Applied Chemistry

Engineering Materials — Metallurgy and Alloys

1. Natural Occurrence of Metals — Minerals and Ores

Most metals, with the exception of a few unreactive (noble) metals such as gold and silver, are not found in a free (native) state in nature, since they readily combine with other elements such as oxygen, sulphur, and carbon to form more stable chemical compounds. These naturally occurring compounds, along with the free metals occasionally found in nature, are known as minerals.

A mineral from which a metal can be extracted conveniently and profitably, on a commercial scale, is called an ore. While every ore is a mineral, not every mineral qualifies as an ore, since some minerals contain too little of the desired metal, or extraction from them may not be economically viable.

The principal ores of iron, aluminium, and copper, which are of great engineering and industrial importance, are given below:

Metal	Principal Ore	Chemical Formula	Type
Iron	Haematite	Fe_2O_3	Oxide ore
Iron	Magnetite	Fe_3O_4	Oxide ore
Aluminium	Bauxite	$Al_2O_3.2H_2O$ (approx.)	Oxide ore (hydrated)
Aluminium	Cryolite	Na_3AlF_6	Fluoride ore (used as flux/solvent)
Copper	Copper Pyrites (Chalcopyrite)	$CuFeS_2$	Sulphide ore
Copper	Copper Glance (Chalcocite)	Cu_2S	Sulphide ore

2. Gangue (Matrix), Flux, and Slag

During the extraction of a metal from its ore, several important terms are used to describe the impurities present and the substances used to remove them:

Term	Definition
Mineral	A naturally occurring inorganic substance, of definite chemical composition and characteristic physical properties, found in the Earth's crust.

Ore	A mineral (or a mixture of minerals) from which a metal can be extracted profitably and conveniently, on a commercial scale.
Gangue (Matrix)	The unwanted earthy, rocky, or sandy impurities (such as silica, clay, or limestone) naturally associated with an ore, which must be removed during the extraction process.
Flux	A substance added during smelting that chemically combines with the gangue present in the ore, converting it into a fusible (easily melted) substance called slag, which can then be separated from the molten metal.
Slag	The fusible, low-density compound formed when the flux chemically combines with the gangue during smelting; being lighter than the molten metal, slag floats on top and can be conveniently removed.

The relationship between these terms can be summarised simply: Gangue (an unwanted impurity in the ore) + Flux (a substance deliberately added) → Slag (a fusible compound that is removed, separating the impurity from the valuable metal).

3. Metallurgy — General Principles

Metallurgy is the branch of applied science concerned with the extraction of metals from their ores and the subsequent refining, processing, and study of metals and their alloys for practical use. Although the specific method used to extract a metal depends on its reactivity and the nature of its ore, the extraction of most metals from their ores generally follows a broad sequence of steps, outlined below:

Step	Purpose
Crushing and Grinding	The mined ore is crushed and ground into small pieces or a fine powder, to increase its surface area and prepare it for subsequent concentration and chemical treatment.
Concentration (Ore Dressing)	Removal of the major bulk of gangue (unwanted earthy impurities) from the crushed ore, using suitable physical or chemical methods, to increase the percentage of the valuable mineral content before further processing.
Calcination / Roasting	The concentrated ore is heated strongly, either in the absence of air (calcination, mainly for carbonate and hydrated ores, to drive off moisture and carbon dioxide) or in the presence of excess air (roasting, mainly for sulphide ores, to convert them into oxides and drive off volatile impurities such as sulphur and arsenic).
Reduction (Smelting)	The roasted or calcined ore is heated strongly with a suitable reducing agent (such as coke) and a flux, converting the metal oxide into free molten metal, while the flux combines with the gangue to form slag, which separates from the molten metal.

Refining	The crude metal obtained after reduction, which usually still contains some impurities, is further purified using suitable methods (such as electrolytic refining) to obtain the metal in a pure or sufficiently pure form for practical use.

These general principles form the foundation for the extraction of specific metals, such as iron, aluminium, and copper, discussed in detail below, although the exact methods and conditions used at each stage vary depending on the particular metal and ore involved.

4. Extraction of Iron from Haematite Using the Blast Furnace

Iron is extracted on an industrial scale from its principal ore, haematite (Fe_2O_3), using a tall, cylindrical furnace called a blast furnace. The concentrated and roasted ore is charged into the furnace from the top, along with coke (which acts as both fuel and reducing agent) and limestone (which acts as a flux), while a continuous blast of hot air is blown in from the bottom, giving the furnace its name.

As the charge descends through the furnace, it passes through several temperature zones, and the following important reactions take place:

- Combustion of coke near the bottom of the furnace, in the hot air blast, produces carbon dioxide and a large amount of heat: $C + O_2 \rightarrow CO_2$
- The carbon dioxide formed reacts with excess hot coke to form carbon monoxide, the main reducing agent in the furnace: $CO_2 + C \rightarrow 2\ CO$
- The carbon monoxide gas reduces the iron oxide ore to metallic iron, as it rises through the furnace: $Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$
- The limestone added as flux decomposes on heating to give calcium oxide (quicklime) and carbon dioxide: $CaCO_3 \rightarrow CaO + CO_2$
- The calcium oxide then combines with the silica (SiO_2) present as gangue in the ore, forming molten calcium silicate, which is the slag: $CaO + SiO_2 \rightarrow CaSiO_3$ (slag)

The molten iron produced, being denser, collects at the bottom of the furnace, while the lighter molten slag floats above it and is tapped off (drained) separately at intervals. The molten iron itself is periodically drawn off from the very bottom of the furnace. This crude iron obtained directly from the blast furnace is called pig iron, which contains a relatively high percentage of carbon and other impurities, and is subsequently processed further (for example, in a steel-making furnace) to produce various grades of cast iron, wrought iron, or steel, suited to different engineering applications.

5. Extraction of Aluminium from Bauxite

Aluminium is extracted from its principal ore, bauxite (hydrated aluminium oxide, $Al_2O_3.2H_2O$ approximately), through two main stages: first, the purification of bauxite to obtain pure alumina (aluminium oxide), and second, the electrolytic reduction of the purified alumina to obtain metallic aluminium.

5.1 Purification of Bauxite (Bayer's Process)

Raw bauxite ore contains impurities such as iron oxide and silica, which must be removed before electrolytic extraction. In Bayer's process, powdered bauxite is treated with a hot, concentrated solution of sodium hydroxide under pressure, which dissolves the aluminium oxide present in the ore (since it is amphoteric) as soluble sodium aluminate, while insoluble impurities such as iron oxide remain undissolved and are filtered off:

- $Al_2O_3 + 2\ NaOH \rightarrow 2\ NaAlO_2 + H_2O$

The filtered sodium aluminate solution is then diluted and cooled, causing pure aluminium hydroxide to precipitate out, which is filtered, washed, and then strongly heated (calcined) to obtain pure alumina (aluminium oxide):

- $2\ Al(OH)_3 \rightarrow Al_2O_3 + 3\ H_2O$ (on strong heating)

5.2 Electrolytic Extraction of Aluminium (Hall–Héroult Process)

Since aluminium is a highly reactive metal, it cannot be extracted from its oxide by reduction with coke (as with iron); instead, pure alumina is extracted by electrolytic reduction. In the Hall–Héroult process, purified alumina is dissolved in molten cryolite (Na_3AlF_6), which serves to lower the very high melting point of pure alumina and improve the electrical conductivity of the melt, making electrolysis practical and energy-efficient.

This molten mixture is electrolysed in a steel tank lined with carbon (which also serves as the cathode), using carbon rods as the anode. During electrolysis, molten aluminium is deposited at the cathode, while oxygen gas is liberated at the carbon anode, which gradually reacts with and consumes the anode itself:

- At the cathode: $Al^{3+} + 3e^- \rightarrow Al$ (molten aluminium collects at the bottom of the cell)
- At the anode: $2\ O^{2-} \rightarrow O_2 + 4e^-$ (the oxygen released reacts with the carbon anode, forming CO and CO_2, gradually consuming the anode)

The molten aluminium collected at the bottom of the electrolytic cell is periodically tapped off, cooled, and cast into ingots for further industrial use.

6. Reactions During Copper Extraction

Copper is most commonly extracted from its principal sulphide ore, copper pyrites ($CuFeS_2$), through a sequence of concentration, roasting, smelting, and refining steps.

- The crushed ore is first concentrated by the froth flotation process, which separates the valuable sulphide mineral particles from the gangue based on differences in their surface wetting properties.
- The concentrated ore is then roasted in a controlled supply of air, which removes moisture, sulphur (partly, as sulphur dioxide gas), and other volatile impurities such as arsenic and antimony: $2\ CuFeS_2 + O_2 \rightarrow Cu_2S + 2\ FeS + SO_2$
- The roasted ore is then smelted in a furnace with silica (added as flux) and coke, where the iron sulphide present reacts with the added silica flux to form iron silicate slag, which is removed, while a molten mixture of copper(I) sulphide and iron(II) sulphide, called copper matte, is obtained: $FeS + SiO_2 \rightarrow FeSiO_3$ (slag)
- The copper matte is then transferred to a converter, where a further blast of hot air oxidises the remaining iron sulphide (removed as slag) and part of the copper sulphide to copper(I) oxide, which then reacts with the remaining copper sulphide to liberate crude, impure copper metal (called blister copper, due to the blistered appearance caused by the escape of sulphur dioxide gas trapped within it as it solidifies): $2\ Cu_2S + 3\ O_2 \rightarrow 2\ Cu_2O + 2\ SO_2$, followed by $2\ Cu_2O + Cu_2S \rightarrow 6\ Cu + SO_2$
- Finally, the impure blister copper is refined to obtain high-purity copper, most commonly by electrolytic refining, in which impure copper is made the anode and pure copper the cathode in a bath of copper sulphate solution, so that pure copper is deposited at the cathode while impurities either dissolve into solution or settle as anode mud.

7. Alloys

An alloy is defined as a homogeneous mixture (or, in some cases, a solid solution or intermetallic compound) of two or more metals, or of a metal with certain non-metallic elements, prepared by melting the constituents together and allowing them to solidify, such that the resulting material retains overall metallic properties while exhibiting characteristics that differ from those of its individual constituent elements.

7.1 Purposes of Alloying

Metals are alloyed with other elements for several important reasons:

- To increase the strength and hardness of the base metal, beyond what is achievable with the pure metal alone.
- To improve resistance to corrosion and oxidation, extending the useful working life of components made from the alloy.
- To modify other physical properties, such as melting point, electrical conductivity, ductility, or malleability, to suit specific engineering requirements.
- To reduce the overall cost of a material, in cases where a cheaper alloying element can replace part of a more expensive base metal without significantly compromising performance.
- To improve castability and ease of fabrication, making the material easier to shape, machine, or cast into finished components.

7.2 Ferrous and Non-Ferrous Alloys

Alloys are broadly classified into two categories, based on whether iron is the principal constituent:

- Ferrous alloys: Alloys in which iron is the main constituent metal, such as various types of steel and cast iron.
- Non-ferrous alloys: Alloys that do not contain iron as the main constituent, being based instead on metals such as copper, aluminium, zinc, or tin.

Examples of common ferrous and non-ferrous alloys, along with their approximate composition, properties, and typical applications, are given below:

Category	Alloy	Approximate Composition	Properties	Applications
Ferrous Alloy	Mild Steel	Iron with a small percentage of carbon (up to about 0.25%)	Moderately strong, ductile, and easily machined and welded	Structural sections, sheets, wires, general engineering components
Ferrous Alloy	Stainless Steel	Iron, chromium (about 12–20%), and nickel	Highly resistant to corrosion and rusting, strong and durable	Kitchen utensils, surgical instruments, chemical plant equipment
Ferrous Alloy	Cast Iron	Iron with a relatively high carbon content (about 2–4%)	Hard, brittle, and has good compressive	Engine blocks, pipes, machine

			strength and castability	bases, manhole covers
Non-Ferrous Alloy	Brass	Copper and zinc	Good corrosion resistance, malleable, and has an attractive golden appearance	Musical instruments, decorative fittings, electrical connectors, plumbing fittings
Non-Ferrous Alloy	Bronze	Copper and tin	Hard, resistant to corrosion (including seawater), and has good wear resistance	Statues, medals, bearings, marine fittings, bells
Non-Ferrous Alloy	Duralumin	Aluminium, copper, magnesium, and manganese	Light in weight, yet strong (comparable to some steels) and resistant to corrosion	Aircraft bodies, automobile parts, other lightweight structural applications

These examples illustrate how alloying allows engineers to tailor the mechanical, chemical, and physical properties of a base metal to suit a wide range of specific structural, mechanical, decorative, and industrial applications, making alloys indispensable materials in modern engineering practice.

8. Multiple Choice Questions (MCQs)

Answer the following questions by selecting the most appropriate option.

1. A mineral from which a metal can be extracted profitably on a commercial scale is called:

A) A flux
B) A slag
C) An ore
D) A gangue

2. The unwanted earthy or rocky impurities naturally present in an ore are called:

A) Flux
B) Gangue (matrix)
C) Slag
D) Alloy

3. A substance added to an ore during smelting to remove gangue by forming a fusible compound is called:

A) Ore
B) Mineral
C) Flux
D) Alloy

4. The fusible compound formed by the chemical combination of flux and gangue during smelting is called:

A) Ore
B) Slag
C) Matte
D) Mineral

5. Haematite, the principal ore of iron, has the chemical formula:

A) Fe_3O_4
B) Fe_2O_3
C) $FeCO_3$
D) FeS_2

6. Bauxite, the principal ore of aluminium, is mainly composed of:

A) Aluminium sulphide
B) Hydrated aluminium oxide
C) Aluminium carbonate
D) Aluminium chloride

7. Copper pyrites, an important ore of copper, has the chemical formula:

A) Cu_2O
B) $CuFeS_2$
C) $CuCO_3$
D) $CuSO_4$

8. In a blast furnace used for the extraction of iron, the reducing agent used is:

A) Limestone
B) Coke
C) Silica
D) Cryolite

9. In the blast furnace, limestone is added mainly to act as:

A) A reducing agent
B) A flux, to remove silica (gangue) as slag
C) A fuel
D) An oxidising agent

10. The main product obtained from the bottom of a blast furnace, apart from slag, is:

A) Pure iron
B) Pig iron (crude iron)
C) Stainless steel
D) Cast iron directly ready for use

11. Bauxite ore is first purified by which process before electrolytic extraction of aluminium?

A) Hall-Héroult process
B) Bayer's process
C) Bessemer process
D) Froth flotation only

12. In the Hall-Héroult process, molten cryolite is used mainly to:

A) Increase the melting point of alumina
B) Lower the melting point of alumina and improve conductivity
C) Act as the reducing agent
D) Remove sulphur impurities

13. Aluminium is extracted from purified alumina mainly by:

A) Roasting in air
B) Electrolytic reduction (Hall-Héroult process)
C) Heating with coke in a blast furnace
D) Simple heating alone

14. In the extraction of copper from copper pyrites, roasting is carried out mainly to remove:

A) Water of crystallisation
B) Sulphur, as sulphur dioxide gas
C) Aluminium impurities
D) Carbon dioxide

15. The final step in refining crude (blister) copper to obtain high-purity copper is generally carried out by:

A) Roasting again
B) Electrolytic refining
C) Calcination
D) Simple filtration

16. An alloy is best defined as:

A) A pure metal in its natural state
B) A homogeneous mixture of two or more metals (or a metal and a non-metal) with metallic properties
C) An ore of a metal
D) A type of flux used in metallurgy

17. One of the main purposes of alloying a metal is to:

A) Reduce its cost to zero

B) Improve properties such as strength, hardness, or corrosion resistance

C) Convert it back into its ore

D) Make it magnetic in all cases

18. Stainless steel is an example of:

A) A non-ferrous alloy

B) A ferrous alloy

C) A pure metal

D) An ore

19. Brass, an alloy of copper and zinc, is classified as:

A) A ferrous alloy

B) A non-ferrous alloy

C) An ore of copper

D) A flux

20. Duralumin, valued for its light weight and strength, is mainly used in:

A) Kitchen utensils only

B) Aircraft and automobile body construction

C) Electrical wiring exclusively

D) Jewellery making

Answer Key

1. C) An ore | 2. B) Gangue (matrix) | 3. C) Flux | 4. B) Slag | 5. B) Fe2O3 | 6. B) Hydrated aluminium oxide | 7. B) CuFeS2 | 8. B) Coke | 9. B) A flux, to remove silica (gangue) as slag | 10. B) Pig iron (crude iron) | 11. B) Bayer's process | 12. B) Lower the melting point of alumina and improve conductivity | 13. B) Electrolytic reduction (Hall-Héroult process) | 14. B) Sulphur, as sulphur dioxide gas | 15. B) Electrolytic refining | 16. B) A homogeneous mixture of two or more metals (or a metal and a non-metal) with metallic properties | 17. B) Improve properties such as strength, hardness, or corrosion resistance | 18. B) A ferrous alloy | 19. B) A non-ferrous alloy | 20. B) Aircraft and automobile body construction

9. Broad / Long Answer Questions

1. Define mineral and ore, and explain the difference between the two terms.

2. Define gangue, flux, and slag, and explain the relationship between them during the process of smelting.

3. Describe the general principles (main steps) involved in the metallurgy of a metal, from ore to refined metal.

4. Describe the construction and working of a blast furnace used for the extraction of iron from haematite ore, giving the important chemical reactions involved.

5. Explain the role of limestone as a flux in the blast furnace process, giving the relevant chemical reaction.

6. Describe the extraction of aluminium from bauxite, explaining briefly the purification of bauxite (Bayer's process) and the electrolytic extraction of aluminium (Hall-Héroult process), along with the relevant reactions.

7. Describe the main steps and reactions involved in the extraction of copper from copper pyrites ore.

8. Define an alloy, and explain the main purposes of alloying a metal.

9. Distinguish between ferrous and non-ferrous alloys, giving two examples of each along with their composition, properties, and applications.

10. Explain, with examples, how the properties of a metal can be significantly modified by alloying, referring to at least two specific alloys and the property each is valued for.