Materials Data Book

2003 Edition

Cambridge University Engineering Department

PHYSICAL CONSTANTS IN SI UNITS

Absolute zero of temperature	– 273.15 °C
Acceleration due to gravity, *g*	9. 807 m/s^2
Avogadro's number, N_A	6.022×10^{26} /kmol
Base of natural logarithms, e	2.718
Boltzmann's constant, *k*	1.381×10^{-26} kJ/K
Faraday's constant, *F*	9.648×10^{7} C/kmol
Universal Gas constant, $\overline{R}$	8.3143 kJ/kmol K
Permeability of vacuum, μ_o	1.257×10^{-6} H/m
Permittivity of vacuum, ε_o	8.854×10^{-12} F/m
Planck's constant, *h*	6.626×10^{-37} kJ/s
Velocity of light in vacuum, *c*	2.998×10^{8} m/s
Volume of perfect gas at STP	22.41 m^3/kmol

CONVERSION OF UNITS

Angle, θ	1 rad	57.30 °
Energy, U	See inside back cover	
Force, F	1 kgf 1 lbf	9.807 N 4.448 N
Length, ℓ	1 ft 1 inch 1 Å	304.8 mm 25.40 mm 0.1 nm
Mass, M	1 tonne 1 lb	1000 kg 0.454 kg
Power, P	See inside back cover	
Stress, σ	See inside back cover	
Specific Heat, C_p	1 cal/g.°C	4.188 kJ/kg.K
Stress Intensity, K	1 ksi $\sqrt{in}$	1.10 MPa $\sqrt{m}$
Temperature, T	1 °F	0.556 K
Thermal Conductivity, λ	1 cal/s.cm.°C	4.18 W/m.K
Volume, V	1 Imperial gall 1 US gall	4.546×10^{-3} m^3 3.785×10^{-3} m^3
Viscosity, η	1 poise 1 lb ft.s	0.1 N.s/m^2 0.1517 N.s/m^2

CONTENTS

V. CLASSIFICATION AND APPLICATIONS OF ENGINEERING MATERIALS

VI. EQUILIBRIUM (PHASE) DIAGRAMS

VII. HEAT TREATMENT OF STEELS

VIII. PHYSICAL PROPERTIES OF SELECTED ELEMENTS

INTRODUCTION

The data and information in this booklet have been collected for use in the Materials Courses in Part I of the Engineering Tripos (as well as in Part II, and the Manufacturing Engineering Tripos). Numerical data are presented in tabulated and graphical form, and a summary of useful formulae is included. A list of sources from which the data have been prepared is given below. Tabulated material and process data or information are from the Cambridge Engineering Selector (CES) software (Educational database Level 2), copyright of Granta Design Ltd, and are reproduced by permission; the same data source was used for the material property and process attribute charts.

It must be realised that many material properties (such as toughness) vary between wide limits depending on composition and previous treatment. Any final design should be based on manufacturers' or suppliers' data for the material in question, and not on the data given here.

SOURCES

Cambridge Engineering Selector software (CES 4.1), 2003, Granta Design Limited, Rustat House, 62 Clifton Rd, Cambridge, CB1 7EG

M F Ashby, Materials Selection in Mechanical Design, 1999, Butterworth Heinemann

M F Ashby and D R H Jones, Engineering Materials, Vol. 1, 1996, Butterworth Heinemann

M F Ashby and D R H Jones, Engineering Materials, Vol. 2, 1998, Butterworth Heinemann

M Hansen, Constitution of Binary Alloys, 1958, McGraw Hill

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C J Smithells, Metals Reference Book, 6th Ed., 1984, Butterworths

Transformation Characteristics of Nickel Steels, 1952, International Nickel

I. FORMULAE AND DEFINITIONS

STRESS AND STRAIN

$$\sigma_t = \frac{F}{A} \qquad \sigma_n = \frac{F}{A_o} \qquad \varepsilon_t = \ln\left(\frac{\ell}{\ell_o}\right) \qquad \varepsilon_n = \frac{\ell - \ell_o}{\ell_o}$$

F = normal component of force

A_o = initial area

A = current area

ℓ_o = initial length

ℓ = current length

σ_t = true stress

σ_n = nominal stress

ε_t = true strain

ε_n = nominal strain

Poisson's ratio, $\nu = -\dfrac{\text{lateral strain}}{\text{longitudinal strain}}$

Young's modulus E = initial slope of $\sigma_t - \varepsilon_t$ curve = initial slope of $\sigma_n - \varepsilon_n$ curve.

Yield stress σ_y is the nominal stress at the limit of elasticity in a tensile test.

Tensile strength σ_{ts} is the nominal stress at maximum load in a tensile test.

Tensile ductility ε_f is the nominal plastic strain at failure in a tensile test. The gauge length of the specimen should also be quoted.

ELASTIC MODULI

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

For polycrystalline solids, as a rough guide,

Poisson's Ratio $\nu \approx \frac{1}{3}$

Shear Modulus $G \approx \frac{3}{8} E$

Bulk Modulus $K \approx E$

These approximations break down for rubber and porous solids.

STIFFNESS AND STRENGTH OF UNIDIRECTIONAL COMPOSITES

$$E_{II} = V_f E_f + (1 - V_f) E_m$$

$$E_{\perp} = \left(\frac{V_f}{E_f} + \frac{1 - V_f}{E_m} \right)^{-1}$$

$$\sigma_{ts} = V_f \sigma_f^{\mathrm{f}} + (1 - V_f) \sigma_y^{\mathrm{m}}$$

E_{II} = composite modulus parallel to fibres (upper bound)
$E_{\perp}$ = composite modulus transverse to fibres (lower bound)
V_f = volume fraction of fibres
E_f = Young's modulus of fibres
E_m = Young's modulus of matrix
σ_{ts} = tensile strength of composite parallel to fibres
σ_f^{f} = fracture strength of fibres
σ_y^{m} = yield stress of matrix

DISLOCATIONS AND PLASTIC FLOW

The force per unit length F on a dislocation, of Burger's vector b, due to a remote shear stress τ, is $F = \tau b$. The shear stress τ_y required to move a dislocation on a single slip plane is

$\tau_y = \dfrac{cT}{bL}$ where T = line tension (about $\frac{1}{2} G b^2$, where G is the shear modulus)

L = inter-obstacle distance
c = constant ($c \approx 2$ for strong obstacles, $c < 2$ for weak obstacles)

The **shear yield stress** k of a **polycrystalline solid** is related to the shear stress τ_y required to move a dislocation on a single slip plane: $k \approx \frac{3}{2} \tau_y$.

The **uniaxial yield stress** σ_y of a **polycrystalline solid** is approximately $\sigma_y = 2k$, where k is the shear yield stress.

Hardness H (in MPa) is given approximately by: $H \approx 3\sigma_y$.

Vickers Hardness HV is given in kgf/mm^2, i.e. $HV = H / g$, where g is the acceleration due to gravity.

FAST FRACTURE

The stress intensity factor, K: $K = Y\,\sigma\sqrt{\pi a}$

Fast fracture occurs when $K = K_{IC}$

In plane strain, the relationship between stress intensity factor K and strain energy release rate G is:

$$K = \sqrt{\frac{EG}{1-\nu^2}} \approx \sqrt{EG} \quad (\text{as } \nu^2 \approx 0.1)$$

Plane strain fracture toughness and toughness are thus related by: $K_{IC} = \sqrt{\dfrac{E\,G_{IC}}{1-\nu^2}} \approx \sqrt{E\,G_{IC}}$

"Process zone size" at crack tip given approximately by: $r_p = \dfrac{K_{IC}^2}{\pi\,\sigma_f^2}$

Note that K_{IC} (and G_{IC}) are only valid when conditions for linear elastic fracture mechanics apply (typically the crack length and specimen dimensions must be at least 50 times the process zone size).

In the above:

σ = remote tensile stress
a = crack length
Y = dimensionless constant dependent on geometry; typically $Y \approx 1$
K_{IC} = plane strain fracture toughness;
G_{IC} = critical strain energy release rate, or toughness;
E = Young's modulus
ν = Poisson's ratio
σ_f = failure strength

STATISTICS OF FRACTURE

Weibull distribution, $P_s(V) = \exp\left\{\int_V -\left(\dfrac{\sigma}{\sigma_o}\right)^m \dfrac{dV}{V_o}\right\}$

For constant stress: $P_s(V) = \exp\left\{-\left(\dfrac{\sigma}{\sigma_o}\right)^m \dfrac{V}{V_o}\right\}$

P_s = survival probability of component
V = volume of component
σ = tensile stress on component
V_o = volume of test sample
σ_o = reference failure stress for volume V_o, which gives $P_s = \frac{1}{e} = 0.37$
m = Weibull modulus

FATIGUE

Basquin's Law (high cycle fatigue):

$$\Delta\sigma \; N_f^{\alpha} \; = \; C_1$$

Coffin-Manson Law (low cycle fatigue):

$$\Delta\varepsilon^{p\ell} \; N_f^{\beta} \; = \; C_2$$

Goodman's Rule. For the same fatigue life, a stress range $\Delta\sigma$ operating with a mean stress σ_m, is equivalent to a stress range $\Delta\sigma_o$ and zero mean stress, according to the relationship:

$$\Delta\sigma = \Delta\sigma_o\left(1-\frac{\sigma_m}{\sigma_{ts}}\right)$$

Miner's Rule for cumulative damage (for i loading blocks, each of constant stress amplitude and duration N_i cycles):

$$\sum_i \frac{N_i}{N_{fi}} \; = \; 1$$

Paris' crack growth law:

$$\frac{d\,a}{d\,N} \; = A \;\; \Delta K^n$$

In the above:

$\Delta\sigma$ = stress range;
$\Delta\varepsilon^{p\ell}$ = plastic strain range;
ΔK = tensile stress intensity range;
N = cycles;
N_f = cycles to failure;
$\alpha, \beta, C_1, C_2, A, n$ = constants;
a = crack length;
σ_{ts} = tensile strength.

CREEP

Power law creep: $\dot{\varepsilon}_{ss} \; = \; A \; \sigma^n \exp(-Q\,/\,RT\,)$

$\dot{\varepsilon}_{ss}$ = steady-state strain-rate
Q = activation energy (kJ/kmol)
R = universal gas constant
T = absolute temperature
A, n = constants

DIFFUSION

Diffusion coefficient: $D = D_o \exp(-Q/RT)$

Fick's diffusion equations: $J = -D\dfrac{dC}{dx}$ and $\dfrac{\partial C}{\partial t} = D\dfrac{\partial^2 C}{\partial x^2}$

C = concentration
x = distance
t = time
J = diffusive flux
D = diffusion coefficient (m^2/s)
D_o = pre-exponential factor (m^2/s)
Q = activation energy (kJ/kmol)

HEAT FLOW

Steady-state 1D heat flow (Fourier's Law): $q = -\lambda\dfrac{dT}{dx}$

Transient 1D heat flow: $\dfrac{\partial T}{\partial t} = a\dfrac{\partial^2 T}{\partial x^2}$

T = temperature (K)
q = heat flux per second, per unit area ($W/m^2.s$)
λ = thermal conductivity (W/m.K)
a = thermal diffusivity (m^2/s)

For many 1D problems of diffusion and heat flow, the solution for concentration or temperature depends on the error function, erf :

$$C(x,t) = f\left[\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad \text{or} \quad T(x,t) = f\left[\mathrm{erf}\left(\frac{x}{2\sqrt{at}}\right)\right]$$

A characteristic diffusion distance in all problems is given by $x \approx \sqrt{Dt}$, with the corresponding characteristic heat flow distance in thermal problems being $x \approx \sqrt{at}$.

The error function, and its first derivative, are:

$$\mathrm{erf}(X) = \frac{2}{\sqrt{\pi}}\int_0^X \exp\left(-y^2\right)dy \quad \text{and} \quad \frac{d}{dX}[\mathrm{erf}(X)] = \frac{2}{\sqrt{\pi}}\exp\left(-X^2\right)$$

The error function integral has no closed form solution – values are given in the Table below.

X	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
$erf(X)$	0	0.11	0.22	0.33	0.43	0.52	0.60	0.68	0.74

X	0.9	1.0	1.1	1.2	1.3	1.4	1.5	∞
$erf(X)$	0.80	0.84	0.88	0.91	0.93	0.95	0.97	1.0

II. PHYSICAL AND MECHANICAL PROPERTIES OF MATERIALS

II.1 MELTING (or SOFTENING) TEMPERATURE, T_m

All data are for melting points at atmospheric pressure. For polymers (and glasses) the data indicate the glass transition (softening) temperature, above which the mechanical properties rapidly fall. Melting temperatures of selected elements are given in section VIII.

		T_m (°C)
Metals		
Ferrous	Cast Irons	1130 - 1250
	High Carbon Steels	1289 - 1478
	Medium Carbon Steels	1380 - 1514
	Low Carbon Steels	1480 - 1526
	Low Alloy Steels	1382 - 1529
	Stainless Steels	1375 - 1450
Non-ferrous	Aluminium Alloys	475 - 677
	Copper Alloys	982 - 1082
	Lead Alloys	322 - 328
	Magnesium Alloys	447 - 649
	Nickel Alloys	1435 - 1466
	Titanium Alloys	1477 - 1682
	Zinc Alloys	375 - 492
Ceramics		
Glasses	Borosilicate Glass (*)	450 - 602
	Glass Ceramic (*)	563 - 1647
	Silica Glass (*)	957 - 1557
	Soda-Lime Glass (*)	442 - 592
Porous	Brick	927 - 1227
	Concrete, typical	927 - 1227
	Stone	1227 - 1427
Technical	Alumina	2004 2096
	Aluminium Nitride	2397 - 2507
	Boron Carbide	2372 - 2507
	Silicon	1407 - 1412
	Silicon Carbide	2152 - 2500
	Silicon Nitride	2388 - 2496
	Tungsten Carbide	2827 - 2920
Composites		
Metal	Aluminium/Silicon Carbide	525 - 627
Polymer	CFRP	n/a
	GFRP	n/a
Natural		
	Bamboo (*)	77 - 102
	Cork (*)	77 - 102
	Leather (*)	107 - 127
	Wood, typical (Longitudinal) (*)	77 - 102
	Wood, typical (Transverse) (*)	77 - 102

		T_m (°C)
Polymers [1]		
Elastomer	Butyl Rubber (*)	– 73 - – 63
	EVA (*)	– 73 - – 23
	Isoprene (IR) (*)	– 83 - – 78
	Natural Rubber (NR) (*)	– 78 - – 63
	Neoprene (CR) (*)	– 48 - – 43
	Polyurethane Elastomers (elPU) (*)	– 73 - – 23
	Silicone Elastomers (*)	– 123 - – 73
Thermoplastic	ABS (*)	88 - 128
	Cellulose Polymers (CA) (*)	– 9 - 107
	Ionomer (I) (*)	27 - 77
	Nylons (PA) (*)	44 - 56
	Polycarbonate (PC) (*)	142 - 205
	PEEK (*)	143 - 199
	Polyethylene (PE) (*)	– 25 - – 15
	PET (*)	68 - 80
	Acrylic (PMMA) (*)	85 - 165
	Acetal (POM) (*)	– 18 - – 8
	Polypropylene (PP) (*)	– 25 - – 15
	Polystyrene (PS) (*)	74 - 110
	Polyurethane Thermoplastics (tpPU) (*)	120 - 160
	PVC	75 - 105
	Teflon (PTFE)	107 - 123
Thermoset	Epoxies	n/a
	Phenolics	n/a
	Polyester	n/a
Polymer Foams		
	Flexible Polymer Foam (VLD) (*)	112 - 177
	Flexible Polymer Foam (LD) (*)	112 - 177
	Flexible Polymer Foam (MD) (*)	112 - 177
	Rigid Polymer Foam (LD) (*)	67 - 171
	Rigid Polymer Foam (MD) (*)	67 - 157
	Rigid Polymer Foam (HD) (*)	67 - 171

[1] For full names and acronyms of polymers – see Section V.
(*) glass transition (softening) temperature
n/a: not applicable (materials decompose, rather than melt)
(Data courtesy of Granta Design Ltd)

II.2 DENSITY, ρ

		ρ (Mg/m^3)
Metals		
Ferrous	Cast Irons	7.05 - 7.25
	High Carbon Steels	7.8 - 7.9
	Medium Carbon Steels	7.8 - 7.9
	Low Carbon Steels	7.8 - 7.9
	Low Alloy Steels	7.8 - 7.9
	Stainless Steels	7.6 - 8.1
Non-ferrous	Aluminium Alloys	2.5 - 2.9
	Copper Alloys	8.93 - 8.94
	Lead Alloys	10 - 11.4
	Magnesium Alloys	1.74 - 1.95
	Nickel Alloys	8.83 - 8.95
	Titanium Alloys	4.4 - 4.8
	Zinc Alloys	4.95 - 7
Ceramics		
Glasses	Borosilicate Glass	2.2 - 2.3
	Glass Ceramic	2.2 - 2.8
	Silica Glass	2.17 - 2.22
	Soda-Lime Glass	2.44 - 2.49
Porous	Brick	1.9 - 2.1
	Concrete, typical	2.2 - 2.6
	Stone	2.5 - 3
Technical	Alumina	3.5 3.98
	Aluminium Nitride	3.26 - 3.33
	Boron Carbide	2.35 - 2.55
	Silicon	2.3 - 2.35
	Silicon Carbide	3 - 3.21
	Silicon Nitride	3 - 3.29
	Tungsten Carbide	15.3 - 15.9
Composites		
Metal	Aluminium/Silicon Carbide	2.66 - 2.9
Polymer	CFRP	1.5 - 1.6
	GFRP	1.75 - 1.97
Natural		
	Bamboo	0.6 - 0.8
	Cork	0.12 - 0.24
	Leather	0.81 - 1.05
	Wood, typical (Longitudinal)	0.6 - 0.8
	Wood, typical (Transverse)	0.6 - 0.8

		ρ (Mg/m^3)
Polymers [1]		
Elastomer	Butyl Rubber	0.9 - 0.92
	EVA	0.945 - 0.955
	Isoprene (IR)	0.93 - 0.94
	Natural Rubber (NR)	0.92 - 0.93
	Neoprene (CR)	1.23 - 1.25
	Polyurethane Elastomers (elPU)	1.02 - 1.25
	Silicone Elastomers	1.3 - 1.8
Thermoplastic	ABS	1.01 - 1.21
	Cellulose Polymers (CA)	0.98 - 1.3
	Ionomer (I)	0.93 - 0.96
	Nylons (PA)	1.12 - 1.14
	Polycarbonate (PC)	1.14 - 1.21
	PEEK	1.3 - 1.32
	Polyethylene (PE)	0.939 - 0.96
	PET	1.29 - 1.4
	Acrylic (PMMA)	1.16 - 1.22
	Acetal (POM)	1.39 - 1.43
	Polypropylene (PP)	0.89 - 0.91
	Polystyrene (PS)	1.04 - 1.05
	Polyurethane Thermoplastics (tpPU)	1.12 - 1.24
	PVC	1.3 - 1.58
	Teflon (PTFE)	2.14 - 2.2
Thermoset	Epoxies	1.11 - 1.4
	Phenolics	1.24 - 1.32
	Polyester	1.04 - 1.4
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.016 - 0.035
	Flexible Polymer Foam (LD)	0.038 - 0.07
	Flexible Polymer Foam (MD)	0.07 - 0.115
	Rigid Polymer Foam (LD)	0.036 - 0.07
	Rigid Polymer Foam (MD)	0.078 - 0.165
	Rigid Polymer Foam (HD)	0.17 - 0.47

1 For full names and acronyms of polymers – see Section V
(Data courtesy of Granta Design Ltd).

II.3 YOUNG'S MODULUS, *E*

		E (GPa)
Metals		
Ferrous	Cast Irons	165 - 180
	High Carbon Steels	200 - 215
	Medium Carbon Steels	200 - 216
	Low Carbon Steels	200 - 215
	Low Alloy Steels	201 - 217
	Stainless Steels	189 - 210
Non-ferrous	Aluminium Alloys	68 - 82
	Copper Alloys	112 - 148
	Lead Alloys	12.5 - 15
	Magnesium Alloys	42 - 47
	Nickel Alloys	190 - 220
	Titanium Alloys	90 - 120
	Zinc Alloys	68 - 95
Ceramics		
Glasses	Borosilicate Glass	61 - 64
	Glass Ceramic	64 - 110
	Silica Glass	68 - 74
	Soda-Lime Glass	68 - 72
Porous	Brick	10 - 50
	Concrete, typical	25 - 38
	Stone	6.9 - 21
Technical	Alumina	215 413
	Aluminium Nitride	302 - 348
	Boron Carbide	400 - 472
	Silicon	140 - 155
	Silicon Carbide	300 - 460
	Silicon Nitride	280 - 310
	Tungsten Carbide	600 - 720
Composites		
Metal	Aluminium/Silicon Carbide	81 - 100
Polymer	CFRP	69 - 150
	GFRP	15 - 28
Natural		
	Bamboo	15 - 20
	Cork	0.013 - 0.05
	Leather	0.1 - 0.5
	Wood, typical (Longitudinal)	6 - 20
	Wood, typical (Transverse)	0.5 - 3

		E (GPa)
Polymers [1]		
Elastomer	Butyl Rubber	0.001 - 0.002
	EVA	0.01 - 0.04
	Isoprene (IR)	0.0014 - 0.004
	Natural Rubber (NR)	0.0015 - 0.0025
	Neoprene (CR)	0.0007 - 0.002
	Polyurethane Elastomers (elPU)	0.002 - 0.003
	Silicone Elastomers	0.005 - 0.02
Thermoplastic	ABS	1.1 - 2.9
	Cellulose Polymers (CA)	1.6 - 2
	Ionomer (I)	0.2 - 0.424
	Nylons (PA)	2.62 - 3.2
	Polycarbonate (PC)	2 - 2.44
	PEEK	3.5 - 4.2
	Polyethylene (PE)	0.621 - 0.896
	PET	2.76 - 4.14
	Acrylic (PMMA)	2.24 - 3.8
	Acetal (POM)	2.5 - 5
	Polypropylene (PP)	0.896 - 1.55
	Polystyrene (PS)	2.28 - 3.34
	Polyurethane Thermoplastics (tpPU)	1.31 - 2.07
	PVC	2.14 - 4.14
	Teflon (PTFE)	0.4 - 0.552
Thermoset	Epoxies	2.35 - 3.075
	Phenolics	2.76 - 4.83
	Polyester	2.07 - 4.41
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.0003 - 0.001
	Flexible Polymer Foam (LD)	0.001 - 0.003
	Flexible Polymer Foam (MD)	0.004 - 0.012
	Rigid Polymer Foam (LD)	0.023 - 0.08
	Rigid Polymer Foam (MD)	0.08 - 0.2
	Rigid Polymer Foam (HD)	0.2 - 0.48

1 For full names and acronyms of polymers – see Section V
(Data courtesy of Granta Design Ltd) .

II.4 YIELD STRESS, σ_y, AND TENSILE STRENGTH, σ_{ts}

		σ_y (MPa)	σ_{ts} (MPa)
Metals			
Ferrous	Cast Irons	215 - 790	350 - 1000
	High Carbon Steels	400 - 1155	550 - 1640
	Medium Carbon Steels	305 - 900	410 - 1200
	Low Carbon Steels	250 - 395	345 - 580
	Low Alloy Steels	400 - 1100	460 - 1200
	Stainless Steels	170 - 1000	480 - 2240
Non-ferrous	Aluminium Alloys	30 - 500	58 - 550
	Copper Alloys	30 - 500	100 - 550
	Lead Alloys	8 - 14	12 - 20
	Magnesium Alloys	70 - 400	185 - 475
	Nickel Alloys	70 - 1100	345 - 1200
	Titanium Alloys	250 - 1245	300 - 1625
	Zinc Alloys	80 - 450	135 - 520
Ceramics			
Glasses	Borosilicate Glass (*)	*264 - 384*	22 - 32
	Glass Ceramic (*)	*750 - 2129*	62 - 177
	Silica Glass (*)	*1100 - 1600*	45 - 155
	Soda-Lime Glass (*)	*360 - 420*	31 - 35
Porous	Brick (*)	*50 - 140*	7 - 14
	Concrete, typical (*)	*32 - 60*	2 - 6
	Stone (*)	*34 - 248*	5 - 17
Technical	Alumina (*)	*690 5500*	350 665
	Aluminium Nitride (*)	*1970 - 2700*	197 - 270
	Boron Carbide (*)	*2583 - 5687*	350 - 560
	Silicon (*)	*3200 - 3460*	160 - 180
	Silicon Carbide (*)	*1000 - 5250*	370 - 680
	Silicon Nitride (*)	*524 - 5500*	690 - 800
	Tungsten Carbide (*)	*3347 - 6833*	370 - 550
Composites			
Metal	Aluminium/Silicon Carbide	280 - 324	290 - 365
Polymer	CFRP	550 - 1050	550 - 1050
	GFRP	110 - 192	138 - 241
Natural			
	Bamboo	35 - 44	36 - 45
	Cork	0.3 - 1.5	0.5 - 2.5
	Leather	5 - 10	20 - 26
	Wood, typical (Longitudinal)	30 - 70	60 - 100
	Wood, typical (Transverse)	2 - 6	4 - 9

(Data courtesy of Granta Design Ltd)

		σ_y (MPa)	σ_{ts} (MPa)
Polymers [1]			
Elastomer	Butyl Rubber	2 - 3	5 - 10
	EVA	12 - 18	16 - 20
	Isoprene (IR)	20 - 25	20 - 25
	Natural Rubber (NR)	20 - 30	22 - 32
	Neoprene (CR)	3.4 - 24	3.4 - 24
	Polyurethane Elastomers (elPU)	25 - 51	25 - 51
	Silicone Elastomers	2.4 - 5.5	2.4 - 5.5
Thermoplastic	ABS	18.5 - 51	27.6 - 55.2
	Cellulose Polymers (CA)	25 - 45	25 - 50
	Ionomer (I)	8.3 - 15.9	17.2 - 37.2
	Nylons (PA)	50 - 94.8	90 - 165
	Polycarbonate (PC)	59 - 70	60 - 72.4
	PEEK	65 - 95	70 - 103
	Polyethylene (PE)	17.9 - 29	20.7 - 44.8
	PET	56.5 - 62.3	48.3 - 72.4
	Acrylic (PMMA)	53.8 - 72.4	48.3 - 79.6
	Acetal (POM)	48.6 - 72.4	60 - 89.6
	Polypropylene (PP)	20.7 - 37.2	27.6 - 41.4
	Polystyrene (PS)	28.7 - 56.2	35.9 - 56.5
	Polyurethane Thermoplastics (tpPU)	40 - 53.8	31 - 62
	PVC	35.4 - 52.1	40.7 - 65.1
	Teflon (PTFE)	15 - 25	20 - 30
Thermoset	Epoxies	36 - 71.7	45 - 89.6
	Phenolics	27.6 - 49.7	34.5 - 62.1
	Polyester	33 - 40	41.4 - 89.6
Polymer Foams			
	Flexible Polymer Foam (VLD)	0.01 - 0.12	0.24 - 0.85
	Flexible Polymer Foam (LD)	0.02 - 0.3	0.24 - 2.35
	Flexible Polymer Foam (MD)	0.05 - 0.7	0.43 - 2.95
	Rigid Polymer Foam (LD)	0.3 - 1.7	0.45 - 2.25
	Rigid Polymer Foam (MD)	0.4 - 3.5	0.65 - 5.1
	Rigid Polymer Foam (HD)	0.8 - 12	1.2 - 12.4

[1] For full names and acronyms of polymers – see Section V.

(*) NB: For ceramics, yield stress is replaced by *compressive strength*, which is more relevant in ceramic design. Note that ceramics are of the order of 10 times stronger in compression than in tension.

II.5 FRACTURE TOUGHNESS (PLANE STRAIN), K_{IC}

		K_{IC} (MPa√m)
Metals		
Ferrous	Cast Irons	22 - 54
	High Carbon Steels	27 - 92
	Medium Carbon Steels	12 - 92
	Low Carbon Steels	41 - 82
	Low Alloy Steels	14 - 200
	Stainless Steels	62 - 280
Non-ferrous	Aluminium Alloys	22 - 35
	Copper Alloys	30 - 90
	Lead Alloys	5 - 15
	Magnesium Alloys	12 - 18
	Nickel Alloys	80 - 110
	Titanium Alloys	14 - 120
	Zinc Alloys	10 - 100
Ceramics		
Glasses	Borosilicate Glass	0.5 - 0.7
	Glass Ceramic	1.4 - 1.7
	Silica Glass	0.6 - 0.8
	Soda-Lime Glass	0.55 - 0.7
Porous	Brick	1 - 2
	Concrete, typical	0.35 - 0.45
	Stone	0.7 - 1.5
Technical	Alumina	3.3 4.8
	Aluminium Nitride	2.5 - 3.4
	Boron Carbide	2.5 - 3.5
	Silicon	0.83 - 0.94
	Silicon Carbide	2.5 - 5
	Silicon Nitride	4 - 6
	Tungsten Carbide	2 - 3.8
Composites		
Metal	Aluminium/Silicon Carbide	15 - 24
Polymer	CFRP	6.1 - 88
	GFRP	7 - 23
Natural		
	Bamboo	5 - 7
	Cork	0.05 - 0.1
	Leather	3 - 5
	Wood, typical (Longitudinal)	5 - 9
	Wood, typical (Transverse)	0.5 - 0.8

(Data courtesy of Granta Design Ltd)

		K_{IC} (MPa√m)
Polymers [1]		
Elastomer	Butyl Rubber	0.07 - 0.1
	EVA	0.5 - 0.7
	Isoprene (IR)	0.07 - 0.1
	Natural Rubber (NR)	0.15 - 0.25
	Neoprene (CR)	0.1 - 0.3
	Polyurethane Elastomers (elPU)	0.2 - 0.4
	Silicone Elastomers	0.03 - 0.5
Thermoplastic	ABS	1.19 - 4.30
	Cellulose Polymers (CA)	1 - 2.5
	Ionomer (I)	1.14 - 3.43
	Nylons (PA)	2.22 - 5.62
	Polycarbonate (PC)	2.1 - 4.60
	PEEK	2.73 - 4.30
	Polyethylene (PE)	1.44 - 1.72
	PET	4.5 - 5.5
	Acrylic (PMMA)	0.7 - 1.6
	Acetal (POM)	1.71 - 4.2
	Polypropylene (PP)	3 - 4.5
	Polystyrene (PS)	0.7 - 1.1
	Polyurethane Thermoplastics (tpPU)	1.84 - 4.97
	PVC	1.46 - 5.12
	Teflon (PTFE)	1.32 - 1.8
Thermoset	Epoxies	0.4 - 2.22
	Phenolics	0.79 - 1.21
	Polyester	1.09 - 1.70
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.005 - 0.02
	Flexible Polymer Foam (LD)	0.015 - 0.05
	Flexible Polymer Foam (MD)	0.03 - 0.09
	Rigid Polymer Foam (LD)	0.002 - 0.02
	Rigid Polymer Foam (MD)	0.007 - 0.049
	Rigid Polymer Foam (HD)	0.024 - 0.091

[1] For full names and acronyms of polymers – see Section V.

Note: K_{IC} only valid for conditions of linear elastic fracture mechanics (see I. Formulae & Definitions). Plane Strain Toughness, G_{IC}, may be estimated from $K_{IC}^2 = E\,G_{IC}/(1-\nu^2) \approx E\,G_{IC}$ (as $\nu^2 \approx 0.1$).

II.6 ENVIRONMENTAL RESISTANCE

Class	Material	Flammability	Fresh water	Salt water	Sunlight (UV)	Wear resistance
Metals						
Ferrous	Cast Irons	A	B	C	A	A
	High Carbon Steels	A	B	C	A	A
	Medium Carbon Steels	A	B	C	A	A
	Low Carbon Steels	A	B	C	A	A
	Low Alloy Steels	A	B	C	A	A
	Stainless Steels	A	A	A	A	B
Non-ferrous	Aluminium Alloys	B	A	B	A	C
	Copper Alloys	A	A	A	A	A
	Lead Alloys	A	A	A	A	C
	Magnesium Alloys	A	A	D	A	C
	Nickel Alloys	A	A	A	A	B
	Titanium Alloys	A	A	A	A	C
	Zinc Alloys	A	A	C	A	E
Ceramics						
Glasses	Borosilicate Glass	A	B	B	A	A
	Glass Ceramic	A	A	A	A	A
	Silica Glass	A	A	A	A	B
	Soda-Lime Glass	A	A	A	A	A
Porous	Brick, Concrete, Stone	A	A	A	A	C
Technical	Alumina	A	A	A	A	A
	Aluminium Nitride	A	A	A	A	A
	Boron Carbide	A	A	A	A	A
	Silicon	A	A	B	A	B
	Silicon Carbide	A	A	A	A	A
	Silicon Nitride	A	A	A	A	A
	Tungsten Carbide	A	A	A	A	A
Composites						
Metal	Aluminium/Silicon Carbide	A	A	B	A	B
Polymer	CFRP	B	A	A	B	C
	GFRP	B	A	A	B	C
Natural						
	Bamboo	D	C	C	B	D
	Cork	D	B	B	A	B
	Leather	D	B	B	B	B
	Wood	D	C	C	B	D

Class	Material	Flammability	Fresh water	Salt water	Sunlight (UV)	Wear resistance
Polymers [1]						
Elastomer	Butyl Rubber	E	A	A	B	B
	EVA	E	A	A	B	B
	Isoprene (IR)	E	A	A	B	B
	Natural Rubber (NR)	E	A	A	B	B
	Neoprene (CR)	E	A	A	B	B
	Polyurethane Elastomers (elPU)	E	A	A	B	B
	Silicone Elastomers	B	A	A	B	B
Thermoplastic	ABS	D	A	A	C	D
	Cellulose Polymers (CA)	D	A	A	B	C
	Ionomer (I)	D	A	A	B	C
	Nylons (PA)	C	A	A	C	C
	Polycarbonate (PC)	B	A	A	B	C
	PEEK	B	A	A	A	C
	Polyethylene (PE)	D	A	A	D	C
	PET	D	A	A	B	C
	Acrylic (PMMA)	D	A	A	A	C
	Acetal (POM)	D	A	A	C	B
	Polypropylene (PP)	D	A	A	D	C
	Polystyrene (PS)	D	A	A	C	D
	Polyurethane Thermoplastics (tpPU)	C	A	A	B	C
	PVC	A	A	A	A	C
	Teflon (PTFE)	A	A	A	B	B
Thermoset	Epoxies	B	A	A	B	C
	Phenolics	B	A	A	A	C
	Polyester	D	A	A	A	C
Polymer Foams						
	Flexible Polymer Foams	E	A	A	C	D
	Rigid Polymer Foams	C	A	A	B	E

[1] For full names and acronyms of polymers – see Section V.

Ranking:

A = very good; B = good; C = average; D = poor; E = very poor.

(Data courtesy of Granta Design Ltd)

II.7 UNIAXIAL TENSILE RESPONSE OF SELECTED METALS & POLYMERS

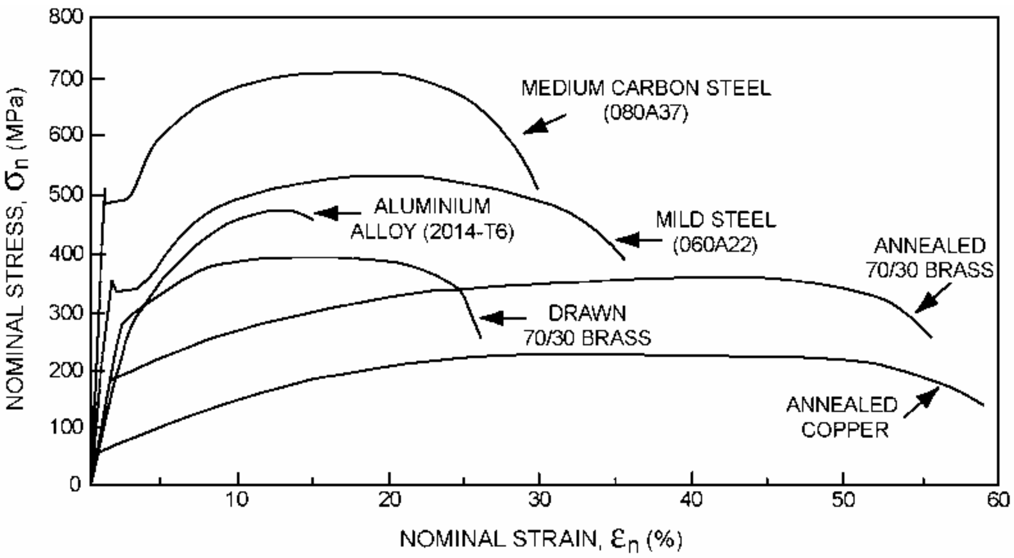

Figure 2.1 Tensile response of some common metals

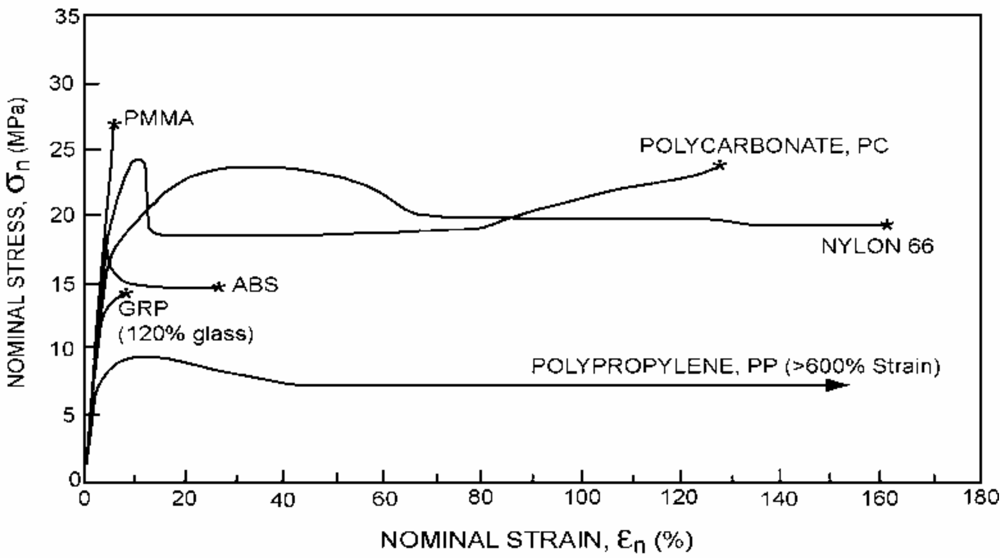

Figure 2.2 Tensile response of some common polymers

III. MATERIAL PROPERTY CHARTS

III.1 YOUNG'S MODULUS – DENSITY

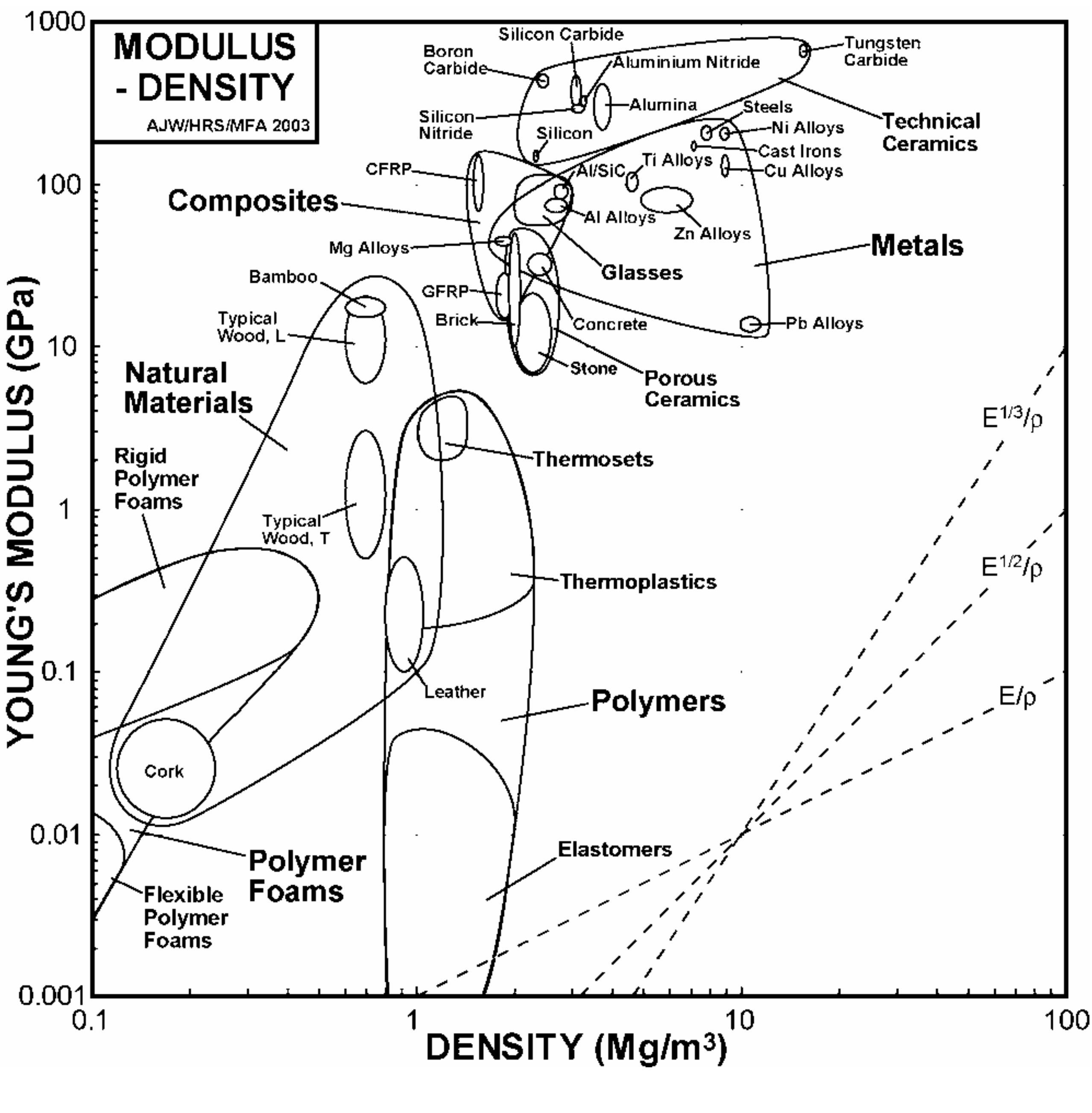

Figure 3.1: Young's modulus, E, against density, ρ. The design guide-lines assist in selection of materials for minimum weight, stiffness-limited design. (Data courtesy of Granta Design Ltd)

III.2 STRENGTH – DENSITY

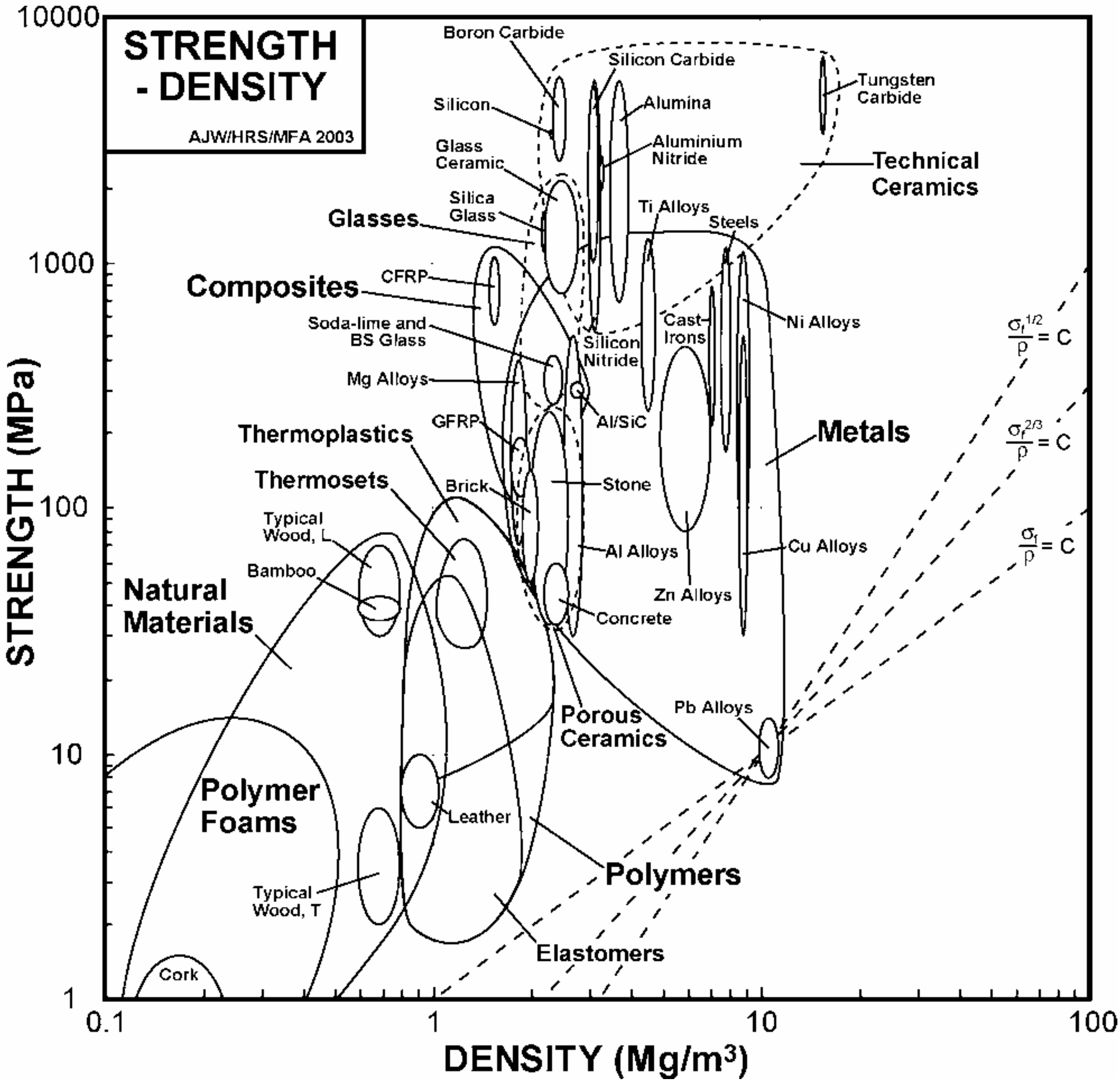

Figure 3.2: Failure strength, σ_f, against density, ρ. Failure strength is defined as the *tensile elastic limit* (usually yield stress) for all materials other than ceramics, for which it is the *compressive strength*. The design guide-lines assist in selection of materials for minimum weight, strength-limited design. (Data courtesy of Granta Design Ltd)

III.3 YOUNG'S MODULUS – STRENGTH

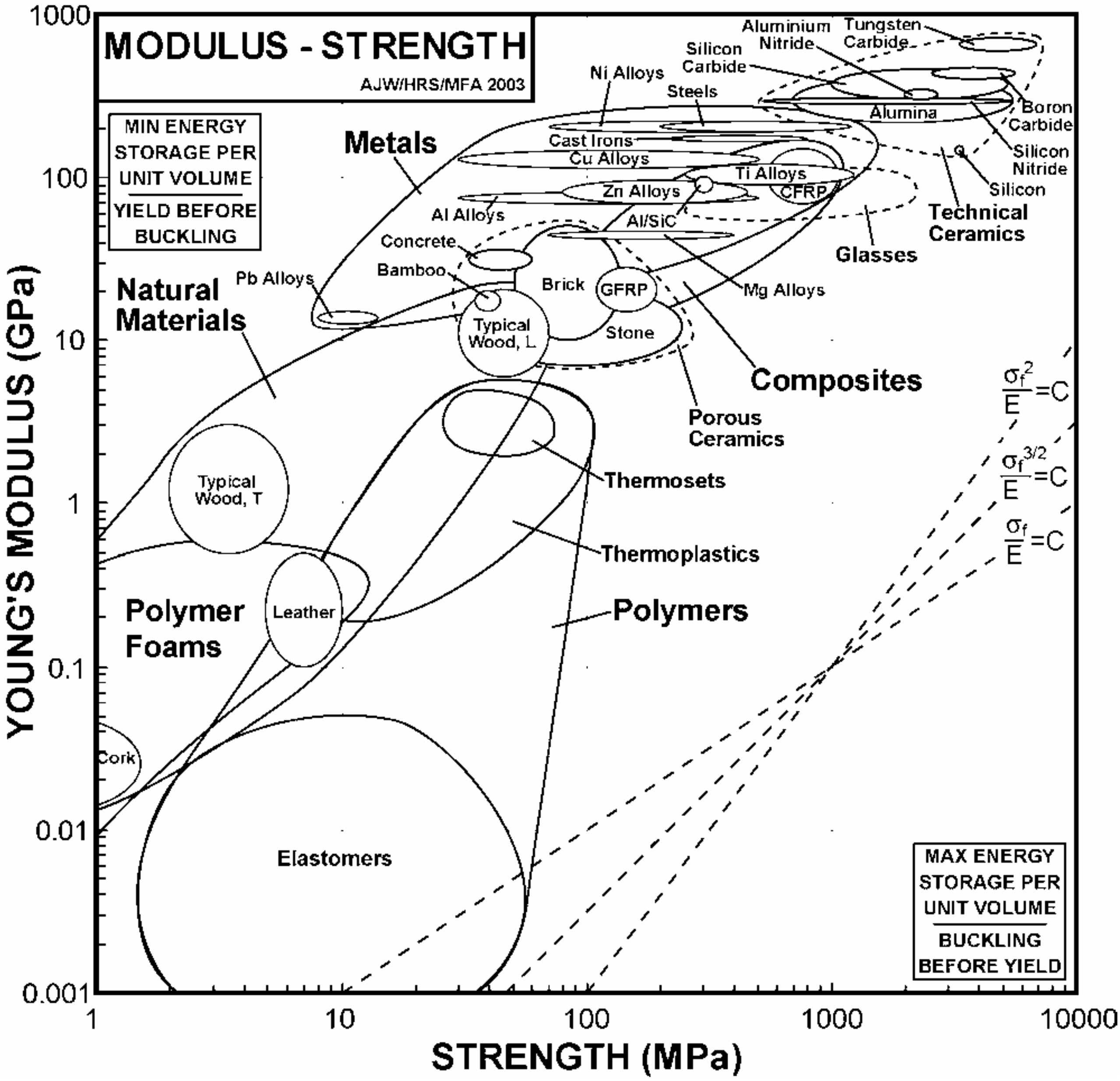

Figure 3.3: Young's modulus, E, against failure strength, σ_f. Failure strength is defined as the *tensile elastic limit* (usually yield stress) for all materials other than ceramics, for which it is the *compressive strength*. The design guide-lines assist in the selection of materials for maximum stored energy, volume-limited design. (Data courtesy of Granta Design Ltd)

III.4 FRACTURE TOUGHNESS – STRENGTH

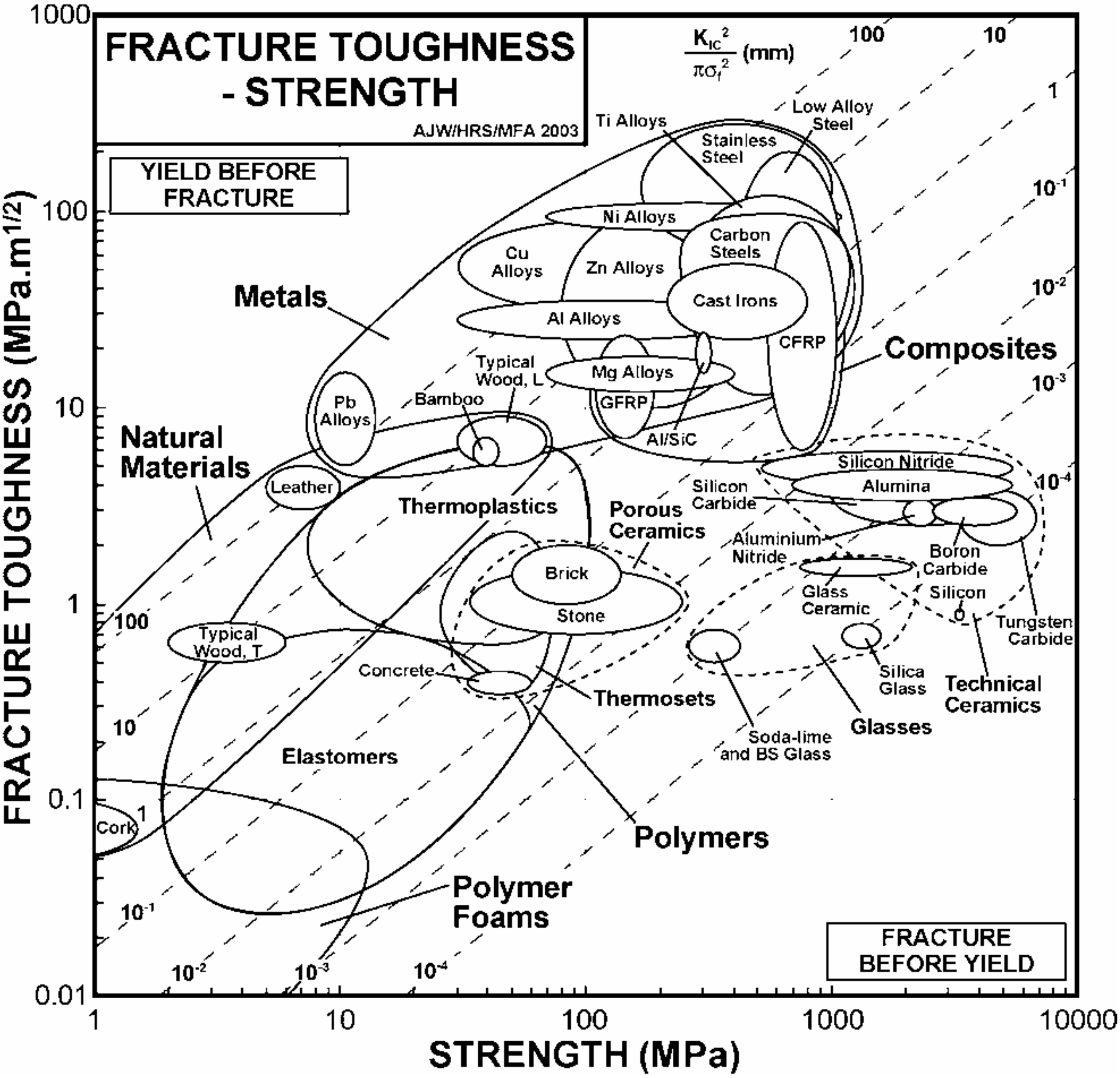

Figure 3.4: Fracture toughness (plane strain), K_{IC}, against failure strength, σ_f. Failure strength is defined as the *tensile elastic limit* (usually yield stress) for all materials other than ceramics, for which it is the *compressive strength*. The contours show $K_{IC}^2 / \pi\sigma_f^2$, which is approximately the diameter of the process zone at a crack tip. Valid application of linear elastic fracture mechanics using K requires that the specimen and crack dimensions are large compared to this process zone. The design guide-lines are used in selecting materials for damage tolerant design. (Data courtesy of Granta Design Ltd)

III.5 MAXIMUM SERVICE TEMPERATURE

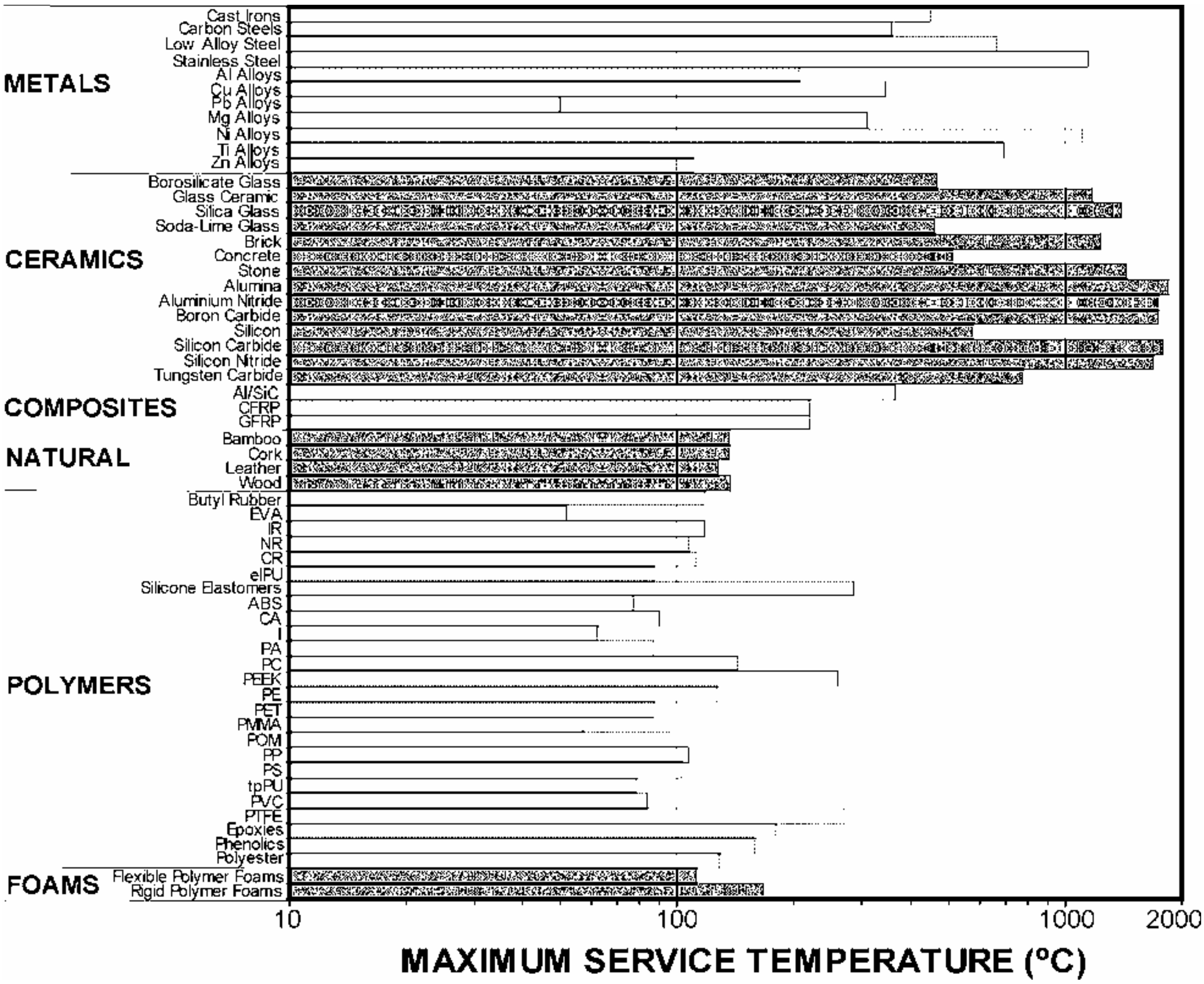

Figure 3.5: Maximum service temperature. The shaded bars extend to the maximum service temperature – materials may be used safely for all temperatures up to this value, without significant property degradation. (Note: there is a modest range of maximum service temperature in a given material class – not all variants within a class may be used up to the temperature shown, so caution should be exercised if a material appears close to its limit).

NB: For full names and acronyms of polymers – see Section V. (Data courtesy of Granta Design Ltd)

III.6 MATERIAL PRICE (PER KG)

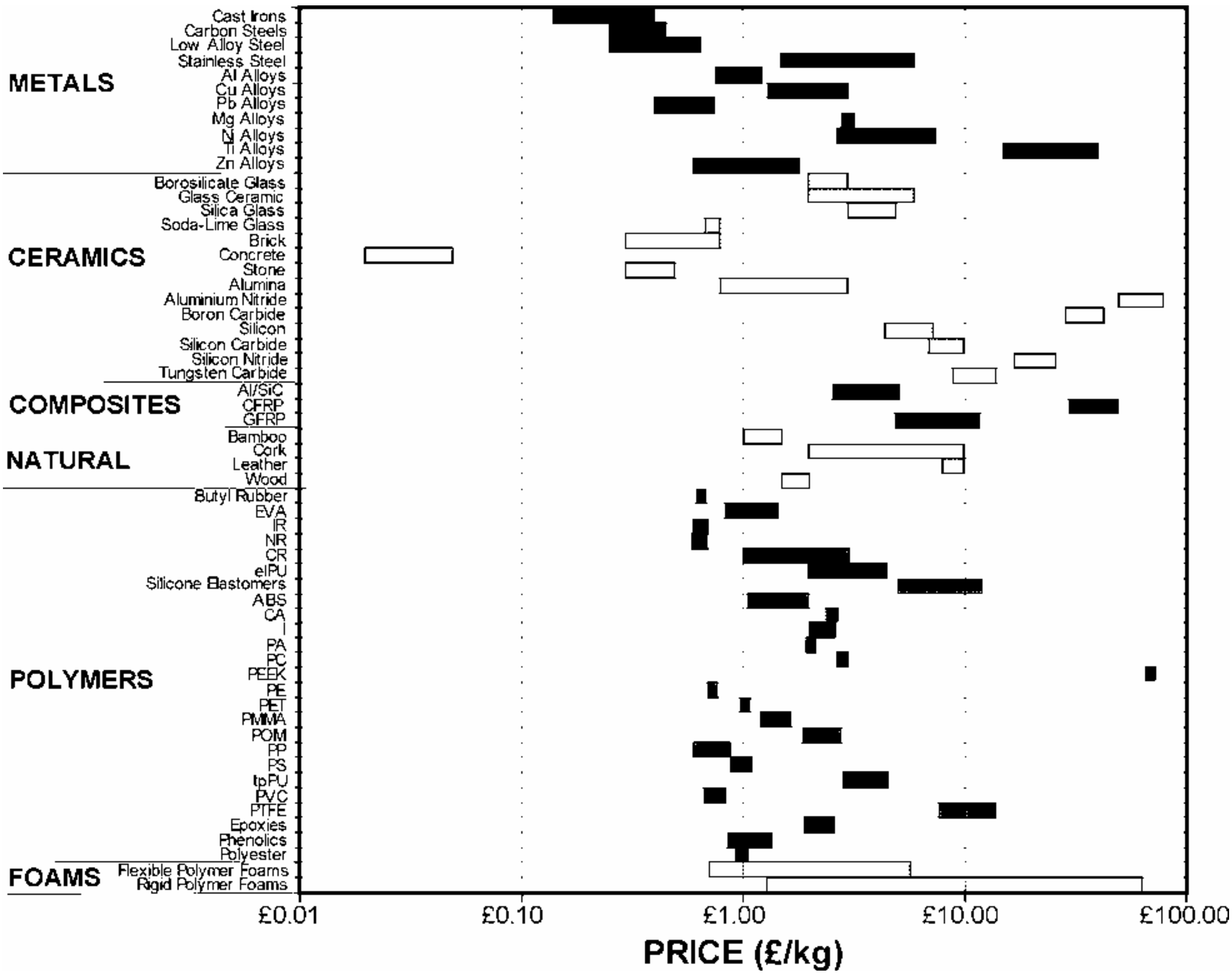

Figure 3.6: Material price (per kg), C_m (2003 data). C_m represents raw material price/kg, and does not include manufacturing or end-of-life costs.
NB: For full names and acronyms of polymers – see Section V. (Data courtesy of Granta Design Ltd)

IV. PROCESS ATTRIBUTE CHARTS

IV.1 MATERIAL – PROCESS COMPATIBILITY MATRIX (SHAPING)

Figure 4.1a: Metals

Metals		Sand Casting	Die Casting	Investment Casting	Rolling/ Forging	Extrusion	Sheet Forming	Powder Methods	Machining
Ferrous	Cast Irons	•	•	•					
	Medium/High Carbon Steels	•		•	•			•	•
	Low Carbon Steels	•		•	•		•	•	•
	Low Alloy/Stainless Steels	•	•	•	•		•	•	•
Non-ferrous	Aluminium, Copper, Lead, Magnesium, Zinc Alloys	•	•	•	•	•	•	•	•
	Nickel Alloys	•	•	•	•		•	•	•
	Titanium Alloys		•		•	•	•	•	•

Figure 4.1b: Polymers and Foams

Polymers	Machining	Injection Moulding	Blow Moulding	Compression Moulding	Rotational Moulding	Polymer Casting	Composite Forming
Elastomers	•			•	•		
Thermoplastics	•	•	•	•	•		
Thermosets				•	•	•	•
Polymer Foams	•	•			•		

Notes on other materials:

Ceramics are all processed by powder methods, and Glasses are also moulded. Both are difficult to machine.

Polymer Composites are shaped by dedicated forming techniques, and are difficult to machine.

Natural Materials can only be machined, though some woods are also hot formed.

(Data courtesy of Granta Design Ltd)

IV.2 MASS

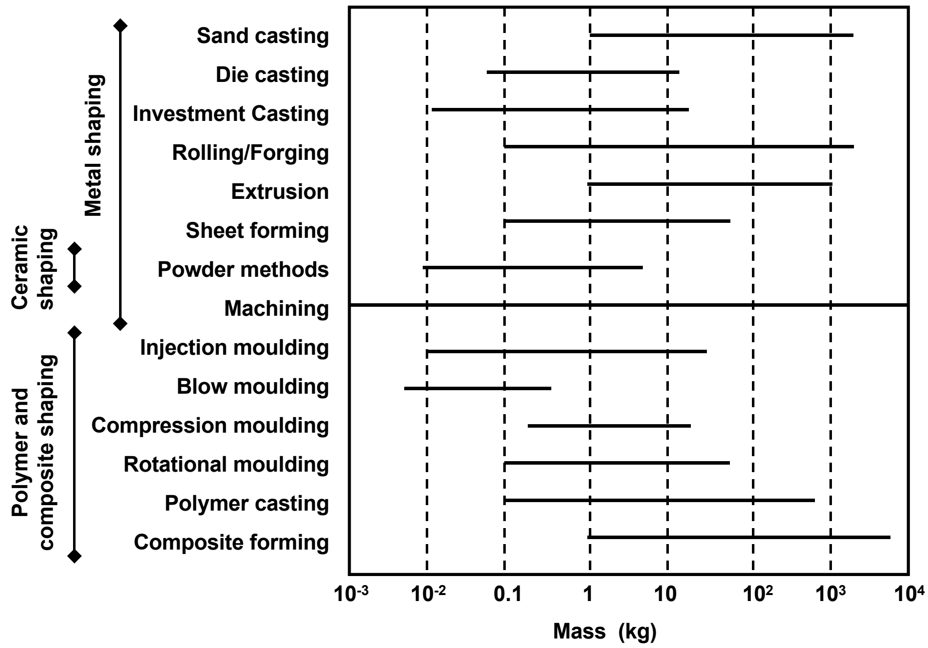

Figure 4.2: Process attribute chart for shaping processes: mass range (kg)

IV.3 SECTION THICKNESS

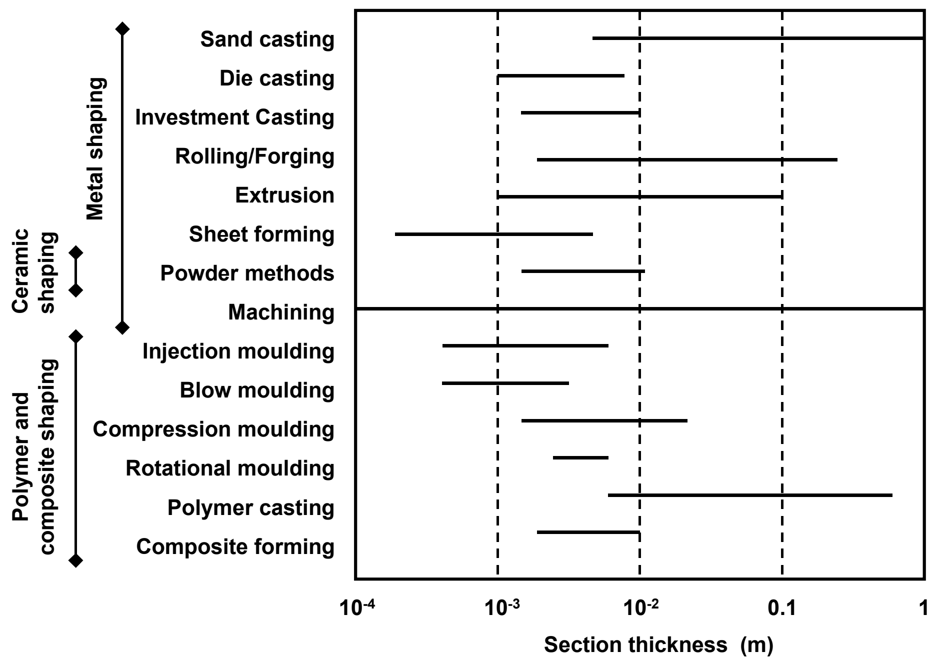

Figure 4.3: Process attribute chart for shaping processes: section thickness (m)

(DATA COURTESY OF GRANTA DESIGN LTD)

IV.4 SURFACE ROUGHNESS

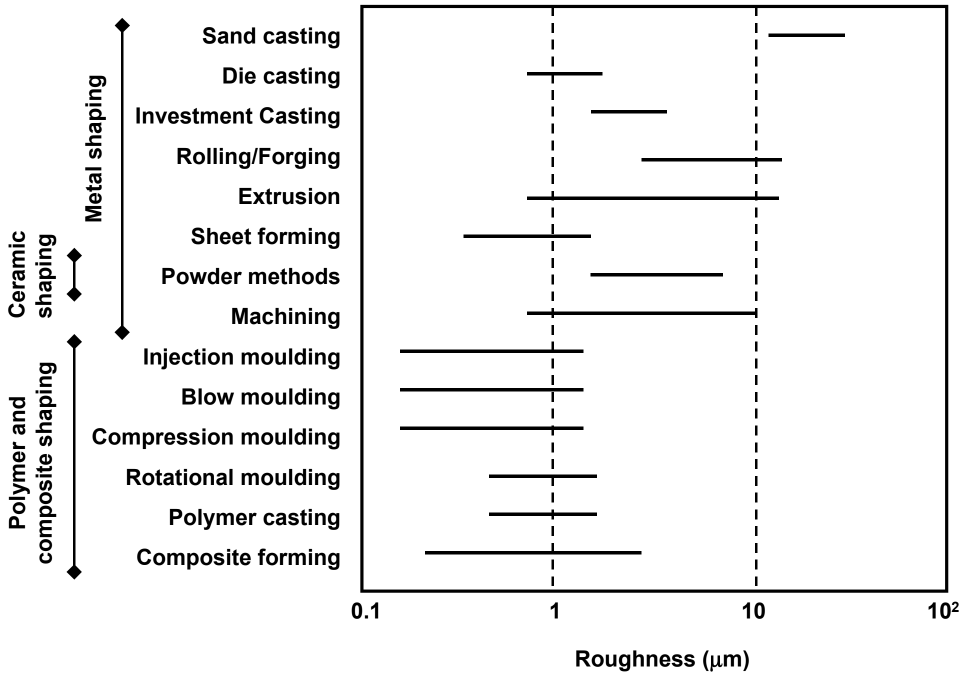

Figure 4.4: Process attribute chart for shaping processes: surface roughness (μm)

IV.5 DIMENSIONAL TOLERANCE

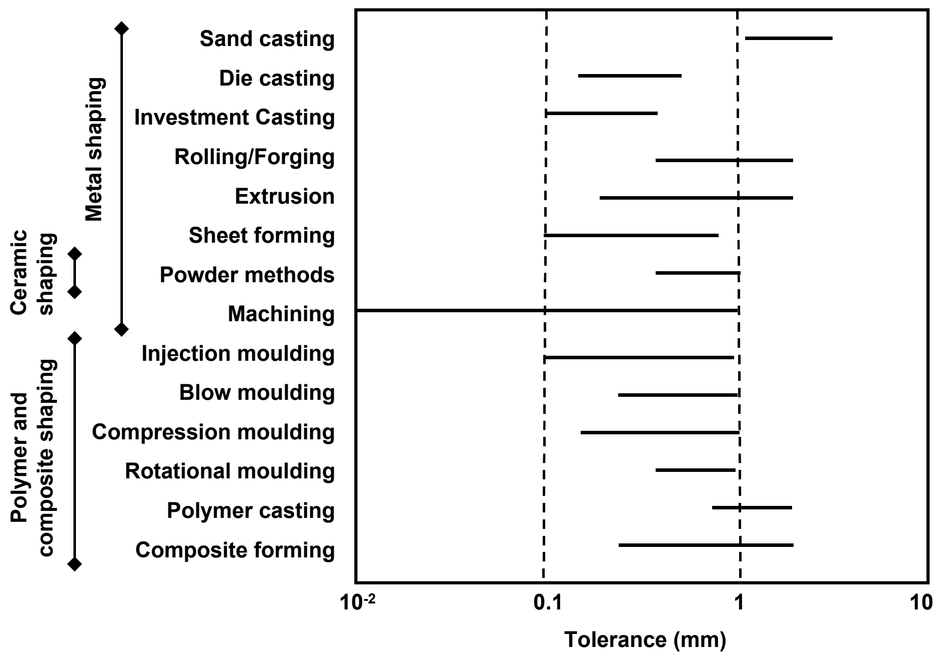

Figure 4.5: Process attribute chart for shaping processes: dimensional tolerance (mm)

IV.6 ECONOMIC BATCH SIZE

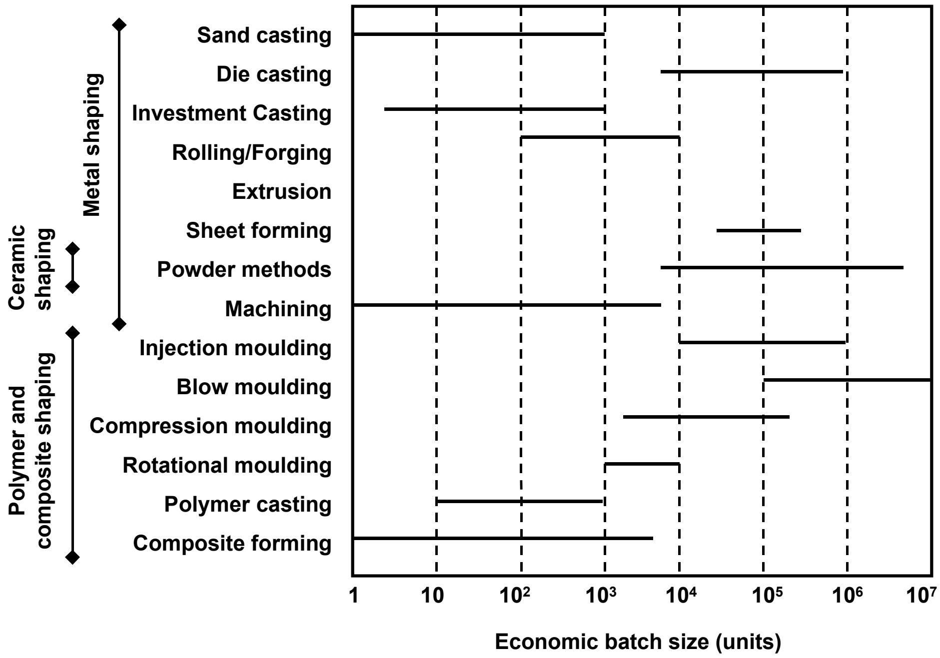

Figure 4.6: Process attribute chart for shaping processes: economic batch size (Data courtesy of Granta Design Ltd)

V. CLASSIFICATION AND APPLICATIONS OF ENGINEERING MATERIALS

V.1 METALS: FERROUS ALLOYS, NON-FERROUS ALLOYS

Metals		Applications
Ferrous	Cast Irons	Automotive parts, engine blocks, machine tool structural parts, lathe beds
	High Carbon Steels	Cutting tools, springs, bearings, cranks, shafts, railway track
	Medium Carbon Steels	General mechanical engineering (tools, bearings, gears, shafts, bearings)
	Low Carbon Steels	Steel structures (“mild steel”) – bridges, oil rigs, ships; reinforcement for concrete; automotive parts, car body panels; galvanised sheet; packaging (cans, drums)
	Low Alloy Steels	Springs, tools, ball bearings, automotive parts (gears connecting rods etc)
	Stainless Steels	Transport, chemical and food processing plant, nuclear plant, domestic ware (cutlery, washing machines, stoves), surgical implements, pipes, pressure vessels, liquid gas containers
Non-ferrous	Aluminium Alloys	
	Casting Alloys	Automotive parts (cylinder blocks), domestic appliances (irons)
	Non-heat-treatable Alloys	Electrical conductors, heat exchangers, foil, tubes, saucepans, beverage cans, lightweight ships, architectural panels
	Heat-treatable Alloys	Aerospace engineering, automotive bodies and panels, lightweight structures and ships
	Copper Alloys	Electrical conductors and wire, electronic circuit boards, heat exchangers, boilers, cookware, coinage, sculptures
	Lead Alloys	Roof and wall cladding, solder, X-ray shielding, battery electrodes
	Magnesium Alloys	Automotive castings, wheels, general lightweight castings for transport, nuclear fuel containers; principal alloying addition to Aluminium Alloys
	Nickel Alloys	Gas turbines and jet engines, thermocouples, coinage; alloying addition to austenitic stainless steels
	Titanium Alloys	Aircraft turbine blades; general structural aerospace applications; biomedical implants.
	Zinc Alloys	Die castings (automotive, domestic appliances, toys, handles); coating on galvanised steel

V.2 POLYMERS AND FOAMS

Polymers		Abbreviation	Applications
Elastomer	Butyl Rubber		Tyres, seals, anti-vibration mountings, electrical insulation, tubing
	Ethylene-vinyl-acetate	EVA	Bags, films, packaging, gloves, insulation, running shoes
	Isoprene	IR	Tyres, inner tubes, insulation, tubing, shoes
	Natural Rubber	NR	Gloves, tyres, electrical insulation, tubing
	Polychloroprene (Neoprene)	CR	Wetsuits, O-rings and seals, footware
	Polyurethane Elastomers	el-PU	Packaging, hoses, adhesives, fabric coating
	Silicone Elastomers		Electrical insulation, electronic encapsulation, medical implants
Thermoplastic	Acrylonitrile butadiene styrene	ABS	Communication appliances, automotive interiors, luggage, toys, boats
	Cellulose Polymers	CA	Tool and cutlery handles, decorative trim, pens
	Ionomer	I	Packaging, golf balls, blister packs, bottles
	Polyamides (Nylons)	PA	Gears, bearings; plumbing, packaging, bottles, fabrics, textiles, ropes
	Polycarbonate	PC	Safety goggles, shields, helmets; light fittings, medical components
	Polyetheretherketone	PEEK	Electrical connectors, racing car parts, fibre composites
	Polyethylene	PE	Packaging, bags, squeeze tubes, toys, artificial joints
	Polyethylene terephthalate	PET	Blow moulded bottles, film, audio/video tape, sails
	Polymethyl methacrylate (Acrylic)	PMMA	Aircraft windows, lenses, reflectors, lights, compact discs
	Polyoxymethylene (Acetal)	POM	Zips, domestic and appliance parts, handles
	Polypropylene	PP	Ropes, garden furniture, pipes, kettles, electrical insulation, astroturf
	Polystyrene	PS	Toys, packaging, cutlery, audio cassette/CD cases
	Polyurethane Thermoplastics	tp-PU	Cushioning, seating, shoe soles, hoses, car bumpers, insulation
	Polyvinylchloride	PVC	Pipes, gutters, window frames, packaging
	Polytetrafluoroethylene (Teflon)	PTFE	Non-stick coatings, bearings, skis, electrical insulation, tape
Thermoset	Epoxies		Adhesives, fibre composites, electronic encapsulation
	Phenolics		Electrical plugs, sockets, cookware, handles, adhesives
	Polyester		Furniture, boats, sports goods
Polymer Foams	Flexible Polymer Foam		Packaging, buoyancy, cushioning, sponges, sleeping mats
	Rigid Polymer Foam		Thermal insulation, sandwich panels, packaging, buoyancy

V.3 COMPOSITES, CERAMICS, GLASSES AND NATURAL MATERIALS

Composites		**Applications**
Metal	Aluminium/Silicon Carbide	Automotive parts, sports goods
Polymer	CFRP	Lightweight structural parts (aerospace, bike frames, sports goods, boat hulls and oars, springs)
	GFRP	Boat hulls, automotive parts, chemical plant
Ceramics		
Glasses	Borosilicate Glass	Ovenware, laboratory ware, headlights
	Glass Ceramic	Cookware, lasers, telescope mirrors
	Silica Glass	High performance windows, crucibles, high temperature applications
	Soda-Lime Glass	Windows, bottles, tubing, light bulbs, pottery glazes
Porous	Brick	Buildings
	Concrete	General civil engineering construction
	Stone	Buildings, architecture, sculpture
Technical	Alumina	Cutting tools, spark plugs, microcircuit substrates, valves
	Aluminium Nitride	Microcircuit substrates and heatsinks
	Boron Carbide	Lightweight armour, nozzles, dies, precision tool parts
	Silicon	Microcircuits, semiconductors, precision instruments, IR windows, MEMS
	Silicon Carbide	High temperature equipment, abrasive polishing grits, bearings, armour
	Silicon Nitride	Bearings, cutting tools, dies, engine parts
	Tungsten Carbide	Cutting tools, drills, abrasives
Natural		
	Bamboo	Building, scaffolding, paper, ropes, baskets, furniture
	Cork	Corks and bungs, seals, floats, packaging, flooring
	Leather	Shoes, clothing, bags, drive-belts
	Wood	Construction, flooring, doors, furniture, packaging, sports goods

VI. EQUILIBRIUM (PHASE) DIAGRAMS

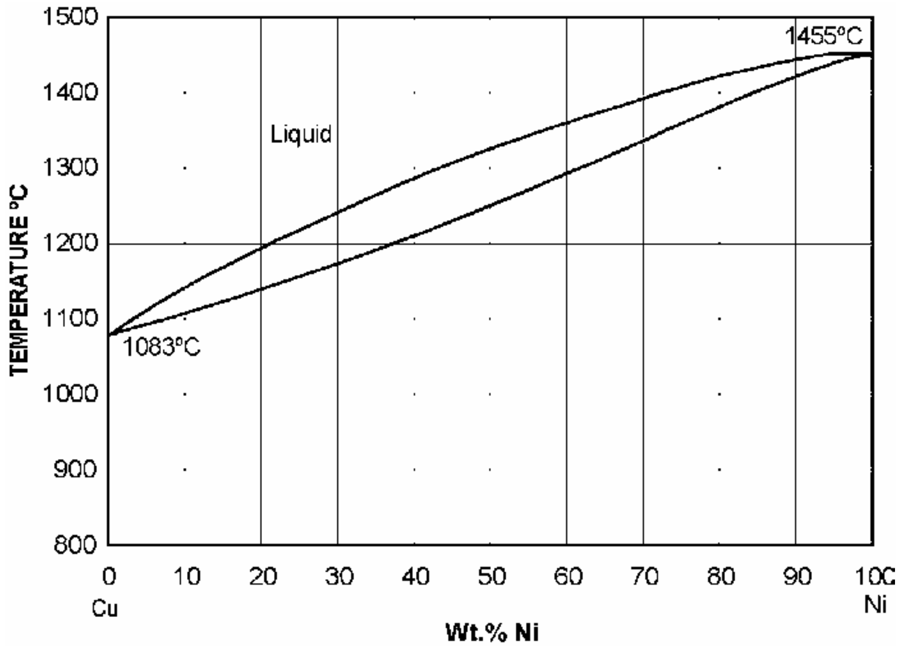

Figure 6.1 Copper – Nickel equilibrium diagram

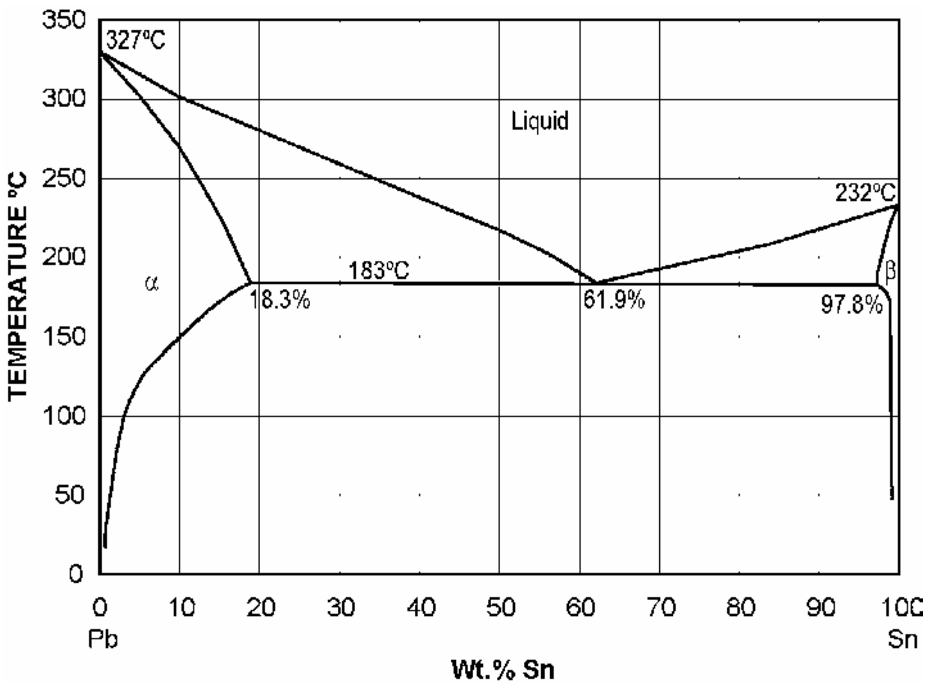

Figure 6.2 Lead – Tin equilibrium diagram

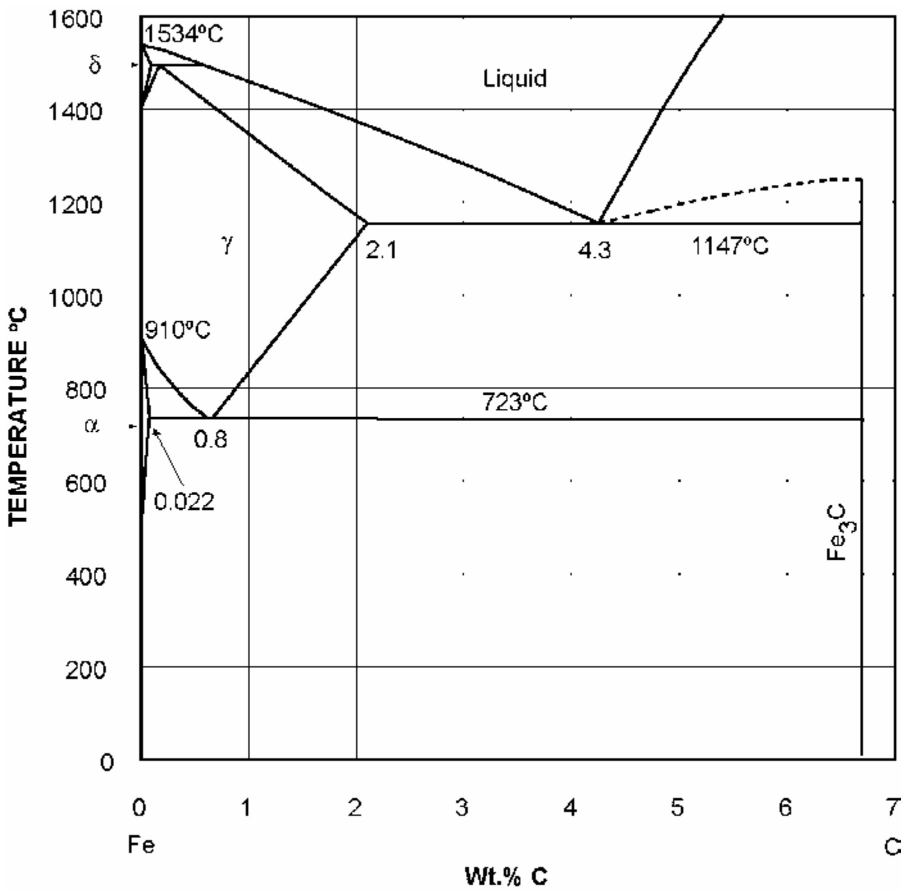

Figure 6.3 Iron – Carbon equilibrium diagram

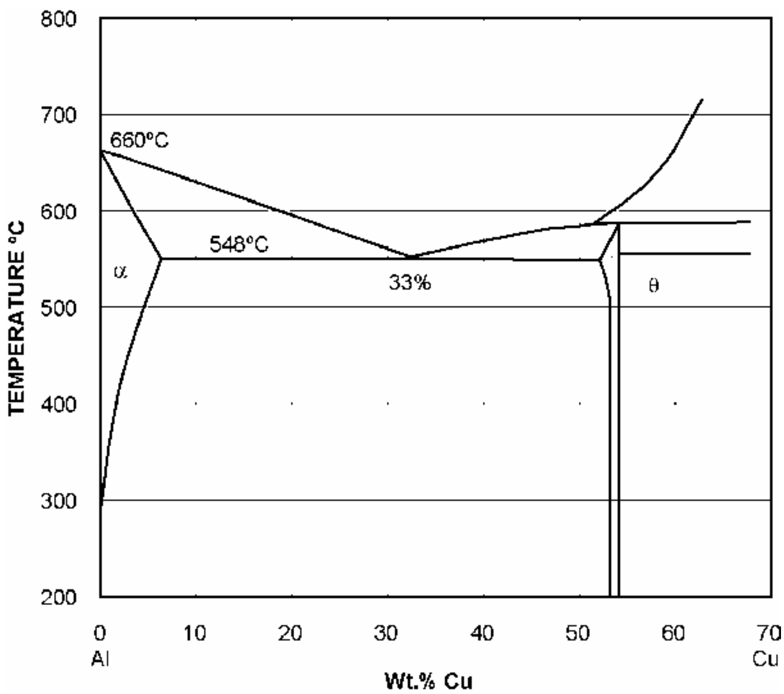

Figure 6.4 Aluminium – Copper equilibrium diagram

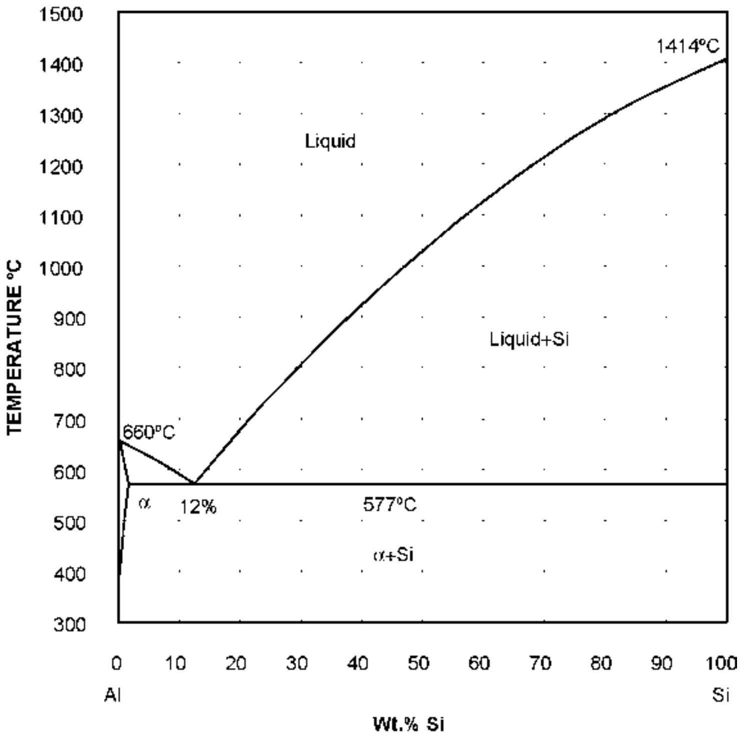

Figure 6.5 Aluminium – Silicon equilibrium diagram

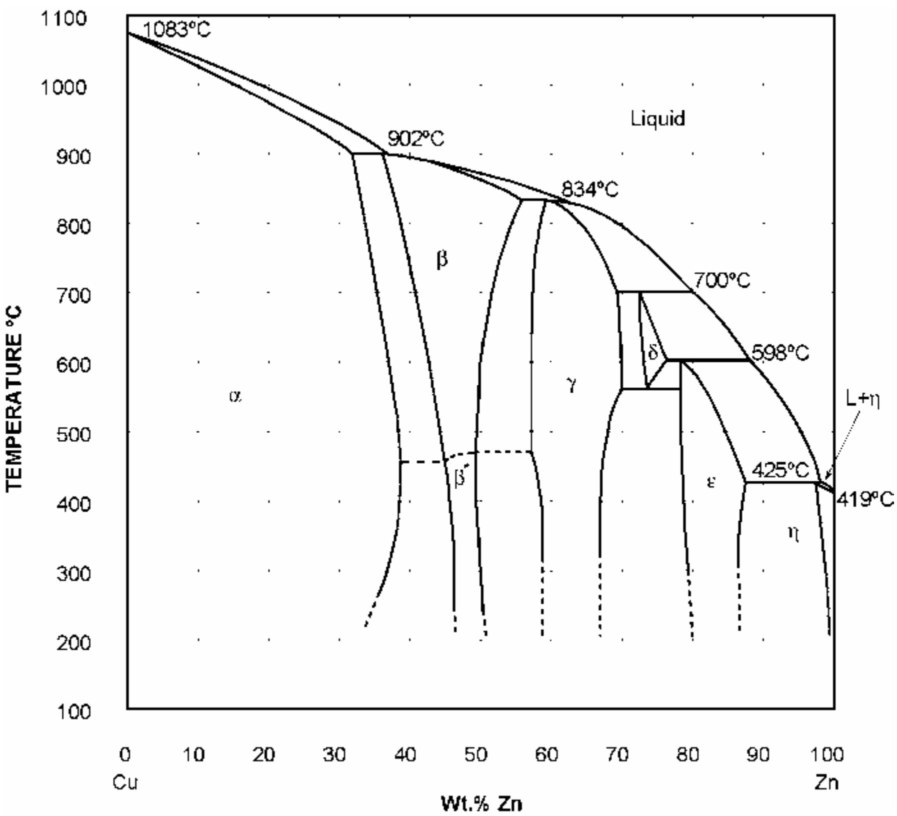

Figure 6.6 Copper – Zinc equilibrium diagram

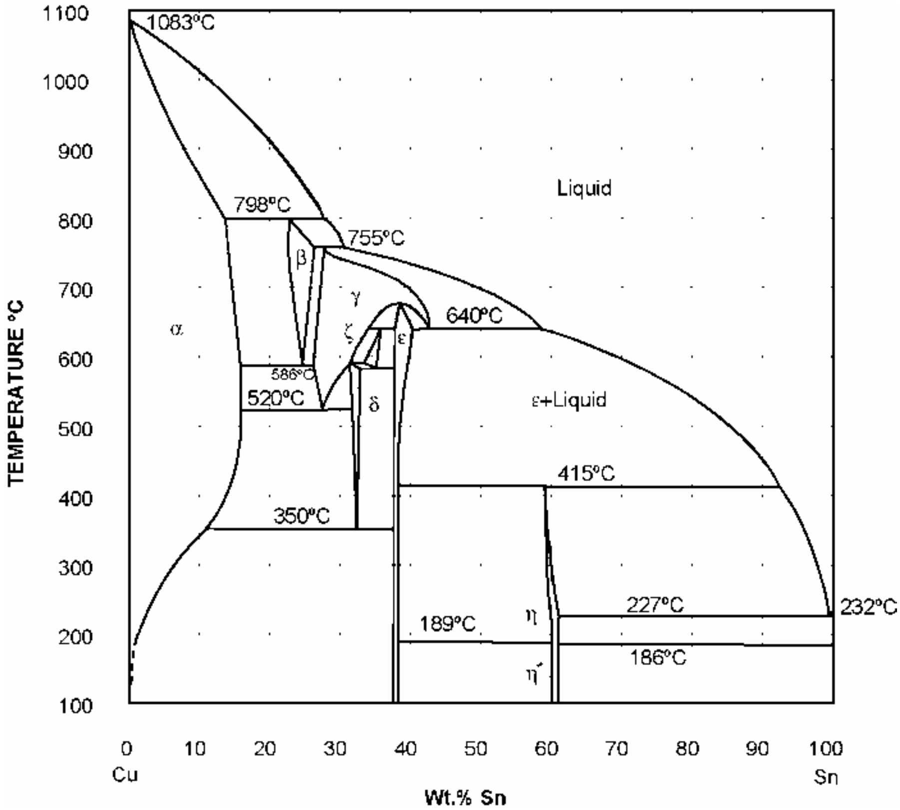

Figure 6.7 Copper – Tin equilibrium diagram

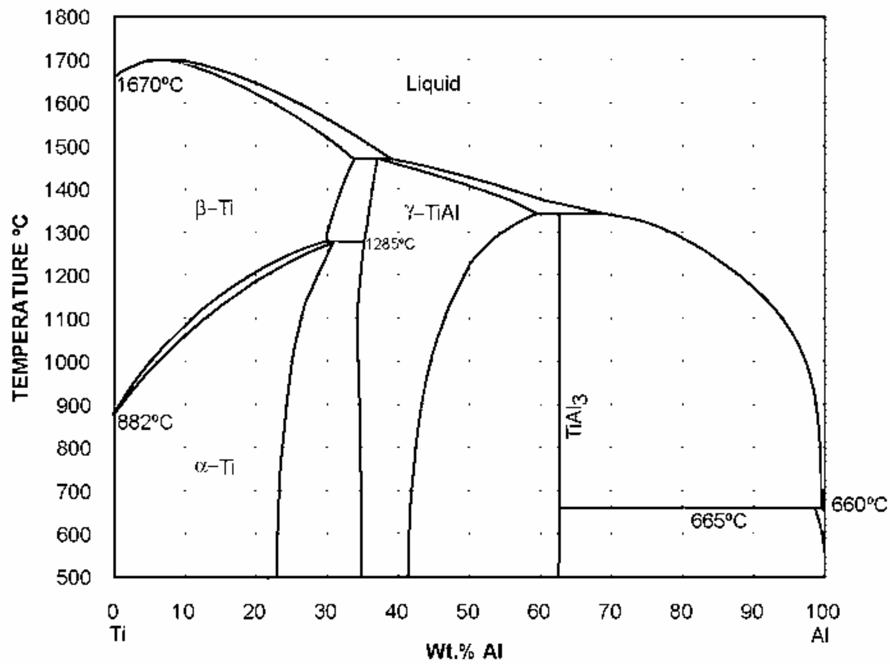

Figure 6.8 Titanium – Aluminium equilibrium diagram

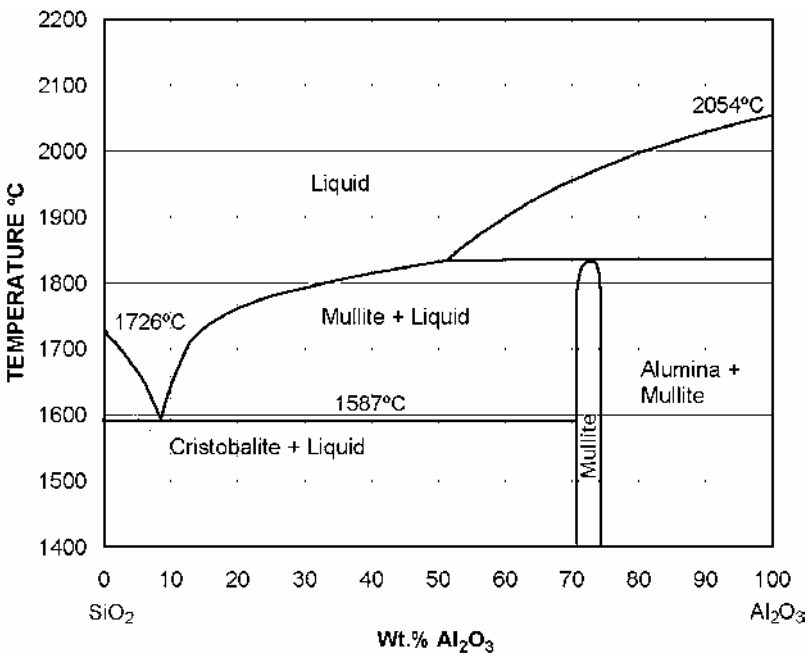

Figure 6.9 Silica – Alumina equilibrium diagram

VII. HEAT TREATMENT OF STEELS

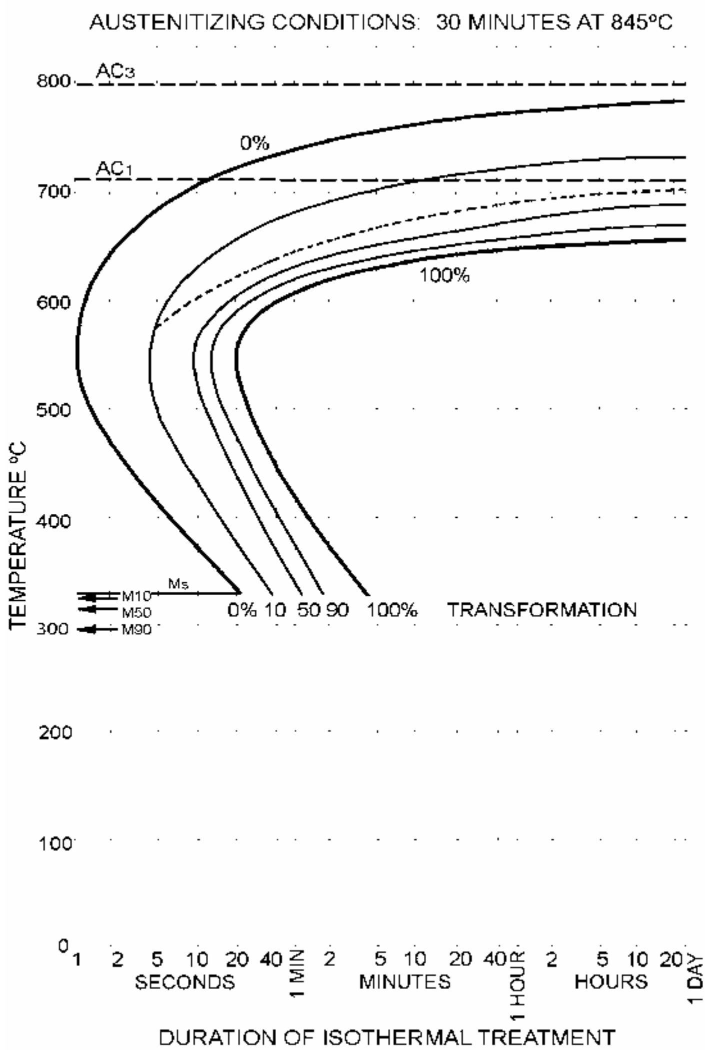

Figure 7.1 Isothermal transformation diagram for 1% nickel steel, BS503M40 (En12)

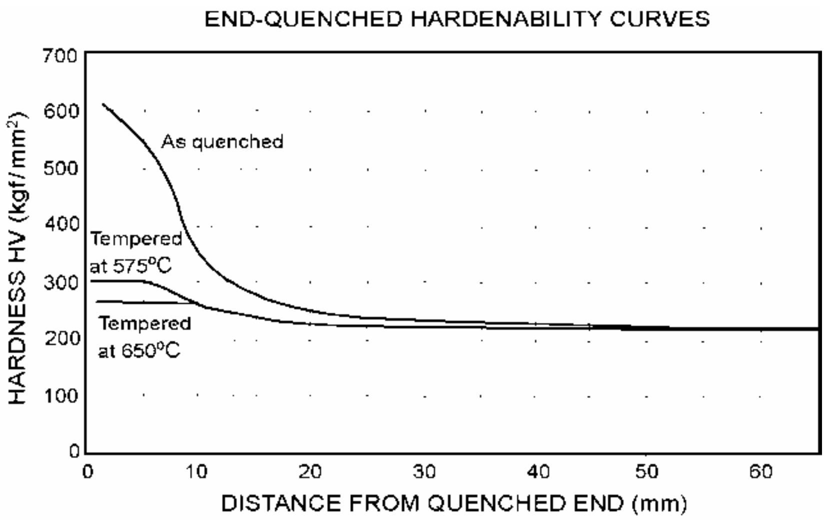

Figure 7.2 Jominy end quench curves for 1% nickel steel, BS503M40 (En12)

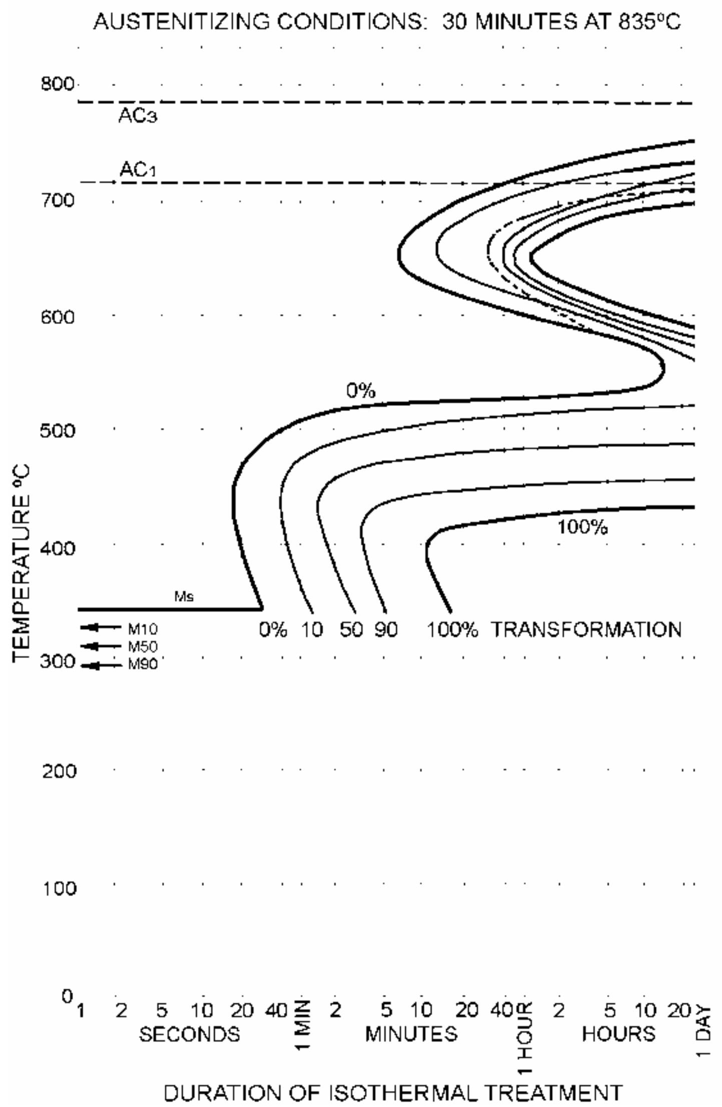

Figure 7.3 Isothermal transformation diagram for 1.5% Ni – Cr – Mo steel, BS817M40 (En24)

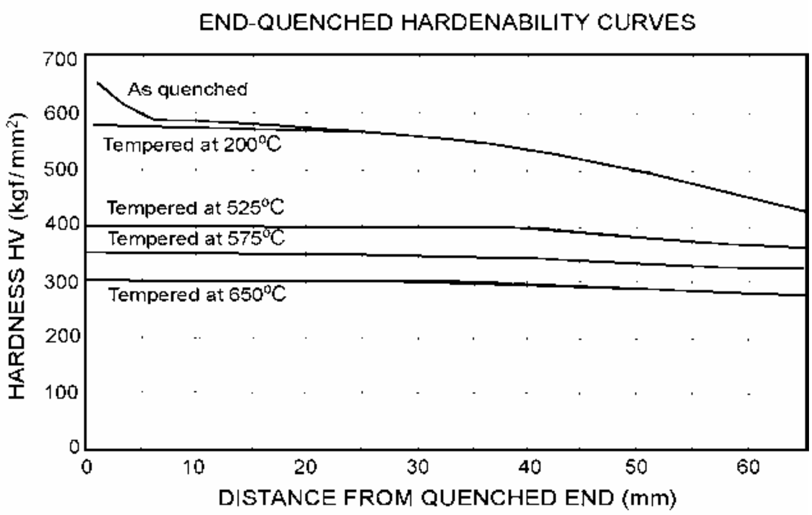

Figure 7.4 Jominy end quench curves for 1.5% Ni – Cr – Mo steel, BS817M40 (En24)

VIII. PHYSICAL PROPERTIES OF SELECTED ELEMENTS

ATOMIC PROPERTIES OF SELECTED ELEMENTS

Element	Symbol	Atomic Number	Relative Atomic Weight [1]	Melting Point (°C)	Crystal structure [2] (at 20°C)	Lattice constants [3] (at 20°C)	
						a, (b) (Å)	c (Å)
Aluminium	Al	13	26.982	660	f.c.c.	4.0496	
Beryllium	Be	4	9.012	1280	h.c.p.	2.2856	3.5843
Boron	B	5	10.811	2300	t.	8.73	5.03
Carbon	C	6	12.011	3500	hex.	2.4612	6.7079
Chlorine	Cl	17	35.453	– 101	–	–	
Chromium	Cr	24	51.996	1900	b.c.c.	2.8850	
Copper	Cu	29	63.54	1083	f.c.c.	2.5053	
Germanium	Ge	32	72.59	958	d.	5.6575	
Gold	Au	79	196.967	1063	f.c.c.	4.0786	
Hydrogen	H	1	1.008	– 259	–	–	
Iron	Fe	26	55.847	1534	b.c.c.	2.8663	
Lead	Pb	82	207.19	327	f.c.c.	4.9505	
Magnesium	Mg	12	24.312	650	h.c.p.	3.2094	5.2103
Manganese	Mn	25	54.938	1250	cub.	8.912	
Molybdenum	Mo	42	95.94	2620	b.c.c.	3.1468	
Nickel	Ni	28	58.71	1453	f.c.c.	3.5241	
Niobium	Nb	41	92.906	2420	b.c.c.	3.3007	
Nitrogen	N	7	14.007	– 210	–	–	
Oxygen	O	8	15.999	– 219	–	–	
Phosphorus	P	15	30.974	44	cub.	7.17 (at – 35°C)	
Silicon	Si	14	28.086	1414	d.	5.4305	
Silver	Ag	47	107.870	961	f.c.c.	4.0862	
Sulphur	S	16	32.064	119	f.c.orth.	10.437, (12.845)	24.369
Tin	Sn	50	118.69	232	b.c.t.	5.8313	3.1812
Titanium	Ti	22	47.90	1670	h.c.p.	2.9504	4.6833
Tungsten	W	74	183.85	3380	b.c.c.	3.1652	
Vanadium	V	23	50.942	1920	b.c.c.	3.0282	
Zinc	Zn	30	65.37	419	h.c.p.	2.6649	4.9468
Zirconium	Zr	40	91.22	1850	h.c.p.	3.2312	5.1476

[1] The values of atomic weight are those in the Report of the International Commission on Atomic Weights (1961). The unit is 1/12th of the mass of an atom of C^{12}.

[2] f.c.c. = face-centred cubic; h.c.p. = hexagonal close-packed; b.c.c. = body-centred cubic; t. = tetragonal; hex. = hexagonal; d. = diamond structure; cub. = cubic; f.c.orth. = face-centred orthorhombic; b.c.t. = body-centred tetragonal.

[3] Lattice constants are in Ångström units (1 Å = 10^{-10} m)

OXIDATION PROPERTIES OF SELECTED ELEMENTS

Standard electrode potentials (300K, molar solutions)

Oxidation reaction for solution of the metal	Normal hydrogen scale (volts)
$Mg \rightarrow Mg^{2+} + 2e^-$	– 2.36
$Al \rightarrow Al^{3+} + 3e^-$	– 1.66
$Zn \rightarrow Zn^{2+} + 2e^-$	– 0.76
$Cr \rightarrow Cr^{3+} + 3e^-$	– 0.74
$Fe \rightarrow Fe^{2+} + 2e^-$	– 0.44
$Ni \rightarrow Ni^{2+} + 2e^-$	– 0.25
$Sn \rightarrow Sn^{2+} + 2e^-$	– 0.14
$Pb \rightarrow Pb^{2+} + 2e^-$	– 0.13
$H_2 \rightarrow 2H^+ + 2e^-$	0.00
$Sn^{2+} \rightarrow Sn^{4+} + 2e^-$	+ 0.15
$Cu \rightarrow Cu^{2+} + 2e^-$	+ 0.34
$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$	+ 0.40
$Fe^{2+} \rightarrow Fe^{3+} + e^-$	+ 0.77
$Ag \rightarrow Ag^+ + e^-$	+ 0.80
$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	+ 1.23
$Au \rightarrow Au^{3+} + 3e^-$	+ 1.42

Free energy of oxidation (at 273K)

Material	Oxide	Free energy (kJ/mol O_2)
Beryllium	BeO	– 1182
Magnesium	MgO	– 1162
Aluminium	Al_2O_3	– 1045
Zirconium	ZrO_2	–1028
Titanium	TiO	– 848
Silicon	SiO_2	– 836
Niobium	Nb_2O_5	– 757
Chromium	Cr_2O_3	– 701
Zinc	ZnO	– 636
Silicon nitride	$3SiO_2 + 2N_2$	– 629
Silicon carbide	$SiO_2 + CO_2$	– 580
Molybdenum	MoO_2	– 534
Tungsten	WO_3	– 510
Iron	Fe_3O_4	– 508
Nickel	NiO	– 439
Most polymers	–	– 400
Diamond, graphite	CO_2	– 389
Lead	Pb_3O_4	– 309
Copper	CuO	– 254
GFRP	–	– 200
Silver	Ag_2O	– 5
Gold	Au_2O_3	+ 80

(Data courtesy of Granta Design Ltd)

CONVERSION OF UNITS – STRESS, PRESSURE AND ELASTIC MODULUS *

	MN/m^2 (or MPa)	lb/in^2	kgf/mm^2	bar
MN/m^2 (or MPa)	1	1.45×10^2	0.102	10
lb/in^2	6.89×10^{-3}	1	7.03×10^{-4}	6.89×10^{-2}
kgf/mm^2	9.81	1.42×10^3	1	98.1
bar	0.10	14.48	1.02×10^{-2}	1

CONVERSION OF UNITS – ENERGY *

	J	cal	eV	ft lbf
J	1	0.239	6.24×10^{18}	0.738
cal	4.19	1	2.61×10^{19}	3.09
eV	1.60×10^{-19}	3.83×10^{-20}	1	1.18×10^{-19}
ft lbf	1.36	0.324	8.46×10^{18}	1

CONVERSION OF UNITS – POWER *

	kW (kJ/s)	hp	ft lbf/s
kW (kJ/s)	1	1.34	7.38×10^2
hp	0.746	1	5.50×10^2
ft lbf/s	1.36×10^{-3}	1.82×10^{-3}	1

* To convert row unit to column unit, multiply by the number at the column-row intersection, thus 1 MN/m^2 = 10 bar