Some Data

	Mg	Al	Ti	Fe
Density / $\mathrm{g\,cm^{-3}}$	1.74	2.7	4.51	7.87
Modulus / GPa	45	70	120	210
Specific Modulus / $\mathrm{GPa\,cm^3\,g^{-1}}$	25.9	26	26	27
Melting Temperature / °C	650	660	1670	1535
Crystal Structure (300 K)	h.c.p.	c.c.p.	c.p.h.	Cubic–I
Production per annum /tonnes	5×10^5	2×10^7	5×10^5	8×10^8
Energy Cost / $\mathrm{MW\,h\,tonne^{-1}}$	??	70	130	15
Relative Cost	7.5	3.7	9	1.0

Table 1: Some properties of commercially pure metals: Polmear (Eb153); *Journal of Metals.* 54 (2002) 42–48 and *Steel World*, 2 (1997) 59.

Material	wt.%
Iron & Steel	61
Non–ferrous	9.5
Plastics	11.5
Glass	3.0
Rubber	5.0
Other	10.0
Total weight / kg	901

Table 2: The European car in 1990. Source: Automotive Consortium on Recycling and Disposal Implementation Plan, July 1994. Total weight in 1985 was 815 kg, the increase being due to the introduction of enhanced passenger protection. The cost of accidents decreased from 32516 to 29220 million ECU's from 1992 to 1995 respectively, in spite of an increase in the number of vehicles from 146 to 153 million (Source: OICA, Paris).

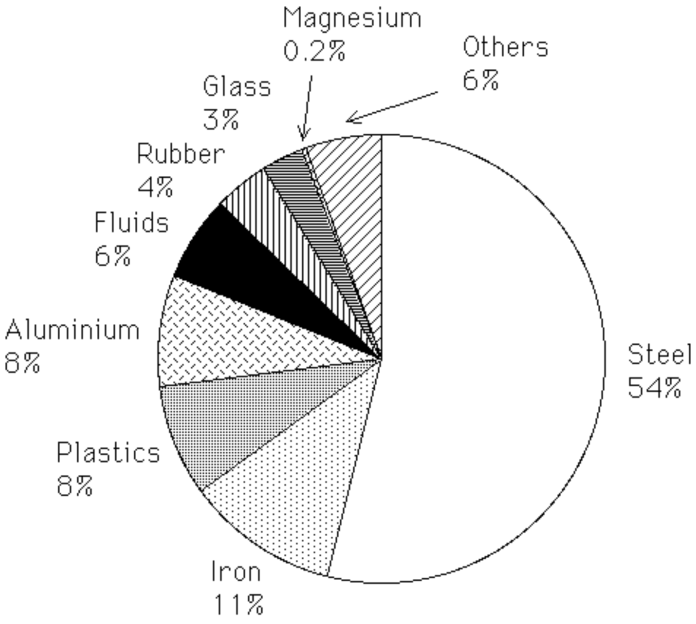

Fig. 1: Materials used in the manufacture of a typical 2000 model year family sedan in North America. Journal of Metals, 54 (2002) 42–50.

	Austin Mini 1959	BMW Mini 2001
Weight / kg	587	1050
Maximum power / bhp	37	90
Maximum speed / mph	72	115
Power/weight ratio / bhp kg^{-1}	0.063	0.086
Fuel consumption / mpg	45	42.2

Table 3: Comparison of 1959 and 2001 *Minis*. From Steel World 7 (2002) 4. Although the weight of the modern Mini is much larger than the 1959 version, its fuel consumption is almost identical and has a much higher performance. This is because of a combination of modern steels and good engineering design.

Aluminium & its Alloys

For a given weight, pure aluminium has the highest electrical conductivity at ambient temperature than any other element; its weight specific electrical conductivity is about twice that of copper. It is therefore used extensively for overhead electrical cables. However, high purity aluminium has a very low yield strength of about 7 MPa. Overhead power distribution cables are therefore reinforced with steel. Alloying can be used to strengthen the aluminium cable but this reduces the electrical conductivity because solute atoms disrupt the periodicity of the lattice. In some applications, such as electical motors, the use of aluminium windings increases the volume of the equipment, so copper is used instead.

Up to 70 wt% of zinc can dissolve in aluminium, followed by magnesium (17.4 wt%), copper (5.7 wt%) and silicon (1.65 wt%). We shall see that the addition of these elements can radically alter the properties of pure aluminium.

Typical Phase Diagrams

Typical eutectic and a peritectic phase diagrams are illustrated in Fig. 2; these two forms describe the vast majority of phase diagrams for aluminium alloys.

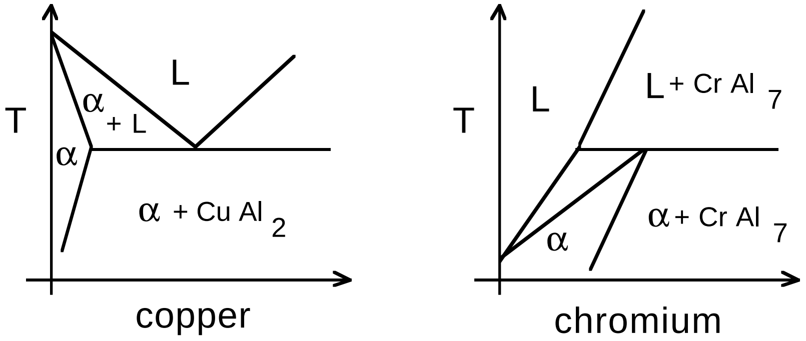

Fig. 2: Typical phase diagrams for aluminium alloys, illustrating a eutectic and peritectic form.

Since there are no allotropic phase transformations in aluminium, much of the control of microstructure and properties relies on precipitation reactions. The *solubility* of solute in the matrix (α) is therefore of importance. This solubility cannot be defined in isolation – it depends on the phase with which the α is in equilibrium with, *e.g.* Fig. 3. In the Al–Cu system, the stable precipitate is $CuAl_2$ but because it is difficult to nucleate, metastable GP1 zones form first. Thus, the free energy curve for GP1 zones is located above that for $CuAl_2$ in Fig. 3b. The common tangent construction shows that this leads to an increase in the solubility of copper in α when it is in equilibrium with GP1 zones. Another interpretation is that a greater undercooling is required before GP1 zones can precipitate.

The Al–Cu system is one in which the enthalpy of mixing, ΔH_M is positive. It follows that at low temperatures, there will be a tendency for like atoms to cluster, giving rise to a miscibility gap (Fig. 4).

$$\Delta H_M = N_a z(1-x)x\omega \qquad \text{where} \qquad \omega = \epsilon_{AA} + \epsilon_{BB} - 2\epsilon_{AB}$$

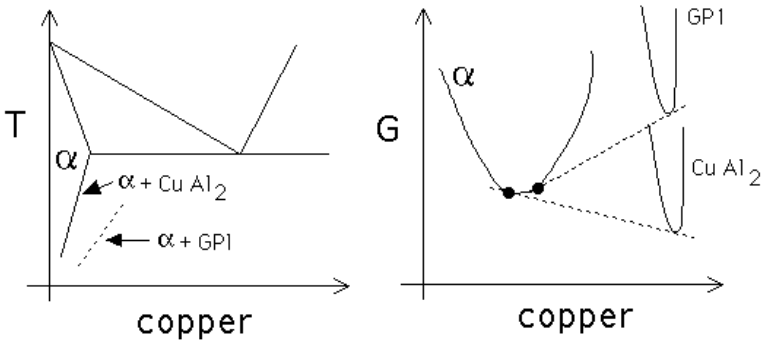

Fig. 3: (a) The solubility of solute in α is larger when it is in equilibrium with GP1 zones compared with when it is in equilibrium with $\mathrm{CuAl_2}$. (b) This can be justified using free energy diagrams.

$$\Delta G_M = N_a z(1-x)x\omega + N_a kT[(1-x)\ln\{1-x\} + x\ln\{x\}] \tag{1}$$

where x is the concentration of component B in a binary A, B solution, z is a coordination number and N_a is Avogadro's number.

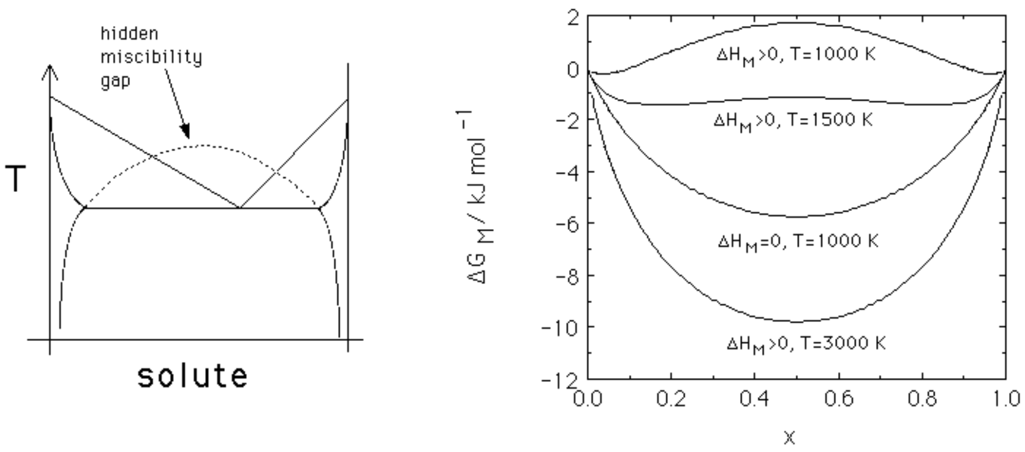

Fig. 4: (a) A eutectic phase diagram with a hidden miscibility gap. (b) Free energy of mixing plotted as a function of temperature and of the enthalpy ΔH_M of mixing. $\Delta H_M = 0$ corresponds to an ideal solution where the atoms of different species always tend to mix at random and it is always the case that $\partial\mu_A/\partial x_A > 0$. When $\Delta H_M < 0$ the atoms prefer unlike neighbours and it is always the case that $\partial\mu_A/\partial x_A > 0$. When $\Delta H_M > 0$ the atoms prefer like neighbours so for low temperatures and for certain composition ranges $\partial\mu_A/\partial x_A > 0$ giving rise to the possibility of uphill diffusion.

The miscibility gap at any temperature can be determined by the usual common tangent construction, for example to the free energy of mixing curve for 1000 or 1500 K in Fig. 4b.

Noting that the regular solution model has symmetry about $x = 0.5$, the compositions corresponding to the common tangent construction can in this special case be obtained by setting

$$\frac{\partial \Delta G_M}{\partial x} = 0$$

that is, $$N_a z(1-2x)\omega + N_a kT \ln \frac{x}{1-x} = 0$$

which in the limit of small x gives $$x = \exp\left\{-\frac{z\omega}{kT}\right\}$$

The solubility therefore changes exponentially with the reciprocal of temperature, and increases as ΔH_M tends to zero. This is illustrated for a variety of solutes in aluminium in Fig. 5. Copper has the largest solubility, *i.e.* the smallest enthalpy of solution. Solid solution strengthening is useful but it leads only to an increase of about 40 MPa in the strength of commercial alloys. But the fact that the solubility decreases exponentially with temperature can be used to precipitation harden aluminium alloys.

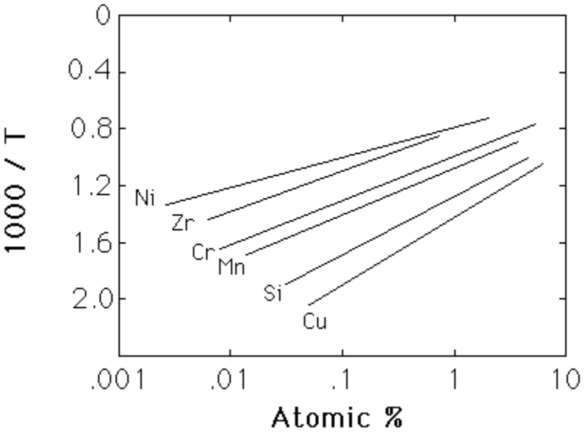

Fig. 5: Solubility of a variety of solutes in aluminium.

Precipitation

See Part IA and Part IB lecture notes covering the following key points:

(a) Age hardening involves the rapid cooling of a solid solution from a high temperature to one where it becomes supersaturated so that precipitation begins on ageing. Note that it is not just the solute concentration which is supersaturated but also the vacancy concentration.

(b) Age in a way which avoids precipitate–free zones. The latter form either due to vacancy or solute depletion in the vicinity of grain boundaries.

(c) Consider the role of metastable precipitates in the development of precipitation hardening.

Alloy Designation	Detail
1XXX	99% pure aluminium
2XXX	Cu containing alloy*
3XXX	Mn containing alloy
4XXX	Si containing alloy**
5XXX	Mg containing alloy
6XXX	Mg and Si containing alloy*
7XXX	Zn containing alloy*
8XXX	Other alloys
Heat Treatment Designation	**Detail**
F	As–fabricated
O	Annealed
H	Strain hardened
T	Heat treated
T4	Solution treated
T6	Solution treated and aged

Table 4: Standard terminology, with key alloying elements identified. The exact details can be seen with the numbers that are used to replace the XXX. * indicates precipitation hardened alloys with strength up to 600 MPa. ** indicates casting alloys covered in Part IB. The silicon–rich casting alloys are often sodium–modified. Condition T4 includes ageing at ambient temperature.

Specific Alloys

The international standard terminology used in the aluminium industry is given in Table 4.

T6 is a very common heat treatment for aircraft alloys, which after solution treatment are aged for 6–8 h at 150–170 °C to obtain the required tensile properties. It has recently been discovered that a more complex heat treatment in which the alloys are aged for a shorter time at 150–170 °C, followed by natural ageing at ambient temperatures, leads to a better combination of tensile and fatigue properties. The natural ageing presumably leads to secondary precipitation on a finer scale. (Materials World, Feb. 2004).

1XXX These alloys are used in the annealed condition and have a yield strength $\sigma_y \simeq 10\,\mathrm{MPa}$, and are used for electrical conductors, chemical equipment, foil and architecture.

3XXX These are the Al–Mn or Al–Mn–Mg alloys with moderate strength ductility and excellent corrosion resistance. The strength, at about $\sigma_y \simeq 110\,\text{MPa}$, comes from dispersoids which form in the early stages of solidification. The Mn concentration is restricted to about 1.25 wt% to avoid excessively large primary Al_6Mn particles. Magnesium (0.5 wt%) gives solid solution strengthening and the Al–Mn–Mg alloy is used in the *H* or *O* conditions. Beverage cans represent the largest single use of aluminium or magnesium. A typical alloy has the chemical composition Al–0.7Mn–0.5Mg wt%.

5XXX The magnesium concentration is usually maintained to less than 3–4 wt% in order to avoid Mg_5Al_8. The strength is in the range $\sigma_y \simeq$ 40-160 MPa with rapid work hardening during deformation. Work hardened aluminium alloys tend to soften with age because the microstructure is not stable even at ambient temperature. Therefore, it is better to excessively work harden and then to anneal to the required strength and stability. The alloys are used to make the bodies of boats or vehicles.

Dispersion Strengthened Alloys

Molten aluminium is broken up into droplets which are oxidised on their surfaces. On compaction the surface oxide breaks up into highly stable dispersoids in an aluminium matrix. There are alloys with up to 20 wt% of alumina. Other particles such as SiC can be added in large quantities – these are often called “metal matrix composites”.

Corrosion

The natural alumina film (2–10 nm thick) on aluminium protects in neutral environments but not in alkaline or in strong acids (with the exception of concentrated nitric acid which is a strong oxidising agent).

The oxide film can be thickened by immersion in hot acid to some 1–2 μm. Even thicker films (10–20 μm) can be obtained by *anodising* aluminium or zirconium. This involves making the component an anode in dilute H_2SO_4 solution. The film contains a cellular structure of open pores; they can be sealed by boiling in water which makes the cells expand by hydration. On drying the cells remain closed. The cells can be filled with dye before sealing to produce coloured aluminium.

An increase in the current density and voltage during anodising causes microscopic arcing which locally induces the oxide to fuse and solidify rapidly. With sufficient arcing, a tenacious, hard and fully dense alumina coating is formed. This *plasma electrolytic oxidation process* can be exploited in making components such as rollers, which require wear resistance.

Zinc in solid solution raises the Al–Zn electrode potential; such alloys are therefore used for cladding and as galvanic anodes for sacrificial protection.

The presence of intermetallic compounds in an aluminium alloy reduces corrosion resistance. For example, iron and silicon compounds are regions where the alumina film is weakened. As a result, pure aluminium corrodes at a much lower rate than alloys. Indeed, pure aluminium is often used to clad aluminium alloys to protect against corrosion.

Fatigue

There are two major difficulties. Coherent precipitates are cut by dislocations; each passage of a dislocation shears the particle, producing steps at the entry and exit sites, thereby reducing the particle cross–section on the slip–plane (Fig. 6). This makes it easier for a subsequent dislocation to cut the particle. Slip then tends to focus on particular planes, leading to stress concentrations which promote fatigue. It is better therefore to have a mixture of fine, coherent and bigger semi–coherent precipitates so that the danger of inhomogeneous slip is reduced.

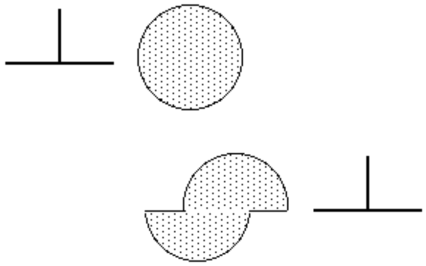

Fig. 6: The effect of a dislocation passing through a coherent precipitate.

Fatigue is also initiated at pores in thick aluminium components. This can only be controlled by careful processing, and by rolling deformation where this is permitted.