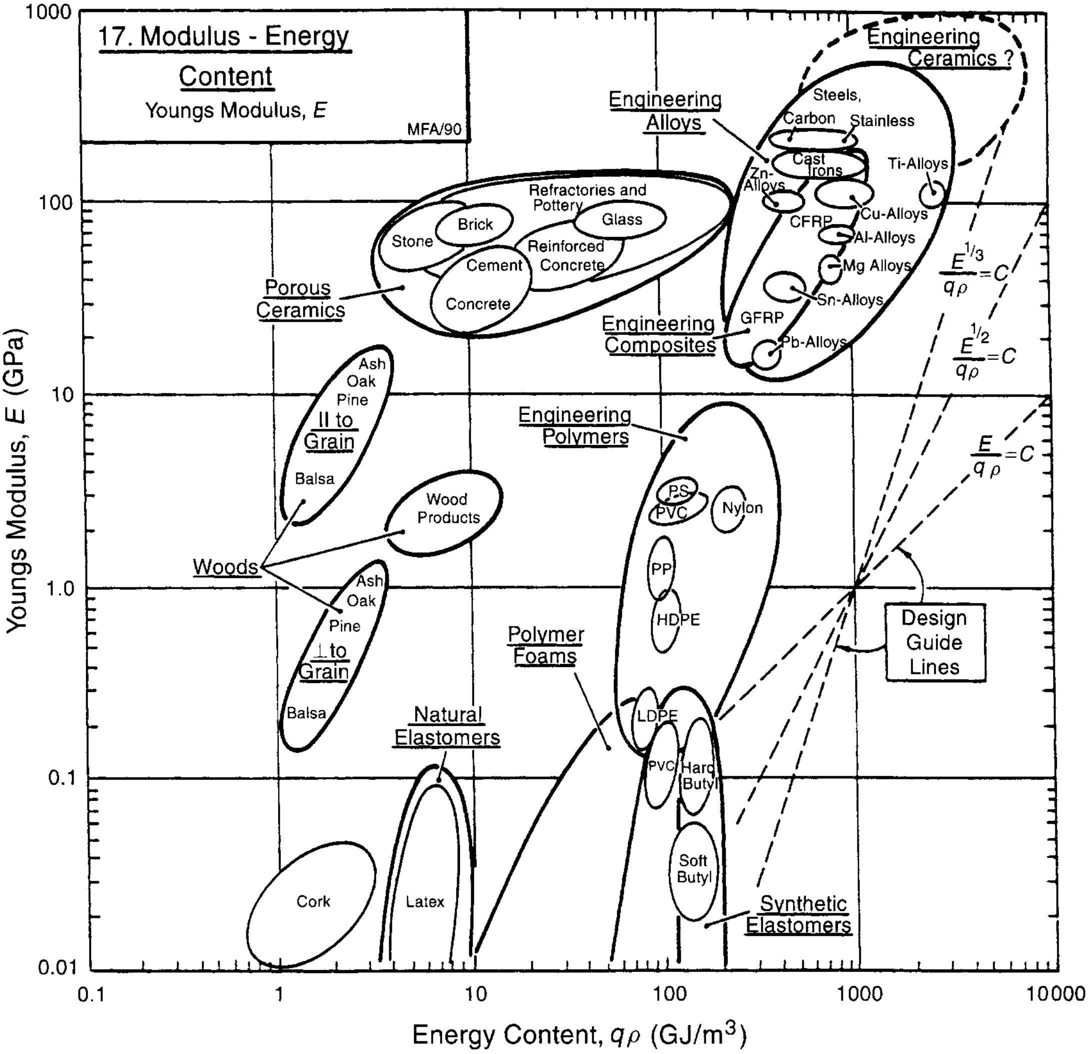
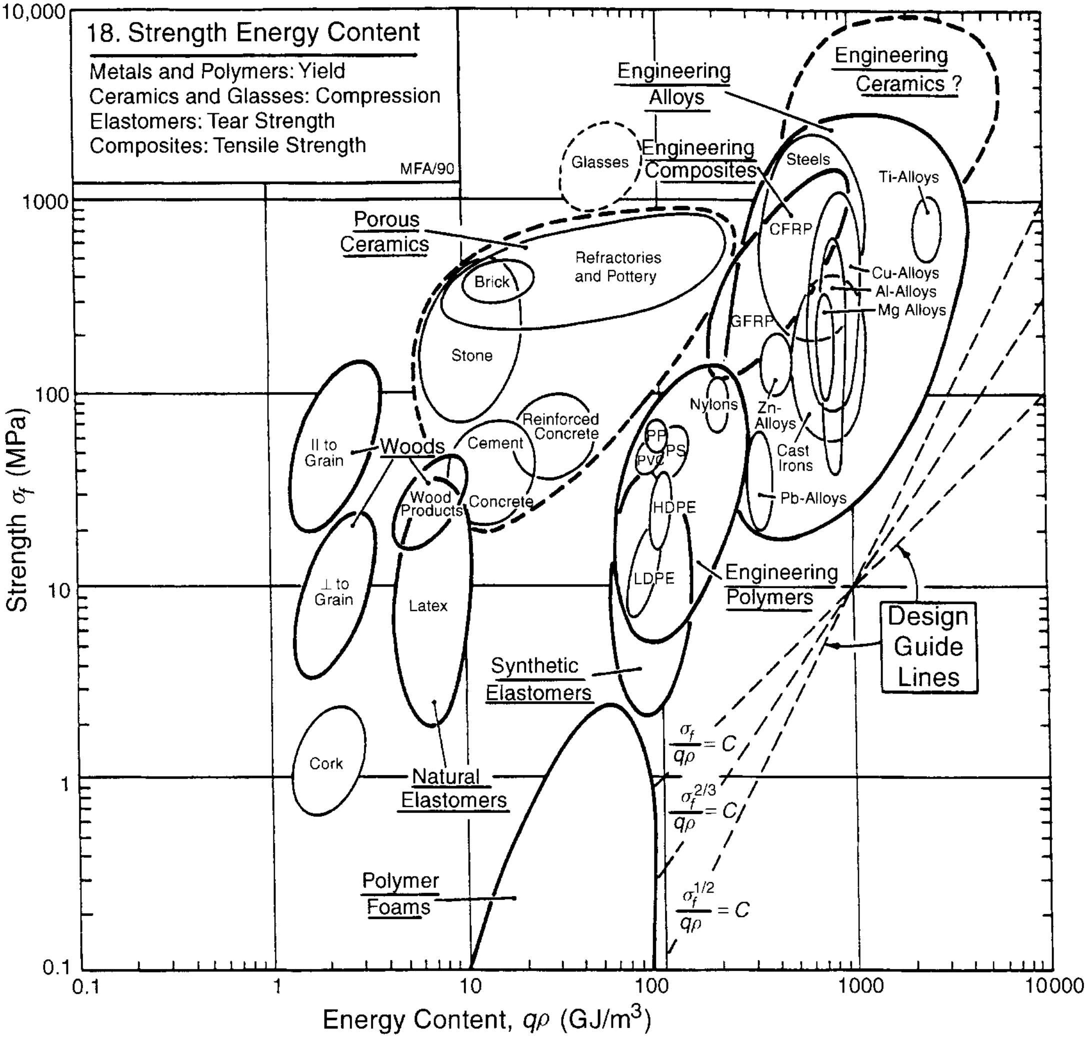

17. Modulus - Energy Content
Youngs Modulus, E
MFA/90
Engineering Ceramics ?
Engineering Alloys
Steels, Carbon
Stainless
Cast Irons
Zn-Alloys
Ti-Alloys
Cu-Alloys
CFRP
Al-Alloys
Mg Alloys
Sn-Alloys
GFRP
Pb-Alloys
Engineering Composites
Refractories and Pottery
Glass
Brick
Stone
Reinforced Concrete
Cement
Concrete
Porous Ceramics
$\frac{E^{1/3}}{q\rho}=C$
$\frac{E^{1/2}}{q\rho}=C$
$\frac{E}{q\rho}=C$
Ash
Oak
Pine
II to Grain
Balsa
Wood Products
Woods
Ash
Oak
Pine
⊥ to Grain
Balsa
Engineering Polymers
PS
PVC
Nylon
PP
HDPE
LDPE
PVC
Hard Butyl
Soft Butyl
Synthetic Elastomers
Polymer Foams
Natural Elastomers
Latex
Cork
Design Guide Lines
Youngs Modulus, E (GPa)
1000
100
10
1.0
0.1
0.01
0.1
1
10
100
1000
10000
Energy Content, $q\rho$ (GJ/m^3)

Chart 18: Strength, σ_f, against energy content, $q\rho$

The chart guides selection of materials for strong, energy-economic components. The 'strength' for metals is the 0.2% offset yield strength. For polymers, it is the stress at which the stress–strain curve becomes markedly non-linear — typically, a strain of about 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The energy content per m^3, $q\rho$, is the energy content per kg, q, multiplied by the density, ρ. The guide lines show the loci of points for which

(a) $\sigma_f/q\rho = C$ (minimum energy design of strong ties; maximum rotational velocity of disks)
(b) $\sigma_f^{2/3}/q\rho = C$ (minimum energy design of strong beams and shafts)
(c) $\sigma_f^{1/2}/q\rho = C$ (minimum energy design of strong plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest strength per unit energy content lie towards the upper left corner.


18. Strength Energy Content
Metals and Polymers: Yield
Ceramics and Glasses: Compression
Elastomers: Tear Strength
Composites: Tensile Strength
MFA/90
Engineering Ceramics ?
Engineering Alloys
Glasses
Engineering Composites
Steels
Ti-Alloys
CFRP
Porous Ceramics
Refractories and Pottery
Brick
Cu-Alloys
Al-Alloys
Mg Alloys
GFRP
Stone
Nylons
Zn-Alloys
Reinforced Concrete
Cement
Il to Grain
Woods
PP
PS
PVC
Cast Irons
Wood Products
Concrete
HDPE
Pb-Alloys
⊥ to Grain
Latex
LDPE
Engineering Polymers
Design Guide Lines
Synthetic Elastomers
$\frac{\sigma_f}{q\rho} = C$
Cork
Natural Elastomers
$\frac{\sigma_f^{2/3}}{q\rho} = C$
Polymer Foams
$\frac{\sigma_f^{1/2}}{q\rho} = C$
Strength σ_f (MPa)
10,000
1000
100
10
1
0.1
Energy Content, $q\rho$ (GJ/m^3)
0.1
1
10
100
1000
10000

C.3 THE PROCESS-SELECTION CHARTS

Chart P1: The material–process matrix

The great number of processes used in manufacture can be classified under the broad headings on the vertical axis of this chart, which is a matrix relating material class to process class. The material classes, listed horizontally, are the usual ones: metals, ceramics and glasses, polymers and elastomers, and composites. These generic classes are subdivided: ferrous and non-ferrous metals, thermoplastic and thermosetting polymers, and so on. The number at a row-column intersection indicates the viability of a process for a material: 2 indicates that it is viable; 1 that it could be under special circumstances; 0 that it is not viable. Because the materials and processes are listed as subclasses (not individuals) some generalizations are inevitable. For a given material-subclass the table yields two short-lists: one of viable processes, the other of those which are possible or potentially viable.

Process Class		Material Class														
		Metals					Ceramics & Glasses				Polymers & Elastomers			Composites		
		Ferrous	Refractory	Precious	Heavy	Light	Cementitous	Vitreous	Fine	Glasses	Thermosets	Thermoplastics	Elastomers	PMCs	MMCs	CMCs
Casting	Gravity	2	1	2	2	2	0	0	0	1	0	0	0	0	0	0
	Low pressure	2	0	2	2	2	0	0	0	2	0	0	0	0	1	0
	High pressure	1	0	2	2	2	0	0	0	1	0	0	0	0	2	0
	Investment	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
Moulding	Injection	0	0	2	0	0	0	0	0	2	2	2	2	2	0	0
	Compress	0	0	2	0	0	0	0	0	2	2	2	2	2	1	0
	Blow	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0
	Foam	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0
Deformation	Cold	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Warm	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Hot	2	2	2	2	2	0	0	0	2	0	0	0	0	0	0
	Sheet	2	1	2	2	2	0	0	0	0	0	2	0	0	1	0
Machining	Turn	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Mill	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Grind	2	2	1	2	2	0	2	2	2	0	0	0	0	2	2
	Polish	2	2	2	2	2	0	2	2	2	0	0	0	0	1	2
Powder Methods	Sinter/HIP	2	2	2	2	2	0	2	2	1	0	2	0	0	2	2
	Slip cast	0	0	0	0	0	0	2	2	1	0	0	0	0	0	1
	Spray forming	2	2	2	2	2	0	2	2	2	2	2	0	2	0	0
	Hydration	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Composite Forming	Lay-up	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
	Mould	0	0	0	0	0	0	0	0	0	2	2	2	2	0	0
	Squeeze-cast	1	0	0	2	2	0	0	0	0	0	0	0	0	2	0
	Filament wind	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Molecular Methods	PVD	0	2	2	2	0	0	0	2	0	0	0	0	0	1	0
	CVD	0	2	2	2	0	0	0	2	0	0	0	0	0	1	2
	Sputtering	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
	Electroforming	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Special Methods	Electrochemical	2	2	2	2	2	0	0	0	0	0	0	0	0	2	0
	Ultrasonic	1	2	0	0	0	0	2	2	2	0	0	0	0	0	2
	Chemical	2	2	2	2	2	0	2	2	2	0	0	0	0	0	0
	Thermal Beam	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
Fabrication	Weld/braze	2	2	2	2	2	0	0	0	0	0	2	0	0	0	0
	Adhesive	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Fasten	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Microfabrication	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2

Chart P2: Hardness, *H*, against melting temperature, T_m

The match between process and material is established by the link to material class of Chart P1 and by the use of the melting point–hardness chart shown here. The melting point imposes limits on the processing of materials by conventional casting methods. Low melting point metals can be cast by any one of many techniques. For those which melt above 2000 K, conventional casting methods are no longer viable, and special techniques such as electron-beam melting must be used. Similarly, the yield strength or hardness of a material imposes limitations on the choice of deformation and machining processes. Forging and rolling pressures are proportional to the flow strength, and the heat generated during machining, which limits tool life, also scales with the ultimate strength or hardness. Generally speaking, deformation processing is limited to materials with hardness values below 3 GPa. Other manufacturing methods exist which are not limited either by melting point or by hardness. Examples are: powder methods, CVD and evaporation techniques, and electro-forming.

The chart presents this information in graphical form. In reality, only part of the space covered by the axes is accessible: it is the region between the two heavy lines. The hardness and melting point of materials are not independent properties: low melting point materials tend to be soft; high melting point materials are generally hard. This information is captured by the equation

$$0.03 < \frac{H\Omega}{kT_m} < 20$$

where Ω is the atomic or molecular volume and k is Boltzmann's Constant (1.38×10^{-26} J/K). It is this equation which defines the two bold lines.

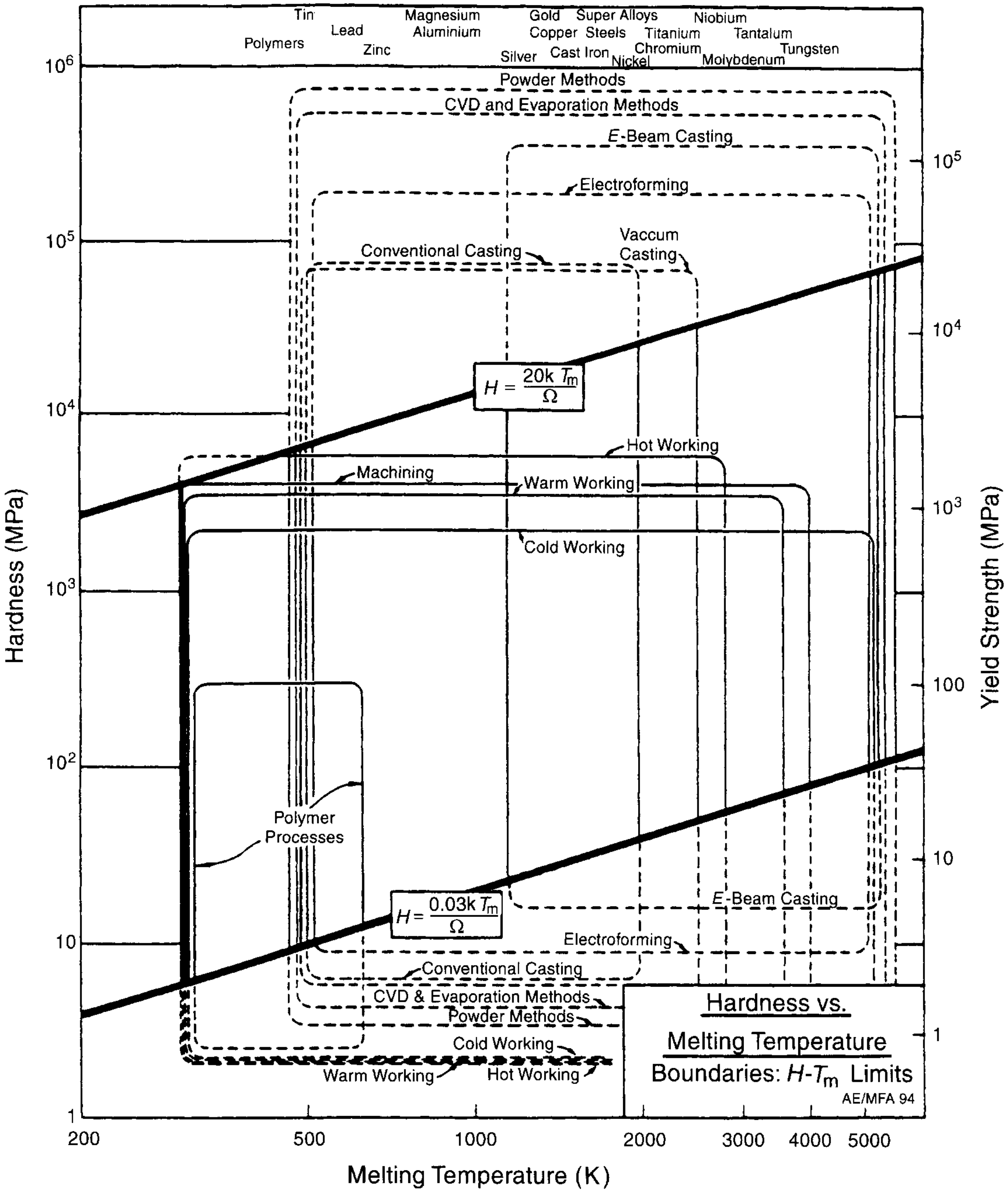

Tin
Lead
Polymers
Zinc
Magnesium
Aluminium
Gold
Copper
Silver
Super Alloys
Steels
Cast Iron
Nickel
Chromium
Titanium
Niobium
Tantalum
Molybdenum
Tungsten
Powder Methods
CVD and Evaporation Methods
E-Beam Casting
Electroforming
Conventional Casting
Vaccum Casting
$H = \frac{20k\,T_m}{\Omega}$
Hot Working
Machining
Warm Working
Cold Working
Polymer Processes
$H = \frac{0.03k\,T_m}{\Omega}$
E-Beam Casting
Electroforming
Conventional Casting
CVD & Evaporation Methods
Powder Methods
Cold Working
Warm Working
Hot Working
Hardness vs.
Melting Temperature
Boundaries: H-Tm Limits
AE/MFA 94
Hardness (MPa)
Yield Strength (MPa)
Melting Temperature (K)
10^6
10^5
10^4
10^3
10^2
10
1
10^5
10^4
10^3
100
10
1
200
500
1000
2000
3000
4000
5000

Chart P3: Volume, *V*, against slenderness, *S*

Manufacturing processes vary widely in their capacity to make thin, slender sections. For our purposes, slenderness, S, is measured by the ratio t/ℓ where t is the minimum section and ℓ is the large dimension of the shape: for flat shapes, ℓ is about equal to $\sqrt{A}$ where A is the projected area normal to t. Thus

$$S = \frac{t}{\sqrt{A}}$$

Size is defined by the minimum and maximum volumes of which the process is capable. The volume, V, for uniform sections is, within a factor of 2, given by

$$V = At$$

Volume can be converted approximately to weight by using an 'average' material density of 5000 kg/m^3; most engineering materials have densities within a factor of 2 of this value. Polymers are the exception: their densities are all around 1000 kg/m^3.

The size-slenderness chart is shown opposite. The horizontal axis is the slenderness, S; the vertical axis is the volume, V. Contours of A and t are shown as families of diagonal lines. *Casting processes* occupy a characteristic field of this space. Surface tension and heat-flow limit the minimum section and the slenderness of gravity cast shapes. The range can be extended by applying a pressure, as in centrifugal casting and pressure die casting, or by preheating the mould. *Deformation processes* — cold, warm and hot — cover a wider range. Limits on forging-pressures set a lower limit on thickness and slenderness, but it is not nearly as severe as in casting. *Machining* creates slender shapes by removing unwanted material. *Powder-forming* methods occupy a smaller field, one already covered by casting and deformation shaping methods, but they can be used for ceramics and very hard metals which cannot be shaped in other ways. *Polymer-forming methods* — injection moulding, pressing, blow-moulding, etc. — share this regime. *Special techniques*, which include electro-forming, plasma-spraying, and various vapour-deposition methods, allow very slender shapes. *Joining* extends the range further: fabrication allows almost unlimited size and complexity.

A real design demands certain specific values of S and V, or A and t. Given this information, a subset of possible processes can be read off.

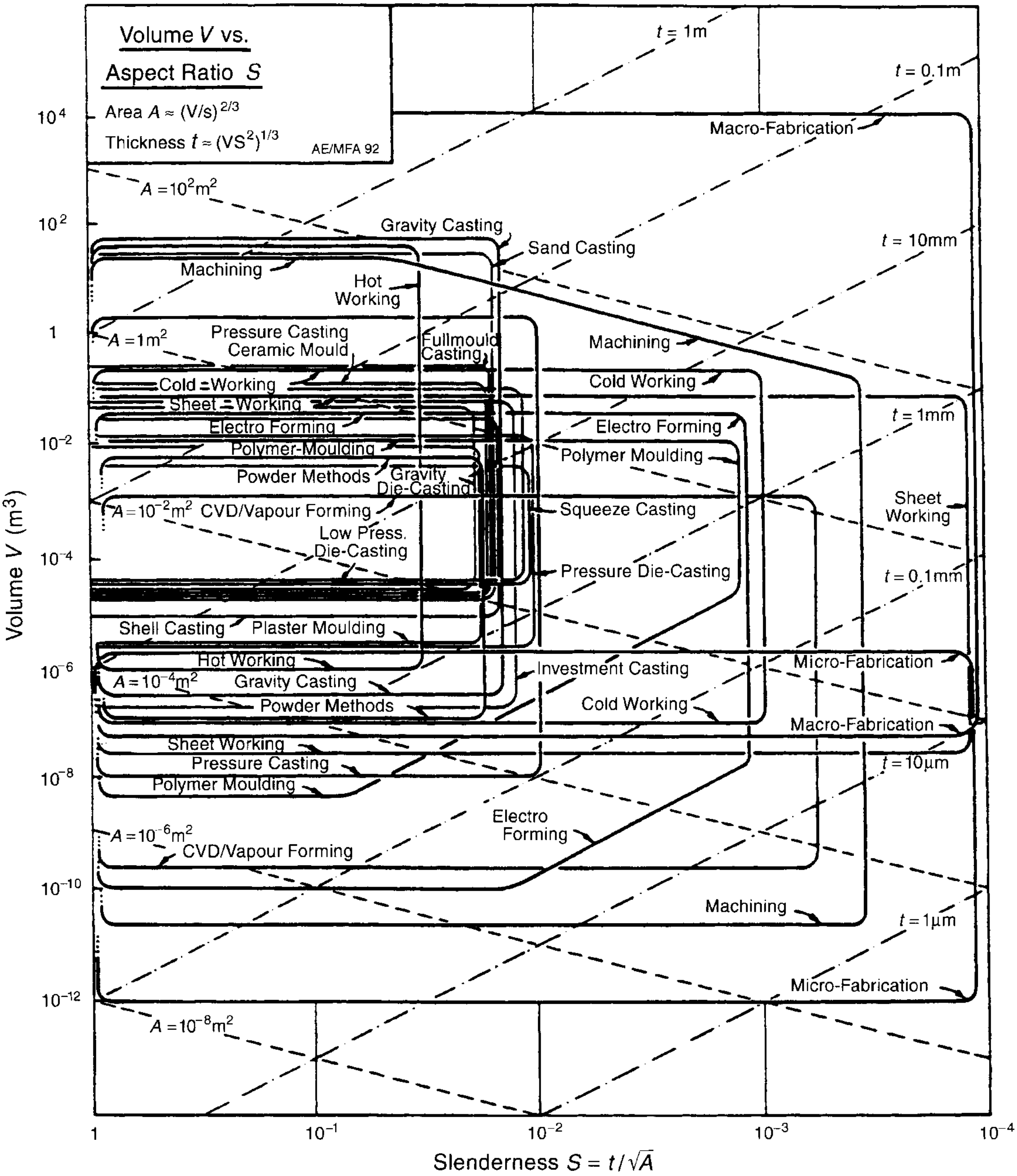

Volume V vs.
Aspect Ratio S
Area A ≈ (V/s)^2/3
Thickness t ≈ (VS^2)^1/3
AE/MFA 92
t = 1m
t = 0.1m
Macro-Fabrication
A = 10^2 m^2
Gravity Casting
Sand Casting
t = 10mm
Machining
Hot Working
A = 1m^2
Pressure Casting
Ceramic Mould
Fullmould Casting
Machining
Cold Working
Cold Working
Sheet Working
t = 1mm
Electro Forming
Electro Forming
Polymer-Moulding
Polymer Moulding
Powder Methods
Gravity Die-Casting
Sheet Working
A = 10^-2 m^2
CVD/Vapour Forming
Squeeze Casting
Low Press. Die-Casting
Pressure Die-Casting
t = 0.1mm
Shell Casting
Plaster Moulding
Micro-Fabrication
Hot Working
Investment Casting
A = 10^-4 m^2
Gravity Casting
Cold Working
Powder Methods
Macro-Fabrication
Sheet Working
t = 10μm
Pressure Casting
Polymer Moulding
Electro Forming
A = 10^-6 m^2
CVD/Vapour Forming
Machining
t = 1μm
Micro-Fabrication
A = 10^-8 m^2
10^4
10^2
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
Volume V (m^3)
1
10^-1
10^-2
10^-3
10^-4
Slenderness S = t/√A

Chart P4: The shape classification scheme

Certain processes are well adapted to the manufacture of shapes with certain symmetries. Lathes, for example, are well adapted to the making of axisymmetric shapes; other shapes are possible but more difficult. Extrusion, drawing and rolling make prismatic shapes. Indexing gives shapes with translational or rotational symmetry. Shapes can be further subdivided into uniform, stepped, angled or dished. Uniform shapes are obviously easier to make than ones which are stepped or have side branches. Some processes are only capable of making hollow shapes, whereas others can make only solid ones.

The chart gives a shape classification which relates to these facts. The shapes are arranged in such a way that complexity, defined here as the difficulty of making the shape, increases downwards and to the right. Examples of each shape are given in order to facilitate the identification of the shape category which describes the desired design.

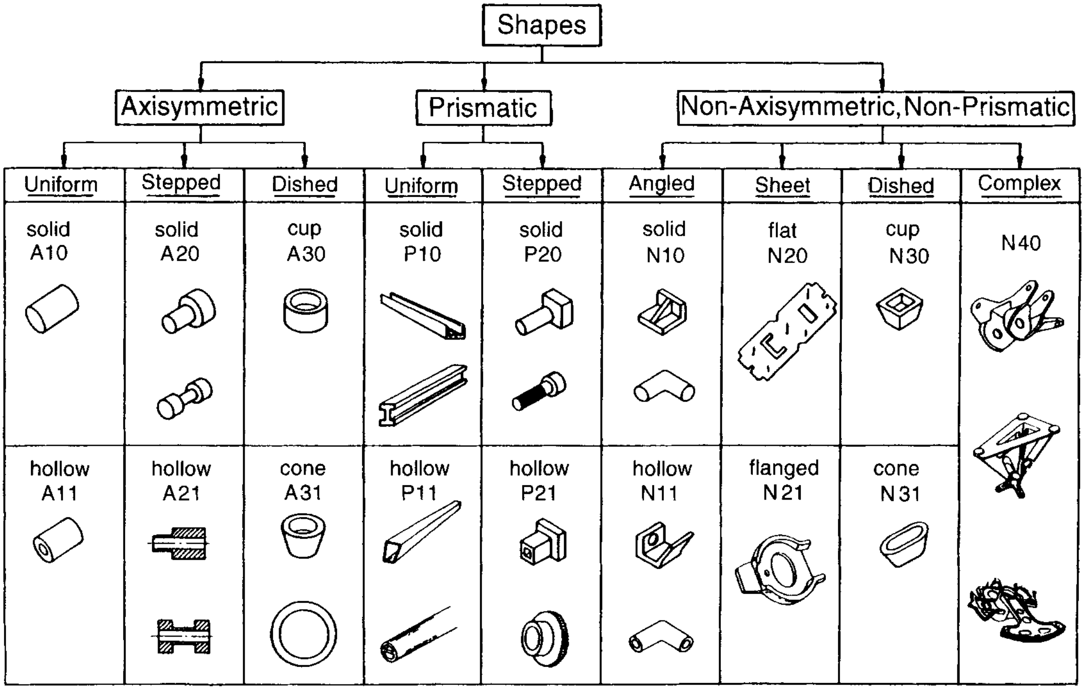

Shapes
Axisymmetric
Prismatic
Non-Axisymmetric, Non-Prismatic
Uniform
Stepped
Dished
Uniform
Stepped
Angled
Sheet
Dished
Complex
solid A10
solid A20
cup A30
solid P10
solid P20
solid N10
flat N20
cup N30
N40
hollow A11
hollow A21
cone A31
hollow P11
hollow P21
hollow N11
flanged N21
cone N31

Chart P5: The shape–process matrix

The shape capabilities of manufacturing processes are summarized in this chart. It uses the same format and classifications as the material–process matrix. Processes are listed vertically and the various shapes (referred to by their codes) are listed horizontally. The capability of a process to make a shape is indicated by the number 0 or 1: the number 1 means that the process can make the shape; the number 0 that it cannot.

			Shapes																
			Axisymmetric						Prismatic				Non-Axisymmetric, Non-Prismatic						
			A10	A11	A20	A21	A30	A31	P10	P11	P20	P21	N10	N11	N20	N21	N30	N31	N40
Process Class	Casting	Gravity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Low pressure	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		High pressure	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Investment	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Moulding	Injection	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Compress	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Blow	0	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0
		Foam	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0
	Deformation	Cold	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Warm	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Hot	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Sheet	0	1	0	1	1	1	0	1	0	1	1	1	1	1	1	1	0
	Machining	Turn	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1
		Mill	0	0	0	0	0	0	1	0	1	1	1	0	1	1	1	1	1
		Grind	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Polish	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Powder Methods	Sinter/HIP	1	1	1	1	0	0	1	1	1	1	0	0	1	1	0	0	0
		Slip cast	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0
		Spray forming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
		Hydration	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Composite Forming	Lay-up	0	1	0	1	1	1	1	1	1	1	1	0	1	1	0	0	1
		Mould	0	1	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1
		Squeeze-cast	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
		Filament wind	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	Molecular Methods	PVD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
		CVD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Sputtering	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Electroforming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Special Methods	Electrochemical	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Ultrasonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Chemical	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Thermal beaming	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Fabrication	Weld/braze	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Adhesive	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Fasten	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Microfabrication	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Chart P6: Complexity against volume, *V*

Complexity is here defined as *the presence of features such as holes, threads, undercuts, bosses, re-entrant shapes, etc., which cause manufacturing difficulty or require additional operations.* For purposes of comparison, a scale of 1 to 5 is used with 1 indicating the simplest shapes and 5 the most complicated. Each process is given a rating for the maximum complexity of which it is capable corresponding to its proximity to the top left or bottom right shapes in Chart P4.

This information is plotted on the complexity level-size chart shown here. *Deformation processes* give shapes of limited complexity. *Powder routes* and *composite forming methods* are also limited compared with other methods. *Polymer moulding* does better. *Casting processes* offer the greatest complexity of all: a cast automobile cylinder block, for instance, is an extremely complicated object. *Machining* processes increase complexity by adding new features to a component. *Fabrication* extends the range of complexity to the highest level.

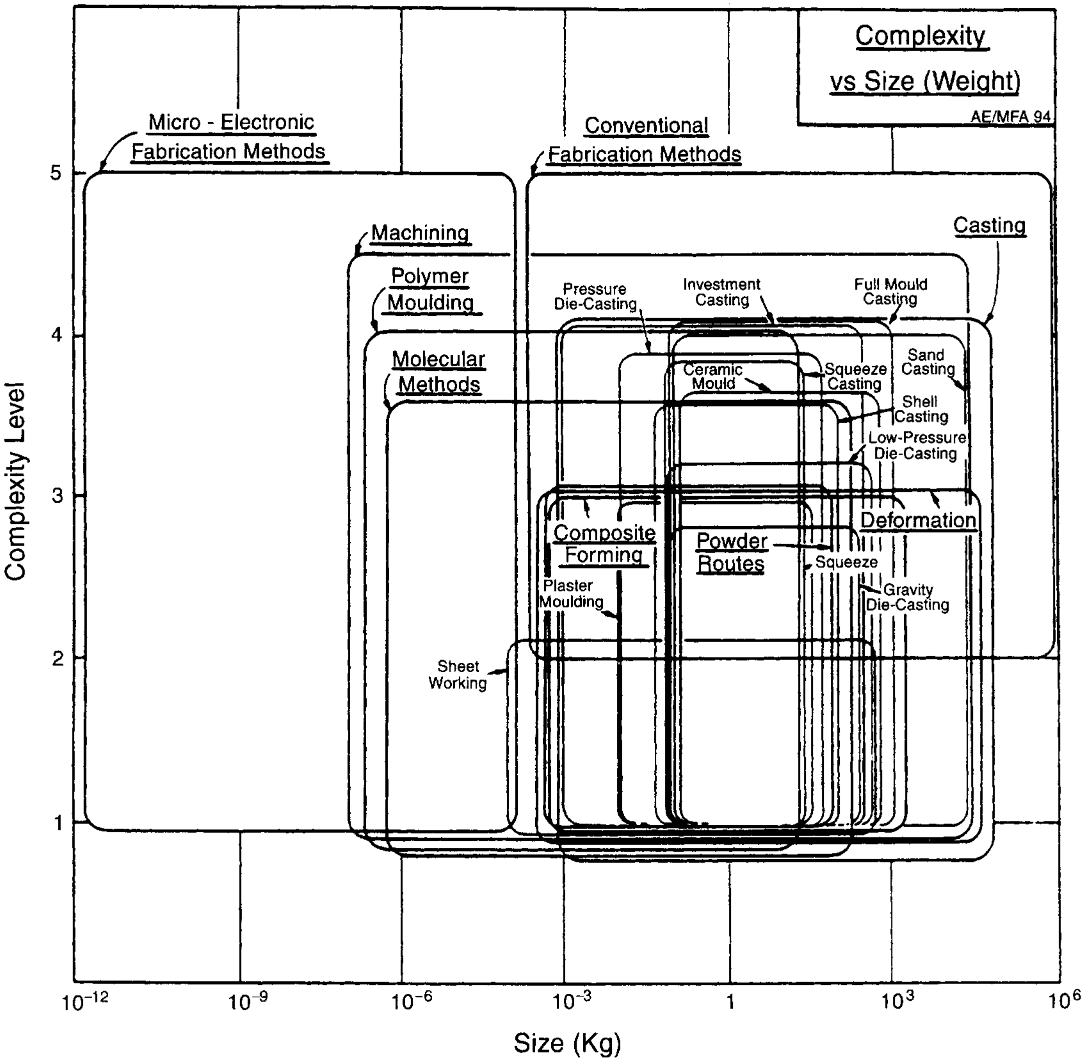

Complexity vs Size (Weight)
AE/MFA 94
Micro - Electronic Fabrication Methods
Conventional Fabrication Methods
Machining
Casting
Polymer Moulding
Molecular Methods
Pressure Die-Casting
Investment Casting
Full Mould Casting
Ceramic Mould
Squeeze Casting
Sand Casting
Shell Casting
Low-Pressure Die-Casting
Deformation
Composite Forming
Powder Routes
Squeeze
Gravity Die-Casting
Plaster Moulding
Sheet Working
Complexity Level
5
4
3
2
1
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
10^{6}
Size (Kg)

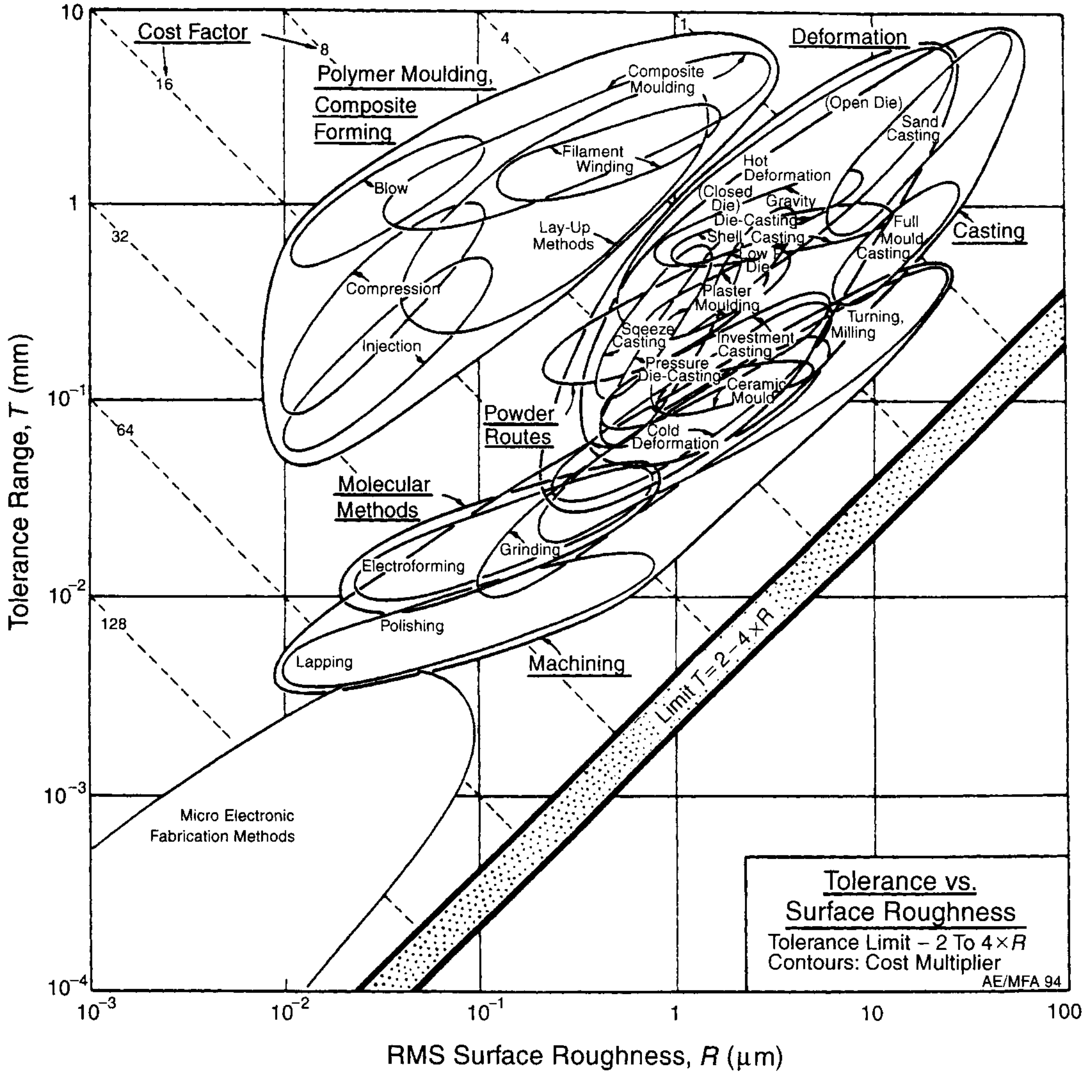
Chart P7: Tolerance range, *T*, against RMS surface roughness, *R*

No process can shape a part *exactly* to a specified dimension. Some deviation Δx from a desired dimension x is permitted; it is referred to as the *tolerance*, T, and is specified as $x = 100 \pm 0.1$ mm, or as $x = 50^{+0.01}_{-0.001}$ mm. Closely related to this is the *surface roughness* R, measured by the root-mean-square amplitude of the irregularities on the surface. It is specified as $R < 100\,\mu\text{m}$ (the rough surface of a sand casting) or $R < 0.01\,\mu\text{m}$ (a lapped surface; Table 11.2).

Manufacturing processes vary in the levels of tolerance and roughness they can achieve economically. Achievable tolerances and roughnesses are shown in this chart. The tolerance is obviously greater than $2R$ (shaded band): indeed, since R is the root-mean-square roughness, the peak roughness is more like $5R$. Real processes give tolerances which range from about $10R$ to $1000R$. Sand casting gives rough surfaces; casting into metal dies gives a better finish. *Moulded polymer* inherit the finish of the moulds and thus can be very smooth, but tolerances better than ±0.2 mm are seldom possible because of internal stresses left by moulding and because polymers creep in service. Machining, capable of high dimensional accuracy and smooth surface finish, is commonly used after casting or deformation processing to bring the tolerance or finish to the desired level. Metals and ceramics can be *surface-ground* and *lapped* to a high tolerance and smoothness.

Precision and high finish are expensive: processing costs increase almost exponentially as the requirements for tolerance and surface roughness are made more severe. The chart shows contours of relative cost: an increase in precision corresponding to the separation of two neighbouring contours gives an increase in cost, for a given process, of a factor of two.

Achievable tolerances depend, of course, on dimensions (those given here apply to a 25 mm dimension) and on material. However, for our purposes, typical ranges of tolerance and surface finish are sufficient and discriminate clearly between various processes.


Cost Factor
8
4
1
16
32
64
128
Polymer Moulding, Composite Forming
Composite Moulding
Filament Winding
Blow
Lay-Up Methods
Compression
Injection
Deformation
(Open Die)
Sand Casting
Hot Deformation
(Closed Die)
Gravity
Die-Casting
Shell Casting
Low P Die
Full Mould Casting
Casting
Plaster Moulding
Squeeze Casting
Investment Casting
Turning, Milling
Pressure Die-Casting
Ceramic Mould
Powder Routes
Cold Deformation
Molecular Methods
Grinding
Electroforming
Polishing
Lapping
Machining
Limit T=2–4×R
Micro Electronic Fabrication Methods
Tolerance vs. Surface Roughness
Tolerance Limit – 2 To 4×R
Contours: Cost Multiplier
AE/MFA 94
Tolerance Range, T (mm)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
100
RMS Surface Roughness, R (μm)