Section 12

Materials

12.1 Observing crystals: order and disorder

The common idea of a crystal is something that is geometrically regular in shape, transparent, and has lustre. While this is sometimes true it is not a good general description of a crystalline material.

All metals are crystalline. The basic reason for this is that the molecules are all attracted to each other by 'binding forces'. These forces are non-directional, giving the tendency to pull the molecules into a regular shape. Every molecule is free to choose where it goes, so it roams around until it finds a location that will make the structure neat and ordered and in which it has the least potential energy. Conceptually, the structure of a metal wants to be arranged like a neat stack of bricks, rather than a random pile. The neat stack is called a crystal.

All solids have some tendency to be crystalline but some manage it and some don't. Metals form highly regular and packed arrangements of molecules which can take forms such as body-centred cubic (bcc), face-centred cubic (fcc) and close-packed hexagonal (cph). Paradoxically, although such crystal structures are an attempt at achieving natural *order*, some metals like to crystallize around an impurity or irregularity of some sort – which you could argue is a search for *disorder*. The existence of dislocations and weakness in materials is proof that a crystal structure, ordered though it is, also contains some disorder at the same time. The science of metallurgy is about trying to improve order (because it makes materials stronger) while also finding, and understanding, the inevitable disorder.

Material properties are of great importance in all aspects of mechanical engineering. It is essential to check the up-to-date version of the relevant European Standards or equivalent when

Engineers' Data Book, Fourth Edition. Clifford Matthews.
© 2012 John Wiley & Sons, Ltd. Published 2012 by John Wiley & Sons, Ltd.

choosing or assessing a material. The most common steels in general engineering use are divided into the generic categories of carbon, low-alloy, alloy, and stainless.

12.2 Carbon steels

The effects of varying the carbon content of plain steels are broadly as shown.

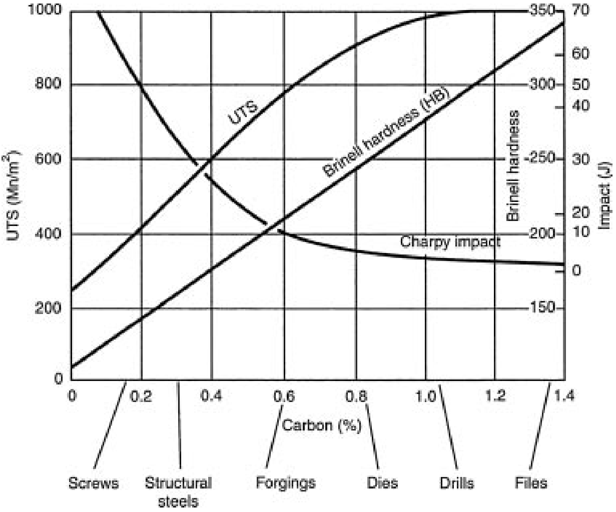

Figure 12.1

Typical properties are shown in Table 12.1.

Table 12.1

Type	*%C*	*%Mn*	*Yield, R_e (MN/m^2)*	*UTS, Rm (MN/m^2)*
Low C steel	0.1	0.35	220	320
General structural steel	0.2	1.4	350	515
Steel castings	0.3	–	270	490
Constructional steel for machine parts	0.4	0.75	480	680

USEFUL STANDARDS

1. BS EN 970: Part 1: 1997: General inspection and testing procedures and specific requirements for carbon, carbon manganese, alloy and stainless steels.
2. BS 4360 (A withdrawn standard).
3. BS EN 10027-2: 1992: Designation systems for steel – steel numbers.
4. BS EN 10025: 2004: Hot rolled products of non alloy structural steels.
5. DIN 17100: 1981: General purpose structural steels.

12.3 Low-alloy steels

Low-alloy steels have small amounts of Ni, Cr, Mn, Mo added to improve properties. Typical properties are shown in Table 12.2.

Table 12.2

Type	*%C*	*Others (%)*	R_e *(MN/m²)*	R_m *(MN/m²)*
Engine crankshafts: Ni/Mn steel	0.4	0.85Mn 1.00Ni	480	680
Ni/Cr Steel	0.3	0.5Mn 2.8Ni 1.0Cr	800	910
Gears: Ni/Cr/Mo steel	0.4	0.5Mn 1.5Ni 1.1Cr 0.3Mo	950	1050

USEFUL STANDARDS

1. BS EN 970 (See 'Carbon steels').
2. BS EN 10083-1: 2006: Technical delivery conditions for special steels.

12.4 Alloy steels

Alloy steels have a larger percentage of alloying elements (and a wider range) to provide strength and hardness properties for special applications. Typical properties are shown in Table 12.3.

Table 12.3

Type	*%C*	*Others (%)*	R_e *(MN/m²)*	R_m *(MN/m²)*
Chisels, dies C/Cr steel	0.6	0.6Mn 0.6Cr	700	870
Heavy-duty Dies	2.0	0.3Mn 12.0Cr	680	920
Extrusion dies	0.32	1.0Si 5.0Cr 1.4Mo 0.3V 1.4W	820	1020
High-speed steel Lathe tools	0.7	4.2Cr 18.0W 1.2V	950	1110
Milling cutters and drills	0.8	4.3Cr 6.5W 1.9V		
5.0Mo	970	1200		

Useful Standards

1. BS 4659: 1989: Specification for tool and die steels.
2. DIN 17201: 2005: Case hardening steels.

12.5 Cast iron (CI)

Cast irons are iron/carbon alloys that possess more than about 2%C. They are classified into specific types as shown in Figure 12.2.

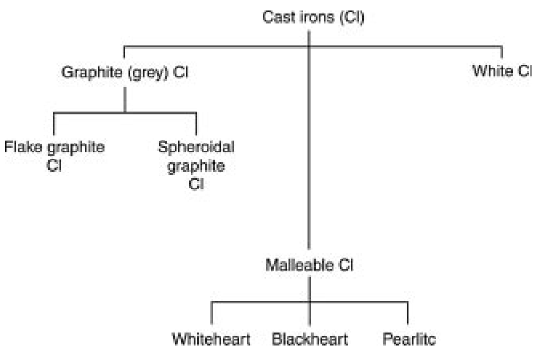

Figure 12.2

General properties and uses are varied as shown in Table 12.4.

Table 12.4

Type	*R_m (MN/m^2)*	*Elongation (%)*	*HB*
Grey CI (engine cylinders)	170–370	0.5–0.8	150–250
Nodular ferritic SG CI (piping)	350–480	6–16	115–215
Nodular pearlitic SG CI (crankshafts)	600–800	2–3	210–300
Pearlitic malleable (camshafts and gears)	450–550	3–8	140–240
'Whiteheart' CI (wheel hubs)	250–400	4–10	120–180
'Blackheart' CI (general hardware)	290–340	6–12	125–150

12.5.1 Grey CI

These types have a structure of ferrite, pearlite, and graphite, giving a grey appearance on a fractured surface. The graphite can exist as either flakes or spheres. Nodular (SG) CI is obtained by adding magnesium, which encourages the graphite to form into spheres or 'nodules'.

12.5.2 White CI

This has a structure of cementite and pearlite making it hard, brittle, and difficult to machine. Its main use is for wear-resisting components. Fracture surfaces have a light- coloured appearance.

12.5.3 Malleable CI

These are heat-treated forms of white CI to improve their ductility while maintaining the benefits of high tensile strength. There are three types:

- *Whiteheart* This is heated with an iron compound to produce a ferrite outer layer and a ferrite/pearlite core.
- *Blackheart* Soaked at high temperature to cause the cementite to break down, then slowly cooled to give ferrite and graphite.
- *Pearlite* Similar to blackheart, but faster cooling to produce a pearlite structure with higher UTS.

Useful Standards

1. BS EN 1561: 1997: Founding – Grey cast iron.
2. BS EN 1563: 1997: Founding – Spheroidal graphite cast iron.
3. BS EN 1562: 1997: Founding – Malleable cast irons.
4. DIN 1691: 1985: Lamellar graphite cast iron.
5. DIN 1693: 1997: Nodular graphite cast iron.

12.6 Stainless steels

Stainless steel is a generic term used to describe a family of steel alloys containing more than about 11 percent chromium. The family consists of four main classes, subdivided into about 100 grades and variants. The main classes are austenitic and duplex – the other two; ferritic and martensitic classes tend to have more specialized application and so are not so commonly found in general use. The basic characteristics of each class are:

- *Austenitic* The most commonly used basic grades of stainless steel are usually austenitic. They have 17–25% Cr, combined with 8–20% Ni, Mn, and other trace alloying elements which encourage the formation of austenite. They have low carbon content, which makes them weldable. They have the highest general corrosion resistance of the family of stainless steels.
- *Ferritic* Ferritic stainless steels have high chromium content (>17% Cr) coupled with medium carbon, which gives them good corrosion resistance properties rather than high strength. They normally have some Mo and Si, which encourage the ferrite to form. They are generally non-hardenable.
- *Martensitic* This is a high-carbon (up to 2% C), low-chromium (12% Cr) variant. The high carbon content can make it difficult to weld.
- *Duplex* Duplex stainless steels have a structure containing both austenitic and ferritic phases. They can have a tensile strength of up to twice that of straight austenitic stainless steels and are alloyed with various trace elements to aid corrosion resistance. In general, they are as weldable as austenitic grades but have a maximum temperature limit, because of the characteristic of their microstructure.

Table 12.5 Stainless steels – basic data

Stainless steels are commonly referred to by their AISI equivalent classification (where applicable)

AISI	*Other classifications*	*Type*[*2]	*Yield* R_e *(MPa)*	*UTS* R_m *(MPa)*	*E(%) 50 mm*	*HRB*	*%C*	*%Cr*	*% others*[*1]	*Properties*
302	ASTM A296 (cast), Wk 1.4300, 18/8, SIS 2331	Austenitic	276	621	55	85	0.15	17–19	8–10 Ni	A general purpose stainless steel
304	ASTM A296, Wk 1.4301, 18/8/LC, SIS 2333, 304S18	Austenitic	290	580	55	80	0.08	18–20	8–12 Ni	An economy grade. Not resistant to seawater
304L	ASTM A351, Wk 1.4306 18/8/ELC, SIS 2352, 304S14	Austenitic	269	552	55	79	0.03	18–20	8–12 Ni	Low C to avoid intercrystalline corrosion after welding
316	ASTM A296, Wk 1.4436 18/8/Mo, SIS 2243, 316S18	Austenitic	290	580	50	79	0.08	16–18	10–14 Ni	Addition of Mo increases corrosion resistance. Better than 304 in seawater.
316L	ASTM A351, Wk 1.4435, 18/8/Mo/ELC, 316S14, SIS 2353	Austenitic	291	559	50	79	0.03	16–18	10–14 Ni	Low C weldable variant of 316
321	ASTM A240, Wk 1.4541, 18/8/Ti, SIS 2337, 321S18	Austenitic	241	621	45	80	0.08	17–19	9–12 Ni	Variation of 304 with Ti added to improve temperature resistance.

Table 12.5 (Cont.)

Stainless steels are commonly referred to by their AISI equivalent classification (where applicable)

AISI	Other classifications	Type*2	Yield R_e (MPa)	UTS R_m (MPa)	E(%) 50 mm	HRB	%C	%Cr	% others*1	Properties
405	ASTM A240/A276/ A351, UNS 40500	Ferritic	276	483	30	81	0.08	11.5–14.5	1 Mn	A general-purpose ferritic stainless steel
430	ASTM A176/A240/ A276, UNS 43000, Wk 1.4016	Ferritic	310	517	30	83	0.12	14–18	1 Mn	Non-hardening grade with good acid-resistance
403	UNS S40300, ASTM A176/A276	Martensitic	276	517	35	82	0.15	11.5–13	0.5 Si	Turbine grade of stainless steel
410	UNS S40300, ASTM A176/A240, Wk 1.4006	Martensitic	276	517	35	82	0.15	11.5–13.5	4.5–6.5 Ni	Used for machine parts, pump shafts etc.
–	255 (Ferralium)	Duplex	650	793	25	280 HV	0.04	24–27	4.5–6.5 Ni	Better resistance to SCC than 316.
–	Avesta SAF 2507*3, UNS S32750	'Super' Duplex 40% ferrite	≃680	≃800	≃25	300 HV	0.02	25	7Ni, 4Mo, 0.3N	High strength. Max 300°C due to embrittlement

*1Main constituents only shown.
*2All austenitic grades are non-magnetic, ferritic and martensitic grades are magnetic.
*3Avesta trade mark.

12.7 Non-ferrous alloys

The term non-ferrous alloys is used for those alloy materials which do not have iron as the base element. The main ones used for mechanical engineering applications, with their tensile strength ranges are:

Nickel alloys	400–1200 MN/m^2
Zinc alloys	200–360 MN/m^2
Copper alloys	200–1100 MN/m^2
Aluminium alloys	100–500 MN/m^2
Magnesium alloys	150–340 MN/m^2
Titanium alloys	400–1500 MN/m^2

12.8 Nickel alloys

Nickel is frequently alloyed with copper or chromium and iron to produce material with high temperature and corrosion resistance. Typical types and properties are shown in Table 12.6.

Table 12.6

Alloy type	*Designation*	*Constituents (%)*	*UTS (MN/m^2)*
Ni–Cu	UNS N04400 (‘Monel’)	66Ni, 31Cu, 1Fe, 1Mn	415
Ni–Fe	‘Ni lo 36’	36Ni, 64Fe	490
Ni–Cr	‘Inconel 600’	76Ni, 15Cr, 8Fe	600
Ni–Cr	‘Inconel 625’	61Ni, 21Cr, 2Fe, 9Mo, 3Nb	800
Ni–Cr	‘Hastelloy C276’	57Ni, 15Cr, 6Fe, 1Co, 16Mo, 4W	750
Ni–Cr (age hardenable)	‘Nimonic 80A’	76Ni 20Cr	800–1200
Ni–Cr (age hardenable)	‘Inco Waspalloy’	58Ni, 19Cr, 13Co, 4Mo, 3Ti, 1Al	800–1000

Useful Standards

1. BS 3072: 1996: Specification for nickel and nickel alloys – sheet and plate.
2. BS 3073: 1996: Specification for nickel and nickel alloys – strip.
3. BS 3074: 1996: Specification for nickel and nickel alloys – seamless tube.

4. ASTM B574: 2005: Specification for low carbon nickel–chromium and other alloys.

12.9 Zinc alloys

The main use for zinc alloys is for die casting. The alloys are widely known by 'letter' designations. Typical types and properties are shown in Table 12.7.

Table 12.7

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Alloy 'A' (for die casting)	4Al, 0.05Mg, 0.03Cu	285	83
Alloy 'B' (for die casting)	4Al, 0.05Mg, 1Cu	330	92
Alloy 'ZA12' (for cold die casting)	11Al, 0.02Mg, 1Cu	400	100

Useful Standards

1. BS 1004: 1985: Specification for zinc alloys for die casting and zinc alloy die castings. Similar to ISO 301.
2. EN ISO 3815: 2005: Zinc and zinc alloys – optical emission spectrometric analysis.

12.10 Copper alloys

- Copper–zinc alloys are *brasses*
- Copper–tin alloys are *tin bronzes*
- Copper–aluminium alloys are *aluminium bronzes*
- Copper–nickel alloys are *cupronickels*

Perhaps the most common range are the brasses, which are made in several different forms.

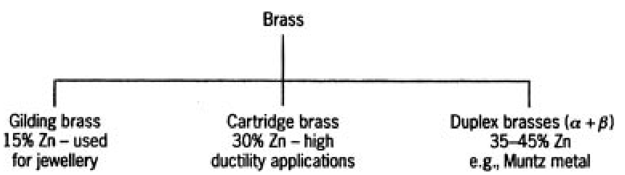

Figure 12.3

Typical types and properties of copper alloys are shown in Table 12.8.

Table 12.8

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Cartridge brass (shells)	30Zn	650	185
Tin bronze	5Sn, 0.03P	700	200
Gunmetal (marine components)	10Sn, 2Zn	300	80
Aluminium bronze (valves)	5Al	650	190
Cupronickel (heat exchanger tubes)	10Ni, 1Fe	320	155
Nickel silver (springs, cutlery)	21Zn, 15Ni	600	180

Useful Standards

There is a wide range of British Standards covering copper alloy products:

1. BS EN 1172: 1997: Copper and copper alloys – sheet and strip for building purposes.
2. BS EN 1652: 1998: Copper and copper alloys for general purposes.
3. BS 1400: 1985: Specification for copper alloy ingots, and copper alloy and high conductivity copper castings.
4. DIN 1705: 1985: Copper–tin and copper–zinc casting alloys.

12.11 Aluminium alloys

Pure aluminium is too weak to be used for anything other than corrosion-resistant linings. The pressure of relatively small percentages of impurities, however, increases significantly the strength and hardness. The mechanical properties also depend on the amount of working of the material. The basic grouping of aluminium alloys is:

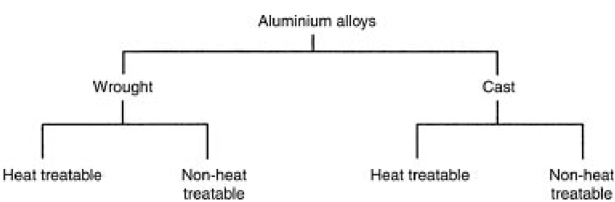

Figure 12.4

Typical alloy types and properties are shown in Table 12.9.

Table 12.9

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Duralumin (wrought, heat treatable) – aircraft components	4Cu, 0.8Mg, 0.5Si, 0.7Mn	190	45
Wrought, non-heat treated	1.25Mn	180	50
Cast, non-heat treated	12Si	185	60
Cast, heat treated	4Cu, 2Ni, 1.5Mg	275	110

Useful Standards

1. BS 1471 to 1475, e.g. BS 1471: 1972: Specification for wrought aluminium and aluminium alloys for general engineering purposes – drawn tube.
2. BS 1490: 1988: Specification for aluminium, and aluminium alloy ingots and castings for general engineering purposes. Similar to ISO 3522/ISO 7722.
3. DIN 1725: 1998: Aluminium casting alloys.

12.12 Titanium alloys

Titanium can be alloyed with aluminium, copper, manganese, molybdenum, tin, vanadium, or zirconium, producing materials which are light, strong and have high corrosion resistance. They are all expensive. Typical alloy types and properties are shown in Table 12.10.

Table 12.10

Alloy type	*Constituents (%)*	*UTS (MN/m^2)*	*HB*
Ti–Cu	2.5Cu	750	360
Ti–Al	5Al, 2Sn	880	360
Ti–Sn	11Sn, 4Mo, 2Al, 0.2Si	1300	380

Useful Standards

1. BS EN 2858-1: 1994: Titanium and titanium alloys – forging stock and forgings – technical specifications. General requirements.
2. BS EN 2808: 2007: Anodizing of titanium and titanium alloys.

12.13 Engineering plastics

Engineering plastics are widely used in engineering components and are broadly divided into three families: thermoplastics, thermosets, and composites.

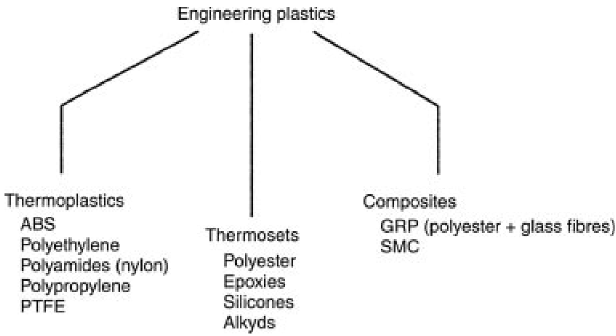

Figure 12.5

Thermoplastic polymers can be resoftened by heating whereas thermosets cannot. Most practical applications of plastic (e.g. car body components) need to use composites to achieve the necessary strength and durability. Typical properties are shown in Table 12.11.

Table 12.11

Alloy type	*UTS (MN/m^2)*	*Modulus E (GN/m^2)*
PVC	50	3.5
PTFE	14	0.3
Nylon	60	2
Polyethylene	20	0.6
GRP	Up to 180	Up to 20
Epoxies	80	8

Useful Standards

1. BS 1755: Part 1: 1982: *Glossary of terms used in the plastics industry*. This is a withdrawn standard – see ISO 472: 1979.
2. BS 3496: 1989: Specification of E glass fibre chopped strand mat for reinforcement of polyester and other liquid laminating systems.
3. BS 2872 (various parts): Methods of testing plastics.
4. BS 3502 (various parts): Symbols for plastics and rubber materials.

5. BS 4618 (various parts): Recommendations for the presentation of plastics design data.

12.14 Material traceability and documentation

Material traceability is a key aspect of the manufacture of mechanical engineering equipment. Fabricated components such as pressure vessels and cranes are subject to statutory requirements which include the need for proper material traceability.

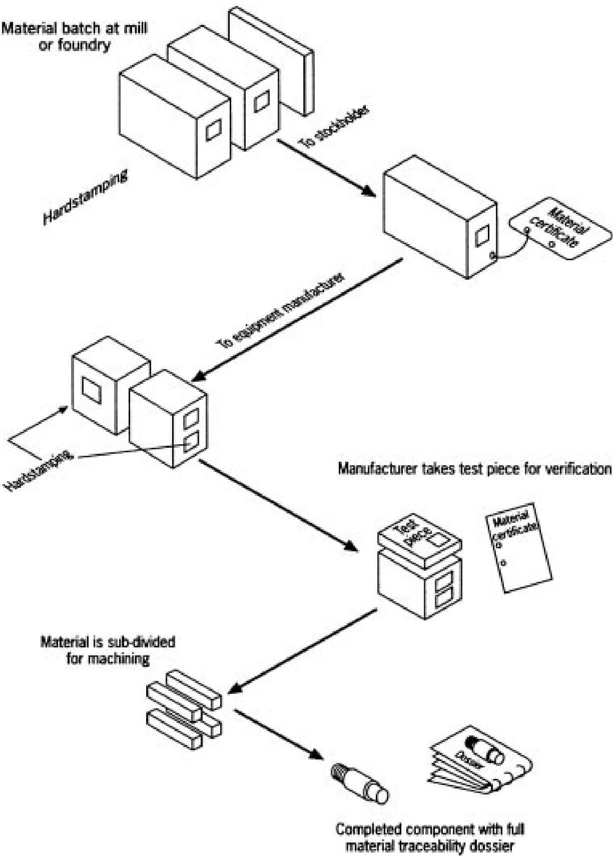

Figure 12.6

12.15 Corrosion

12.15.1 Types of corrosion

There are three basic types of corrosion:

- chemical corrosion;
- galvanic corrosion;
- electrolytic corrosion.

To complicate matters there are a variety of sub-types, some hybrids, and a few which do not fit neatly into any single category at all.

12.15.2 Chemical corrosion

This is caused by attack by chemical compounds in a material's environment. It is sometimes referred to as 'dry' corrosion or oxidation.

Examples are:

- oxidation (scaling) of iron at high temperatures;
- oxidation of nickel in sulphurous gas.

12.15.3 Galvanic corrosion

This is caused by two or more dissimilar metals in contact in the presence of a conducting electrolyte. One material becomes anodic to the other and corrodes (Fig. 12.7). Examples are:

- stainless steel trim causes anodic corrosion on carbon steel vehicle bodywork;
- defective coating of tin on carbon steel increases the corrosion rate of steel.

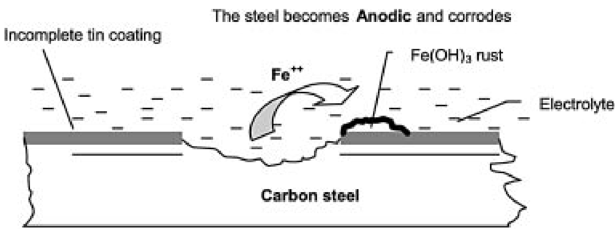

Figure 12.7

The tendency of a metal to become anodic or cathodic is governed by its position in the electrochemical series (Fig. 12.8). This is, strictly, only accurate for pure metals rather than metallic compounds and alloys.

Galvanic corrosion occurs when dissimilar metals are in contact with a conducting electrolyte. The electrochemical series shows the relative potentials of pure metals.

Gold	(Au)	**+ Volts**	
Platinum	(Pt)		
Silver	(Ag)		Noble metals **(Cathodic)**
Copper	(Cu)		
Hydrogen	(H)	**Reference potential 0 Volts**	
Lead	(Pb)		
Tin	(Sn)		
Nickel	(Ni)		
Cadmium	(Cd)		
Iron	(Fe)		
Chromium	(Cr)		Base metals **(Anodic)**
Zinc	(Zn)		
Aluminium	(Al)		
Magnesium	(Mg)		
Lithium	(Li)	**– Volts**	

Remember. Metals higher in the table become cathodic and are protected by the (anodic) metals below them in the table.

Figure 12.8 The electrochemical series

A more general guide to galvanic corrosion attack of common engineering materials is given in Figure 12.9.

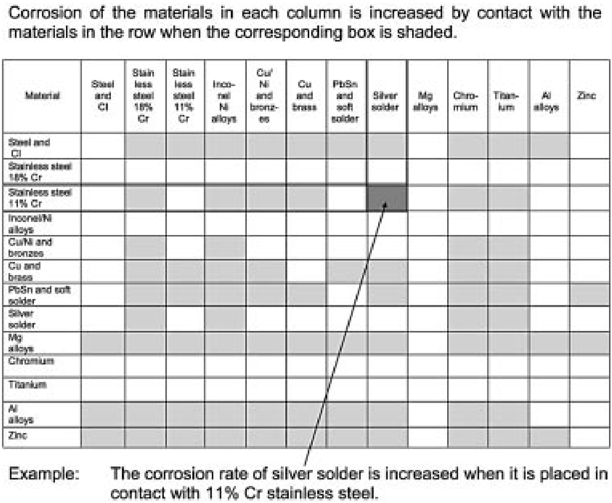

Figure 12.9 Galvanic corrosion attack – guidelines

12.15.4 Electrolytic corrosion

This is sometimes referred to as 'wet' corrosion. It is similar to galvanic corrosion in that it involves a potential difference and an electrolyte but it does not have to have dissimilar materials. The galvanic action often happens on a microscopic scale. Examples are:

- pitting of castings due to galvanic action between different parts of the crystals (which have different composition);
- corrosion of castings due to grain boundary corrosion (Fig. 12.10).

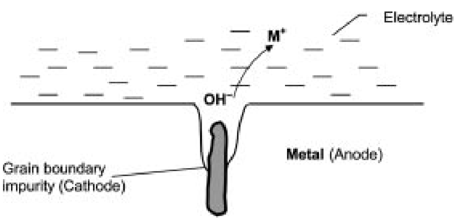

Figure 12.10

12.15.5 Crevice corrosion

This occurs between close-fitting surfaces, crevice faces, or anywhere a metal is restricted from forming a protective oxide layer (Fig. 12.11). Corrosion normally propagates in the form of pitting. Examples are:

- corrosion in crevices in seal welds;
- corrosion in lap-joints used in fabricated components and vessels.

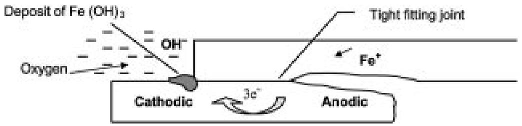

Figure 12.11

12.15.6 Stress corrosion

This is caused by a combination of corrosive environment and tensile loading. Cracks in a material's brittle surface layer propagate into the material, resulting in multiple bifurcated (branching) cracks. Examples are:

- failure in stainless steel pipes and bellows in a chloraterich environment;
- corrosion of austenitic stainless steel pressure vessels.

12.15.7 Corrosion fatigue

This is a hybrid category in which the effect of a corrosion mechanism is increased by the existence of a fatigue condition. Seawater, fresh water, and even air can reduce the fatigue life of a material.

12.15.8 Intergranular corrosion

This is a form of local anodic attack at the grain boundaries of crystals due to microscopic difference in the metal structure and composition. Examples are:

- 'weld decay' in unstabilized 18/8 austenitic stainless steels;
- 'dezincification' of brass in seawater: the selective removal of zinc from the alloy leaving behind a spongy mass of copper.

12.15.9 Erosion–corrosion

Almost any corrosion mechanism is made worse if the material is subject to simultaneous corrosion and abrasion. Abrasion removes the protective passive film that forms on the surface of many metals, thereby exposing the underlying metal. An example is:

- the walls of pipes containing fast-flowing fluids and suspended solids.