

Electronics Materials-Metals basics

Introduction

When you think of the wide range of materials available, it is very helpful to be able to group together those that have some commonality of properties. We have already considered one category, that of polymers, but there are others. Quite often books or materials will distinguish four more categories: metals, ceramics and glasses, semi-conductors and composite materials. All of these are relevant to the EDR professional:

- Metals, as the foil on a PCB, component leads, or cases
- Ceramics and glasses primarily in components
- Semiconductors, as in the active components that pack so much computer power into a small space
- Composites, as in the printed circuit board itself.

In this Unit we are looking at the first of these categories. We won't be dealing with every aspect of metals, but concentrating on those which will help you understand the teaching on topics such as board metallisation, plating and soldering.

Metallic properties

Depending on your background and interests, you might think of a car body, the frame of a building, a paper clip or the core of a piece of cable.

These demonstrate the properties that we think of as being "metallic":

- Metals are strong, but can be formed easily into useful shapes
- Their surfaces have a characteristic metallic lustre
- They are good conductors of electrical current and heat
- They can be deformed, allowing them to yield to sudden and severe loads.

The range of metallic materials covers most of the Periodic Table, with a wide range of engineering alloys, such as irons and steels, alloys of aluminium and magnesium, titanium, nickel and zinc alloys, and copper alloys including brasses (copper/zinc alloys).

But the list is wider – look at Figure 1, which shows a selection from the Periodic Table, with the elements that are inherently metallic in nature shaded in grey. Materials that we haven't mentioned so far, but which are important to the electronics industry are tantalum (capacitors), tungsten (lamps), platinum,

palladium, silver and gold (components and surface finishes), and of course tin and lead, which are used extensively in solders.

1 H Hydrogen 1.0																	2 He Helium 4.0	
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2	
11 Na Sodium 23.0	12 Mg Magnesium 24.3											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 36.0	
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe Iron 55.8	27 Co Cobalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8	
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 92.9	42 Mo Molybdenum 95.9	43 Tc Technetium 98	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3	
55 Cs Cesium 132.9	56 Ba Barium 137.4	Lanthanides 57-71		72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0

Figure 1: Periodic Table, showing metallic elements

1 For those of you who have noticed the absence of the transition elements and the transuranides, all these are also metallic!

So, what features do metals have in common?

- They have similar structural features on an atomic scale – they are crystalline, which means their constituent atoms are stacked together in a regular, repeating pattern.
- The metallic bonding² between adjacent atoms involves electron sharing, but is not directional, because the valence electrons may belong anywhere in the entire material.

2 See Atoms and bonding.

The structure of a metal

Crystalline structure

The atoms in crystals are packed together in a regular, repeating pattern, known as the space lattice: solids with no such order are said to be 'amorphous'. The unit cell is the simplest geometric figure which represents the grouping of particles: a crystal consists of a large number of these unit cells stacked together (Figure 2).

How the atoms are arranged in the solid, and which of the structures will be adopted, depends on the atomic radius of the metal or metals in the material, and the inevitable consequence of thermodynamics that systems will seek their lowest-energy state.

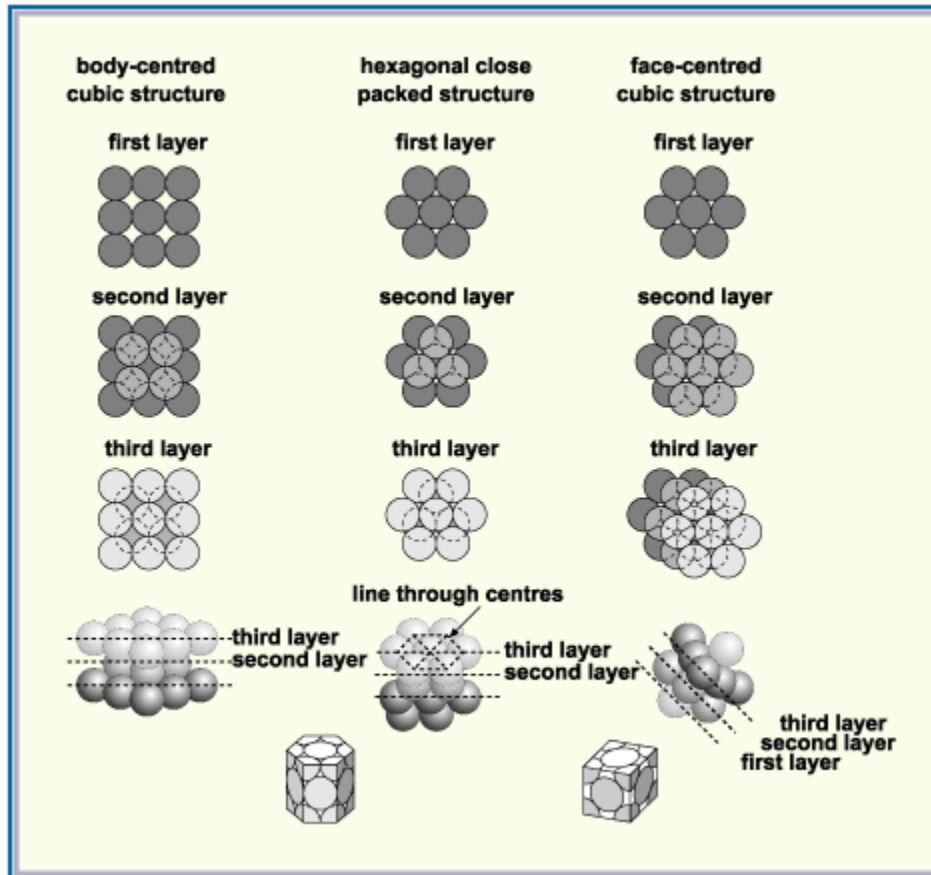


Figure 2: Common cubic crystal structures

There are many other crystal structures found in metals, but we tend to concentrate on these particular close-packed structures because they are the crystal forms found in the metals used for engineering purposes. This is because close-packed structures are linked with ductility, where materials under load start stretching before they break. This movement can be used to give early warning of potential failure, and is to be preferred to the alternative of 'brittle fracture', where there is no similar indication.

Grain structure

Metals are crystalline substances, and the term grain is used to describe the crystals within the metal. A grain lacks the regular shape and flat faces expected of a crystal because its growth was impeded by contact with other crystals, but the arrangement of particles within a grain is just as regular and repetitive as within a crystal with smooth faces. The surfaces that divide the different regions of orderly packed atoms are termed grain boundaries. Grain structure is generally not visible without etching with a chemical which preferentially attacks the grain boundaries.

A simple model of a metal is given by the raft of bubbles on the surface of a liquid (Figure 3). The bubbles pack together in an orderly and repetitive manner, but if 'growth' is started at a number of centres then grains are produced. At the boundaries between the grains, the regular pattern breaks down, as the pattern changes from the orderly pattern of one grain to that of the next.

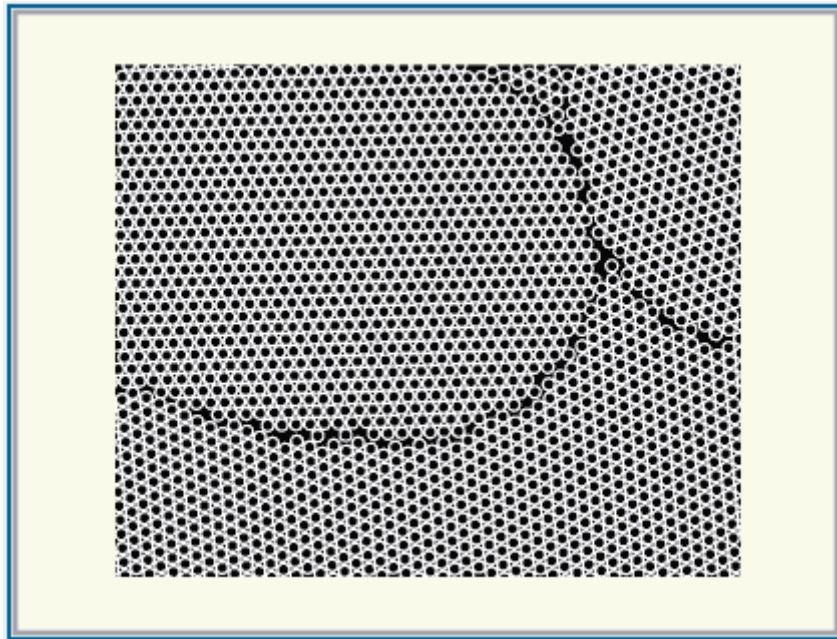


Figure 3: Grains in a bubble raft

Cooling of a liquid metal

Crystallisation occurs around small nuclei, which may be impurity particles. The first crystals have the crystal shape into which the metal would naturally solidify, for example face-centred cubic in the case of copper. However, as the crystal grows, it tends to develop spikes and its shape changes into a tree-like form called a dendrite (Figure 4).

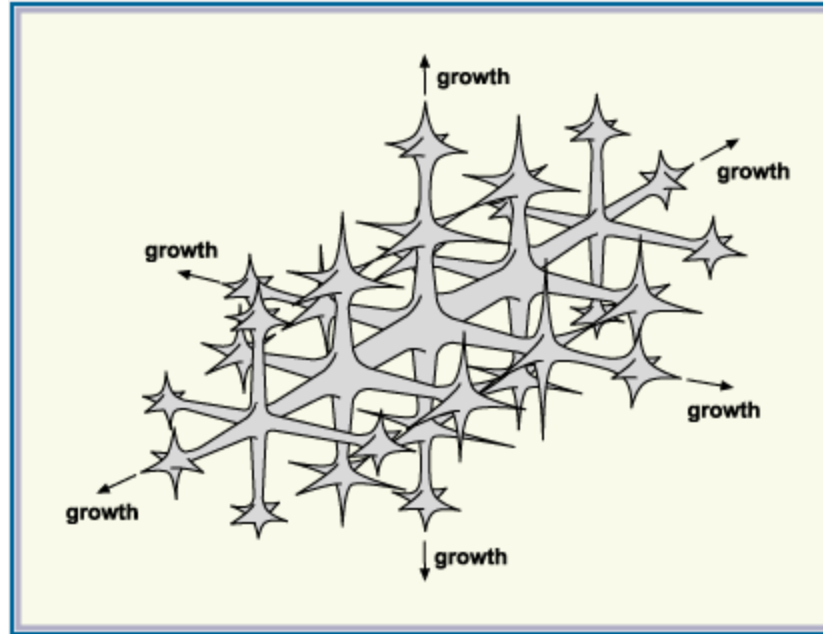


Figure 4: Growth of a metal dendrite

As the dendrite grows, the spaces between its arms fill up. Outward growth stops when growing arms meet others. Eventually the entire liquid solidifies, and there is little trace of the original dendritic structure, only the grain into which the dendrites have grown (Figure 4).

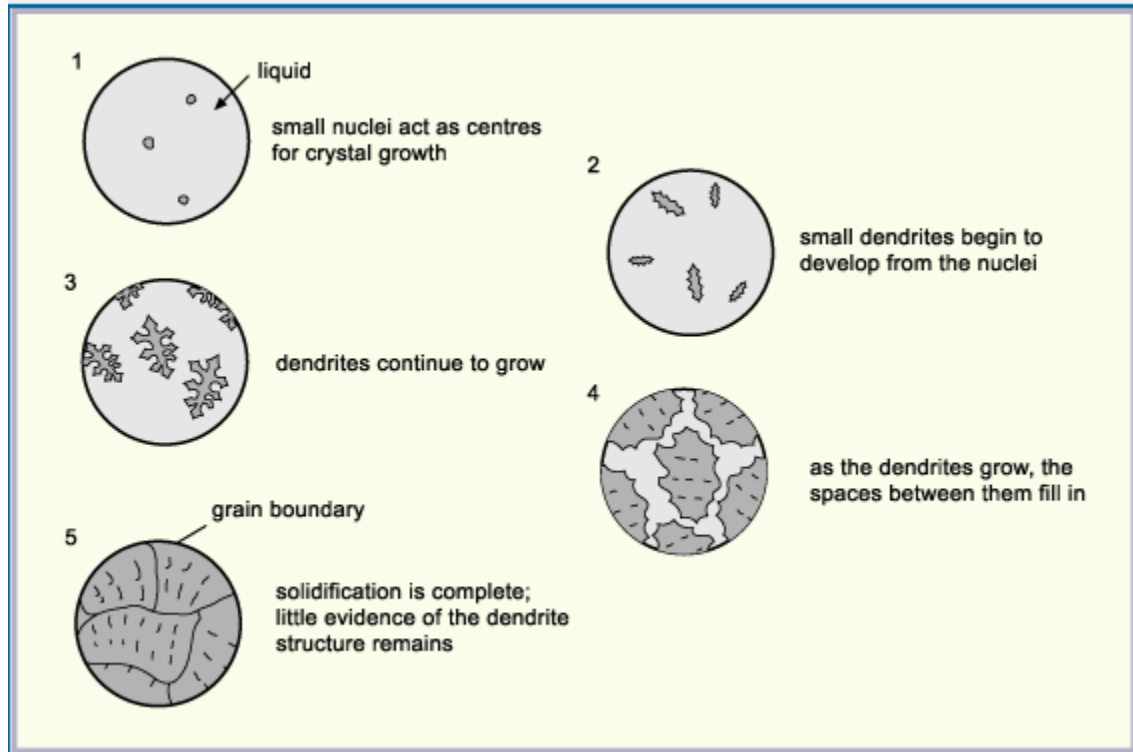


Figure 5: Solidification of a metal

Why do metals tend to grow from the melt as dendrites? 3 When a liquid at its melting point changes to a solid, the energy locked up as its 'latent heat' has to be removed: no reduction in temperature occurs during the change in state. When the liquid immediately ahead of an advancing crystal face solidifies, the energy released warms the liquid in front of it, which slows or stops further growth in that direction. Spikes develop as the crystal grows in the directions in which the liquid is coolest. As these warm up in turn, so secondary, and then tertiary, spikes develop.

3 This explanation applies specifically to pure metals. Dendritic growth also occurs in alloys, but the latent heat cause is only part of the mechanism.

Alloys

Metals have atoms from which electrons are readily released, leaving positive ions. These electrons remain as a cloud of negative charge floating between the ions, which are bonded together by their attraction to the cloud. Because there is no direct interbonding, a metallic solid can be formed from any mixture of two or more metallic elements, and it isn't necessary for the constituents to be present in fixed proportions: the result is an alloy. Where pure metals don't have the appropriate combination of properties needed, an alloy can be designed to have them. The term 'binary' alloy is used to describe one made up of just two components: a 'ternary' alloy contains three components.

The thermal equilibrium diagram

When pure water is cooled to 0°C it changes state from liquid to solid, and ice is formed. The 'cooling curve' in Figure 6 shows a plot of temperature against time: down to 0°C, the water only exists in the liquid state; at 0°C, solidification starts to occur. While this is happening, the temperature remains constant as the latent heat of fusion is lost.

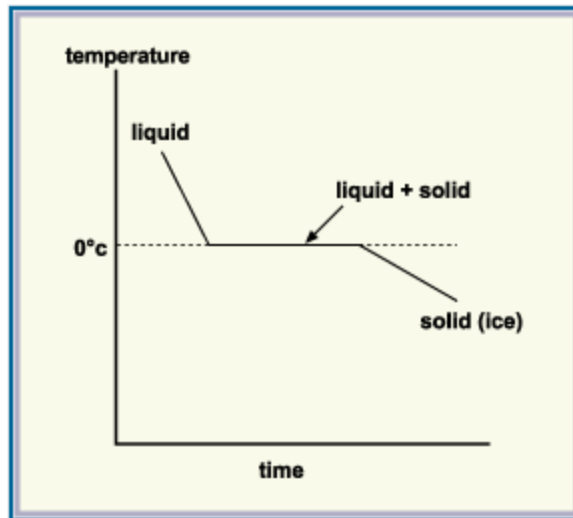


Figure 6: A cooling curve for water during solidification

All pure substances show similar behaviour: with alloys, there is no single temperature 'plateau', and the range over which solidification occurs depends on the proportions of the elements in the alloy (Figure 7). The points marked 'a' and 'b' are referred to as 'arrest points', and the temperatures at which they occur as the 'arrest temperatures'.

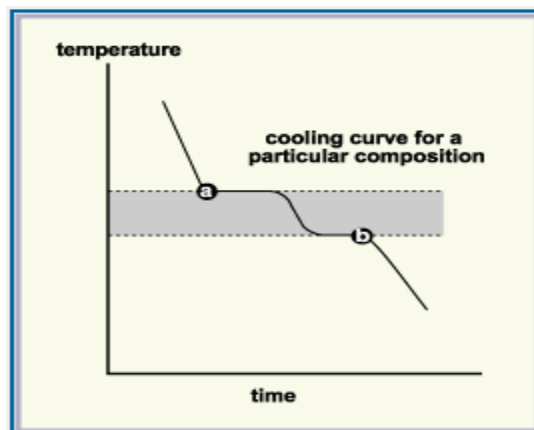


Figure 7: A cooling curve for alloys

If cooling curves are obtained for a range of alloys, a thermal equilibrium (or 'phase') diagram can be compiled. Figure 8, which is a phase diagram for tin-lead alloys, contains the results from the cooling curves for three alloys (X, Y and Z), but obviously needs to have been built up from many detailed experiments.

The diagram shows the effect that the relative proportions of the constituents have upon the temperature at which solidification starts and at which it is complete. The line drawn through the points at which each alloy in the group ceases to be liquid and starts to solidify is called the 'liquidus' line: the equivalent 'solidus' line shows where solidification is complete.

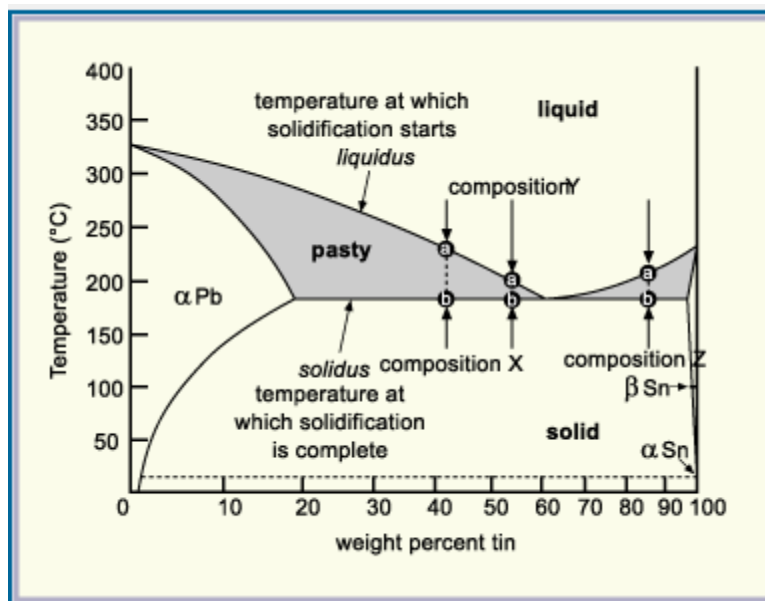


Figure 8: Phase diagram for tin-lead alloys

Cooling

When liquid metals are mixed, usually one is completely dissolved in the other, so that it is no longer possible to identify the separate constituents. When this kind of mixture solidifies from the molten state, there are four possible outcomes, depending on the elements involved and the relative sizes of their atoms.

1. The elements may combine to form a compound referred to as an 'intermediate' or 'intermetallic' compound.
2. The components may remain completely mixed in the solid state, when they are said to be soluble in each other and to form a 'solid solution'.

3. The components may separate, with each metal having its own identity and structure. Both metals crystallise at the same time, and the resulting structure has alternating laminar layers of the two metals. The components are said to be insoluble in each other in the solid state.
4. On solidifying, the metals may be soluble in each other, but only to a limited extent.

Lead and tin are among the many examples of metals which fall within the last category.

The phase diagram of Figure 8 shows that there are two solid solutions, α lead and β tin. The α lead phase has the composition 19.2% tin : 80.8% lead (the maximum amount of tin that can be dissolved in lead in the solid state), and the β tin phase has the composition 97.5% tin : 2.5% lead (the maximum amount of lead that can be dissolved in tin).

The true eutectic composition is 61.9% tin : 38.1% lead. However, when this liquid alloy is cooled to the liquidus temperature, crystals of either β tin or α lead might start to grow. In order to obtain a fully eutectic microstructure with no lead-rich primary crystallites present, the composition usually referred to as eutectic solder is slightly enhanced in tin, with the composition 63% tin: 37% lead.

As β tin crystallites are formed, the remaining liquid alloy locally becomes richer in lead. This continues until the composition reaches that of α lead, when crystals of that phase start to be produced, and the position starts to reverse, with the liquid locally becoming tin-rich. The result is a mixture of crystals of α lead and β tin. The size and arrangement of these crystals depends on the cooling conditions.

Author: Martin Tarr

Source: http://www.ami.ac.uk/courses/topics/0131_mb/index.html