ARCHAEOLOGY DATASHEET 201

Metals and their properties

The HISTORICAL METALLURGY Society

Introduction

Metals are crystalline materials that are good conductors of both electricity and heat; they are usually malleable, ductile and shiny. They are commonly divided into ferrous and non-ferrous metals; the former comprises iron and its alloys, and the latter includes all other metals. Non-ferrous metals are often divided into precious metals (gold, silver and their alloys) and base metals (all other metals). The range of properties displayed by metals has allowed their use in many applications, from currency and jewellery through tools and weapons to structural metal for buildings.

Metals as crystals

Most materials are crystalline and solid metals are no exception. In the liquid state the atoms move quite freely but if the metal cools the atoms will move more slowly until (at the melting temperature) the atoms adopt more-or-less fixed positions. These fixed positions are usually in a regularly-spaced crystal lattice. Different metals will adopt different arrangements and these can have a significant impact on the properties of the metal. There are two common crystalline arrangements: body-centred cubic (each atom is surrounded by eight neighbours) and face-centred cubic (each atoms is surrounded by six neighbours). Any piece of metal is usually made of thousands or millions of crystals; the atoms in each crystal are regularly arranged with respect to each other but each crystal has a different orientation.

Melting and boiling temperatures

Metals (with the exception of mercury) are solids at room temperature but their melting temperatures vary widely. Some metals (tin and lead) have low melting temperatures and can easily be melted in a domestic hearth. Some metals (arsenic and zinc in particular) boil at relatively low temperatures and so easily form vapours at high temperatures. Copper, silver and gold all become molten in the region of 1000°C, requiring specialised structures, tools and fuel. Iron has such a high melting point that the pure metal is rarely produced as a liquid.

Name (symbol)	Melting	Boiling
Mercury (Hg)	-39°C	357°C
Tin (Sn)	232°C	2602°C
Lead (Pb)	328°C	1749°C
Arsenic (As)	sublimes at 617°C	
Zinc (Zn)	420°C	907°C
Antimony (Sb)	631°C	1587°C
Silver (Ag)	962°C	2162°C
Gold (Au)	1064°C	2856°C
Copper (Cu)	1085°C	2927°C
Iron (Fe)	1538°C	2861°C

If a metal can be melted then it opens the possibility of producing shapes by casting in a mould. Casting has been a particularly effective forming technique for extremely complex shapes which could not be achieved through forging.

Thermal and electrical conductivities

Most metals are good conductors of both heat and electricity. Although the individual atoms are bound together in a crystal lattice, their outer electrons are able to move fairly freely and so can transport both electrical and thermal energy.

Name (symbol)	Thermal	Electrical
Mercury (Hg)	8W/mK	1.0MS/m
Antimony (Sb)	24W/mK	2.5MS/m
Lead (Pb)	35W/mK	4.8MS/m
Arsenic (As)	50W/mK	3.3MS/m
Tin (Sn)	67W/mK	9.1MS/m
Iron (Fe)	80W/mK	10MS/m
Zinc (Zn)	120W/mK	17MS/m
Gold (Au)	320W/mK	45MS/m
Copper (Cu)	400W/mK	59MS/m
Silver (Ag)	430W/mK	62MS/m

Deformation and recovery

Metals have physical properties which are quite different to most other materials and are part of the reason why they have been so widely used. Most metals display a degree of elasticity: they can be stretched or bent to a degree, and if the force is removed they will recover their original shape. This elasticity is essential in many applications, such as springs in mechanical devices. The amount of pressure, expressed as Young's Modulus (E), required to achieve the same sort of elastic deformation varies from metal to metal. The higher the Young's Modulus the stiffer the metal.

Name (symbol)	E (GPa)
Arsenic (As)	8
Lead (Pb)	16
Tin (Sn)	50
Antimony (Sb)	55
Gold (Au)	78
Silver (Ag)	83
Zinc (Zn)	108
Copper (Cu)	130
Iron (Fe)	211

If sufficient pressure is applied to a metal then it will not recover its original shape – it has been plastically deformed. At a microscopic level the shapes of the crystals have changed (they become stretched). Plastic deformation is an extremely important phenomenon which is the basis for many metal shaping techniques (forging, drawing, rolling etc). The change in shape during plastic deformation is accomplished by changes in orientation of the crystals and the creation and movement of microscopic defects or dislocations (positions within the crystal lattice where an atom is missing). High degrees of plastic deformation will produce many defects which will tend to accumulate as bands or strain lines.

Plastically deformed metals will either retain the defects and changed crystal shape and orientation, or these will disappear and the metal will recover a microstructure comparable to its original state. Recovery tends to occur spontaneously at temperatures above ~0.4 of the melting temperature (in degrees Kelvin) of the metal. Therefore, any metal with a melting temperature less than 400°C will spontaneously recover (at room temperature) while those with higher melting temperatures can be ‘work hardened’. The recovery temperature varies depending on the purity of a metal: commercial aluminium will work harden but high-purity aluminium (99.9999% Al) will spontaneously recover. Work hardening has been extensively employed to improve the tensile strength of metal objects.

Strength and hardness

The strength of a material (that is its resistance to applied force – stretching or pushing) can be measured in many different ways. The Ultimate Tensile Strength (UTS) is a measure of the maximum pressure required to break a material (under longitudinal stretching). The strength of metals depends on many different factors. Melting temperature has a strong influence on strength: those with low melting temperatures have less strength. Strength can also be affected by mechanical and/or thermal treatments (e.g. grain size, work hardening etc). The strength of alloys (see below) may be quite different from that of pure metals. UTS testing is destructive but an indication of metal strength can be gained from a Vickers Hardness (VH) test. In the VH test, a very small diamond pyramid is pressed into the metal (using a fixed load for a set time). The hardness (VH) of the metal is inversely proportional to the width of the indentation made by the pyramid.

Name (symbol)	UTS (MPa)	HV
Lead (Pb)	12–17	4
Tin (Sn)	30–35	~10
Zinc (Zn)	110–150	40
Silver (Ag)	170	25
Gold (Au)	100	22
Copper (Cu)	120–400	37
Iron (Fe)	100–200	61

Alloys and metallic compounds

Metals can usually be mixed to form new alloys or compounds. In some cases the atoms of a new metal can be accommodated within the crystalline lattice of the parent metal. These *solid solutions* can occur in any proportion from one element to the other, e.g. silver-gold. However, in most cases a parent metal crystalline lattice can only accommodate a certain proportion of a second element: at higher concentrations new phases or intermetallic compounds form with new crystalline arrangements. Metallic compounds and alloys can have subtly or dramatically different physical and chemical properties compared to the pure metals.

Metals and colour

The physical properties of metals provide numerous practical applications (casting, forging, work hardening, conduction of electrical power etc) but the inherent colours of metals have also been important. The aesthetic quality of metal colours have frequently been used in jewellery. Some Roman brooches were made of a copper alloy (brown or golden depending on the alloy) but with parts of the front plated with tin (white or silvery appearance). The colours of metals and alloys have also been used in numerous currency systems to help identify particular denominations. Roman coins included gold *aurei*, silver *denarii* and copper alloy *sestertii*, *dupondii* and *asses*. The *sestertii*, *dupondii* and *asses* were distinguished from each other by the alloys used: a golden brass for the former two and a pinky-brown copper for the latter.

Corrosion and the environment

Some metals occur naturally in the metallic state and are stable under normal conditions while others will rapidly tarnish and corrode on exposure to air. The ease with which metals will react and form compounds (by giving up some of their electrons) is often expressed by their electrode potential (E°). Metals with a high positive value are stable (and it may even be difficult to form compounds with these metals) while those with a high negative value will react spontaneously.

Name (symbol)	E° (v)
Zinc (Zn)	-0.76
Arsenic (As)	-0.68
Iron (Fe)	-0.44
Tin (Sn)	-0.14
Lead (Pb)	-0.13
Antimony (Sb)	+0.10
Copper (Cu)	+0.34
Silver (Ag)	+0.80
Mercury (Hg)	+0.85
Gold (Au)	+1.50

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