UMP OPEN COURSEWARE

Universiti Malaysia PAHANG
Engineering • Technology • Creativity

BFF1113 Engineering Materials

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Course Guidelines:

1. Introduction to Engineering Materials
2. Bonding and Properties
3. Crystal Structures & Properties
4. Imperfection in Solids
5. Mechanical Properties of Materials
6. Physical Properties of Materials
7. Failure & Fundamental of Fracture
8. Metal Alloys
9. Phase Diagram
10. Phase Transformation – Heat Treatment
11. Processing and Application of Metals
12. Ceramic Materials
13. Polymer Materials
14. Composite Materials
15. Corrosion & Degradation of Materials
16. Environment and Sustainability

METAL

1. **INTRODUCTION TO METALS & ALLOYS : GENERAL PROPERTIES & APPLICATIONS**
2. PHASE DIAGRAM
3. FABRICATION & THERMAL PROCESSES OF METALS

By the end of this lecture..

- *You should be able to state examples of ferrous and non-ferrous metal.*

- *You should be able to differentiate between low and high carbon steel and cast iron.*

- *You should be able to state the properties of 4 non-ferrous alloys; Mg, Cu, Ti and Al and relate the properties to suitable applications of these metals*

YOU SHOULD KNOW….

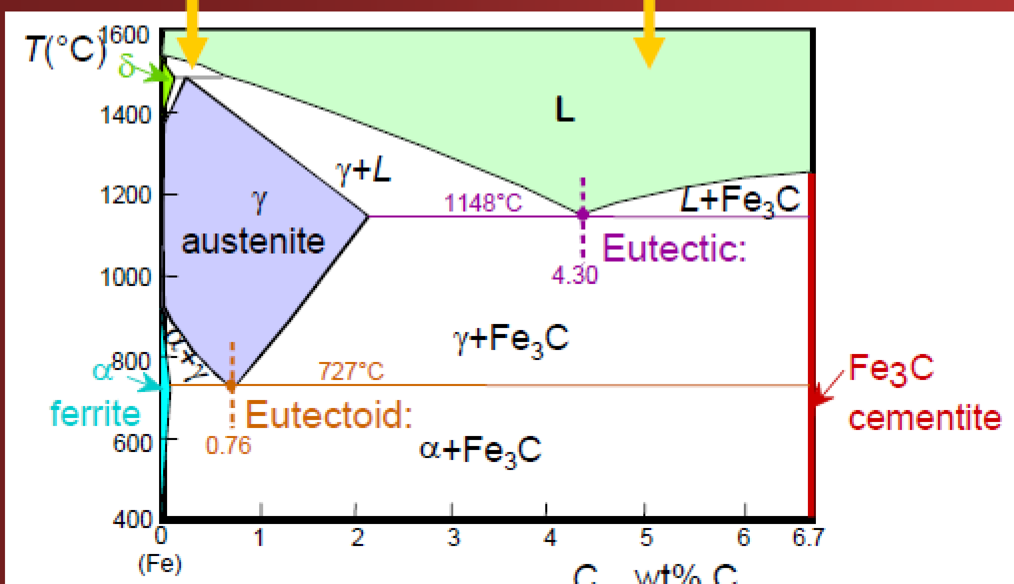
- **METAL** can be alloyed and heat treated to get desired mechanical properties.

- An **alloy** is composed of two or more chemical elements, at least one of which is a **metal.**

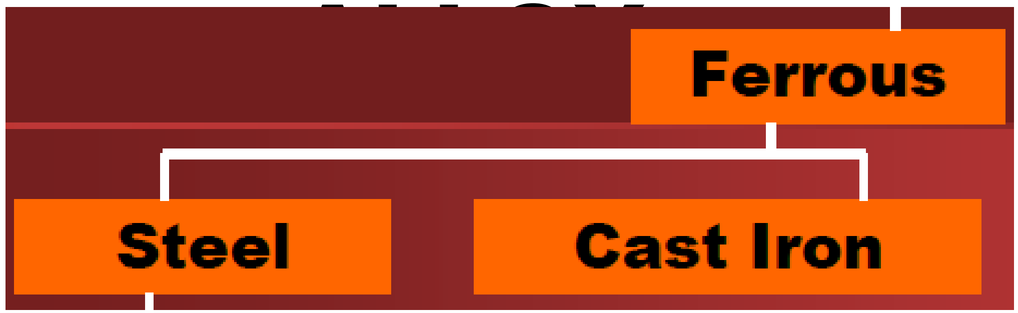
- **Heat treatment** is a process of heating and cooling a metal to achieve specific microstructure which in turns display specific mechanical properties (e.g. Quenching austenite gives martensite which can be heat treated to produce tempered martensite which is more ductile.

Metal Alloys

- **Ferrous**
  - **Steel**
    - **Low Alloy**
    - **High Alloy**
  - **Cast Iron**
- **Non Ferrous**
  - **Cu**
  - **Mg**
  - **Al**
  - **Ti**



FERROUS METAL



- **Ferrous metals and alloys** contain iron as their base metal and are classified as *carbon and alloy steels*, *stainless steels*, *tool and die steels*, and *cast irons*.

- Ferrous alloys are produced as *Sheet steel, Plates, Structural members, Tools, dies, and molds, Rods and wire.*

- Important as engineering construction material (especially steel Fe-C) with the criteria of :
  - –Abundant within the earth-crust –low cost
  - –Easy to be produced
  - –Good strength toughness and ductility
  - –Versatile –wide range of mechanical and physical properties

Carbon Steels are iron-carbon alloys.

Carbon steels are classified by their proportion of carbon content:

1. **Low-carbon steel**, also called **mild steel**, has less than 0.30% C
2. **Medium-carbon steel** has 0.30 to 0.60% C
3. **High-carbon steel** has more than 0.60% C

- Carbon steels containing sulfur and phosphorus are known as **resulfurized** carbon steels and **rephosphorized** carbon steels

4. **Stainless steels** are characterized to have high corrosion resistance, high strength and ductility and high **chromium** content

Low Carbon Steel

- Alloys of low carbon steel being produced in the greatest quantity.
- < 0.25wt %C.
- Consists of ferrites and pearlites hence soft and weak but can be treated to achieve high strength.
- Machinable, weldable and cheap to be produced
- Types:

– i. plain low carbon steel - no alloying, variable tensile strength (TS) (415-550MPa) and Yield Strength (YS)= 275MPa

Applications ––crankshafts, bolts, hammers, hand tools, gears, knives

– ii. High strength low alloy (HSLA) – with alloying, higher TS and YS

- ✓ Applications ––nails, wire, pipe structural and sheet steel, railway cars

Medium Carbon Steel

- 0.25 –0.6 wt %C
- Heat treated to achieve good mechanical properties
- Used in tampered condition (tampered martinsitic)
- Strength --ductility combination can be tailored by heat treatment and alloying (with Ni, Cr and Mo)

High Carbon Steel

- 0.6 –1.4 wt %C
- Hardest, strongest and least ductile carbon steel.
- Used in harden and tempered conditions.
- Can be alloyed with carbon and other metals to form vary hard and wear resistance material (e.g. C, Cr, Ni, W, Mo and V).

Applications: cutting tools, drills, saws, embossing dies, cutlery, paper cutters, concrete drill, blacksmith tools.

Stainless-Steels

- Highly resistance alloy to corrosion (rusting) in a variety of environment. Mechanical integrity maintains.
- Consisting of iron-carbon and chromium (> 11 wt% Cr needed)
- Add nickel and molybdenum as well
- Example 0.08 C, 11.0 Cr, 1.Mn, 0.50 Ni, 0.75 Ti : S409
- Examples of use of stainless:

Tool & Die Steels

Tool and die steels are alloyed steels for high strength, impact toughness, and wear

Basic Types of Tool and Die Steels

Type	AISI
High speed	M (molybdenum base) T (tungsten base)
Hot work	H1 to H19 (chromium base) H20 to H39 (tungsten base) H40 to H59 (molybdenum base)
Cold work	D (high carbon, high chromium) A (medium alloy, air hardening) O (oil hardening)
Shock resisting	S
Mold steels	P1 to P19 (low carbon) P20 to P39 (others)
Special purpose	L (low alloy) F (carbon–tungsten)
Water hardening	W

- Maintain hardness and strength at elevated operating temperatures
- High speed types:
  1. **Molybdenum type** (M-series)
     - higher abrasion resistance
     - less distortion in heat treatment
     - less expensive
  2. **Tungsten type** (T-series)
- **Hot-work steels** (H-series) are for use at elevated temperatures
- High toughness and high resistance to wear and cracking
- **Cold-work steels** (A-, D-, and O-series) are used for cold-working operations
- **Shock-resisting steels** (S-series) are for impact toughness

Cast Irons

Cast iron refers to a family of ferrous alloys composed of **iron, carbon and silicon**

- 3.0 –4.5 wt % C
- Liquid at 1150 –1300^{o}C
- Easily melted and amenable to casting

Classified according to their solidification morphology from the *eutectic temperature*:

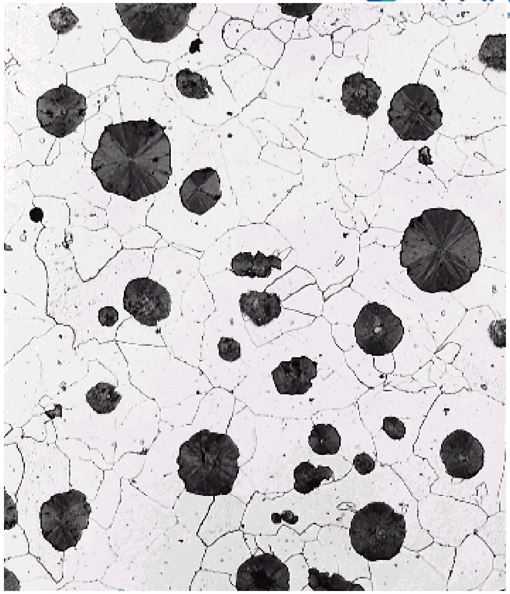
1. ***Gray cast iron***
2. ***Ductile cast iron***
3. ***White cast iron***
4. ***Malleable iron***

GRAY CAST IRON

- ✓ Graphite exists largely in the form of *flakes*
- ✓ **weak & brittle under tension**
- ✓ **stronger under compression**
- ✓ **Excellent vibrational dampening**
- ✓ **wear resistant**
- ✓ 3 types of gray cast iron are **ferritic**, **pearlitic**, and **martensitic:**
  - Each has different properties and applications due to structures, such as:
  - **Ferritic gray iron** structure consists of graphite flakes in an alpha-ferrite matrix
  - **Pearlitic gray iron** has graphite in a matrix of pearlite
- ✓ **Graphitization** can be controlled and accelerated by modifying the composition and the rate of cooling and by the addition of silicon

DUCTILE CAST IRON

- ✓ add Mg or Ce
- ✓ graphite in nodules or spheroid not flakes
- ✓ matrix often pearlite
- ✓ better ductility and shock resistant

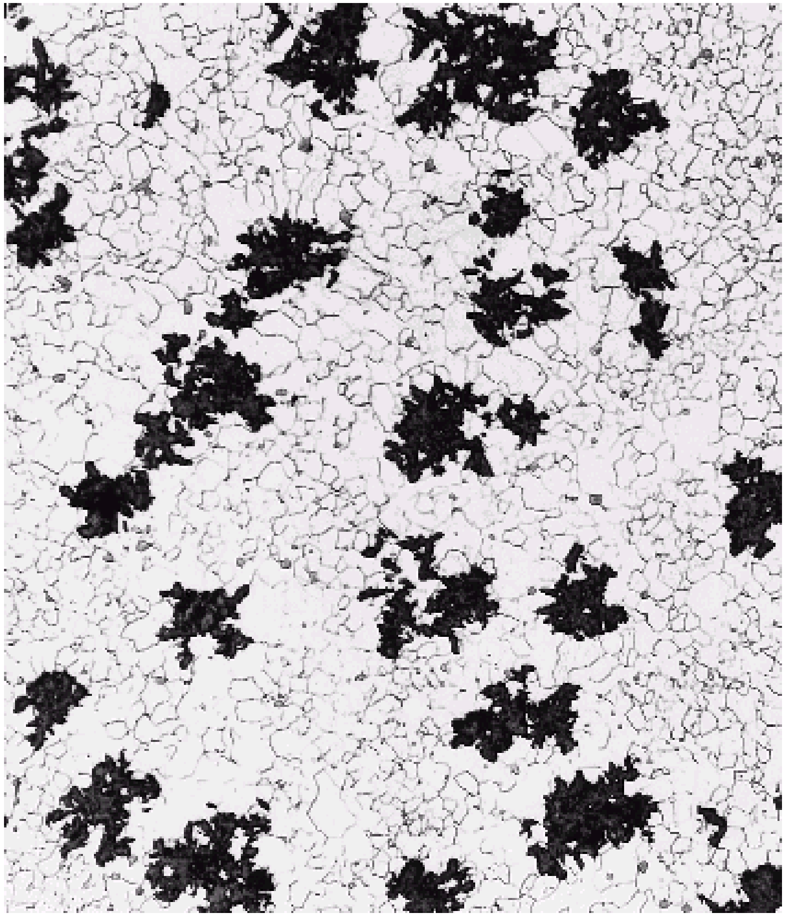


WHITE CAST IRON

- ✓ < 1 wt% Si so harder but brittle
- ✓ more cementite (Fe-C)

MALLEABLE CAST IRON

- ✓ Obtained by annealing white cast iron in an atmosphere of carbon monoxide and carbon dioxide.
- ✓ Cementite decomposes (*dissociates*) into iron and graphite.
- ✓ Graphite exists as ***clusters or rossettes*** in a ferrite or pearlite matrix.
- ✓ **more ductile**



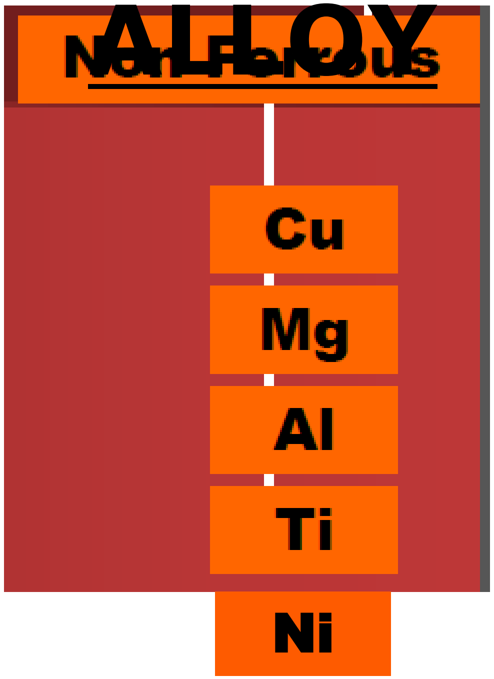
Limitations of Ferrous Alloys

1) Relatively high density

2) Relatively low conductivity

3) Poor corrosion resistance

NON-FERROUS METAL ALLOY



Nonferrous metals and alloys cover a wide range
from metals to high-strength, high-temperature alloys

Non-Ferrous Alloys

NonFerrous Alloys

- **Cu Alloys**

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze: Sn, Al, Si, Ni are subst. impurity (bushings, landing gear)

Cu-Be: precip. hardened for strength

- **Al Alloys**

-lower ρ: 2.7g/cm^3

-Cu, Mg, Si, Mn, Zn additions

-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**

-very low ρ: 1.7g/cm^3

-ignites easily

-aircraft, missles

- **Ti Alloys**

-lower ρ: 4.5g/cm^3 vs 7.9 for steel

-reactive at high T

-space applic.

- **Noble metals**

-Ag, Au, Pt

-oxid./corr. resistant

- **Refractory metals**

-high melting T

-Nb, Mo, W, Ta

General Characteristics of Nonferrous Metals and Alloys

Material	Characteristics
Nonferrous alloys	More expensive than steels and plastics; wide range of mechanical, physical, and electrical properties; good corrosion resistance; high-temperature applications
Aluminum	Alloys have high strength-to-weight ratio; high thermal and electrical conductivity; good corrosion resistance; good manufacturing properties
Magnesium	Lightest metal; good strength-to-weight ratio
Copper	High electrical and thermal conductivity; good corrosion resistance; good manufacturing properties
Superalloys	Good strength and resistance to corrosion at elevated temperatures; can be iron-, cobalt-, and nickel-based alloys
Titanium	Highest strength-to-weight ratio of all metals; good strength and corrosion resistance at high temperatures
Refractory metals	Molybdenum, niobium (columbium), tungsten, and tantalum; high strength at elevated temperatures
Precious metals	Gold, silver, and platinum; generally good corrosion resistance

Engineering Properties of Aluminium and its Alloys

❖ Properties of Pure Aluminium:

– Low density metal (2.7 g/cm^3)
– High electrical and thermal conductivities
– Resistance to corrosion (to ambient atmosphere)
– Ease of formability and machinability
– Ductility retained at very low temperatures
– Low melting point (660^{o}C)
– Useless for high temperature applications

- Properties of pure aluminium can be improved by precipitation hardening (alloying) and/or cold work

- In precipitation hardening, strengthening is created by producing fine dispersion of precipitates particles in a matrix of pure aluminium

- The precipitates particles act as obstacles to dislocation movement and strength aluminium

- For example Al-Mg Mg-Zn alloy. $MgZn_2$ precipitates in aluminium matrix.

- Aluminum alloys are available as wrought products for various shapes by rolling, extrusion, drawing, and forging.

- Aluminium alloys can be classified as; cast or wrought alloys.

- Cast alloys normally have lower tensile strength than wrought alloys.

- 2 types of cast and wrought alloys of aluminium:
  1. Alloys that can be *hardened by cold working* and are not heat treatable
  2. Alloys that can be *hardened by heat treatment*

Properties of Selected Aluminum Alloys at Room Temperature

Alloy (UNS)	Temper	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)
1100 (A91100)	O	90	35	35–45
1100	H14	125	120	9–20
2024 (A92024)	O	190	75	20–22
2024	T4	470	325	19–20
3003 (A93003)	O	110	40	30–40
3003	H14	150	145	8–16
5052 (A95052)	O	190	90	25–30
5052	H34	260	215	10–14
6061 (A96061)	O	125	55	25–30
6061	T6	310	275	12–17
7075 (A97075)	O	230	105	16–17
7075	T6	570	500	11

Manufacturing Characteristics and Typical Applications of Selected Wrought Aluminum Alloys

	Characteristics*			
Alloy	Corrosion resistance	Machinability	Weldability	Typical applications
1100	A	C–D	A	Sheet-metal work, spun hollowware, tin stock
2024	C	B–C	B–C	Truck wheels, screw machine products, aircraft structures
3003	A	C–D	A	Cooking utensils, chemical equipment, pressure vessels, sheet-metal work, builders' hardware, storage tanks
5052	A	C–D	A	Sheet-metal work, hydraulic tubes, and appliances; bus, truck, and marine uses
6061	B	C–D	A	Heavy-duty structures where corrosion resistance is needed; truck and marine structures, railroad cars, furniture, pipelines, bridge railings, hydraulic tubing
7075	C	B–D	D	Aircraft and other structures, keys, hydraulic fittings

*A, excellent; D, poor.

Applications of Al and Al-Alloys

Aluminum, 99.00% minimum and greater	1xxx
Aluminum alloys grouped by major alloying elements:	
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other element	8xxx
Unused series	9xxx

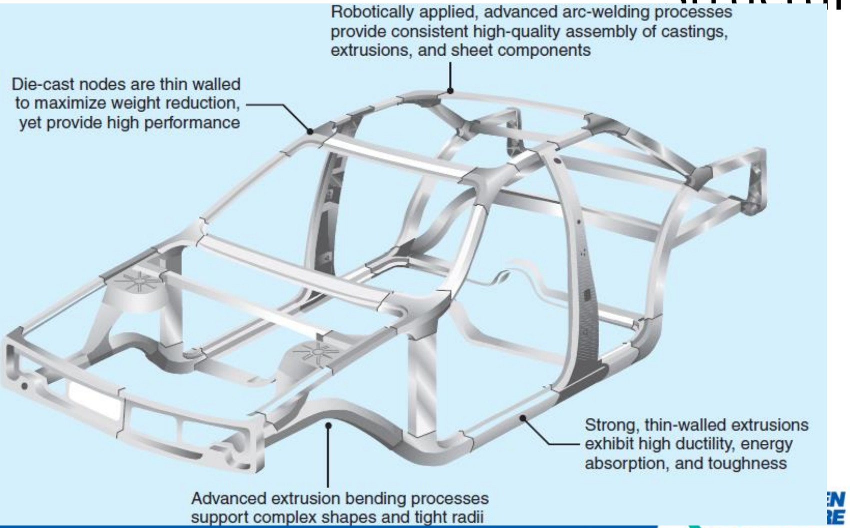
- Classification: According to major alloying lements.

- Four digits: **First digit** -major group of alloying elements. • **Second digit** - Impurity limits / modification of the alloy
- Last 2 digits - Identify aluminum alloy / min amount of Al in the alloy

- Typical applications:
- Al-Cu -> food/chemicals handling and storage equipments
- Al-Cu-Mn-Zn -> Cooking utensils
- Automotive parts
- Al-Zn-Mg-Cu-Cr -> Aircraft structural parts

EXAMPLE : An All-aluminum Automobile

Audi A8 automobile has an all-aluminum body structure



Aluminum body structure, has components made by extrusion, sheet forming, and casting processes

Engineering Properties of Magnesium and its Alloys

Properties of Pure Magnesium:

– **Magnesium** (Mg) is a light metal and has good vibration damping characteristics. Low density metal (1.7 g/cm^3)

– Relatively soft low elastic modulus

– Easily oxidised

- Not sufficiently strong in its pure form

– Magnesium is expensive compared to Al

– Mg is difficult to cast and it burn in air (handling must be with with care and cannot be used at high temperature)

- Also an alloying element in various non-ferrous metals

Properties of Mg-alloys

- Alloys are used in structural and non-structural applications due to light weight

– Mg-Al-Zn alloys – improve strength

- Magnesium alloys have good casting, forming, and machining characteristics

- Mg-alloys replace engineering plastics that have similar densities

– Mg-alloys are cheaper and can be recycled

Applications of Magnesium Alloys

<u>Applications:</u>

– Hand held devices (chain saw, power tool, etc)
– Automobiles (steering wheels, tyre ream, seat frames)
– Laptop computers, cam coders, TV, etc

Engineering Properties of Titanium and its Alloys

Titanium is a silvery white metal.

Properties of Titanium:

–Low density metal (4.5 g/cm_3)

–High melting point = 1668^oC,

– Elastic modulus = 107 MPa

–Chemical reactivity with other material at elevated temperatures

– Corrosion resistance

- Expensive

- High strength-to-weight ratio

Properties of Ti—alloys:

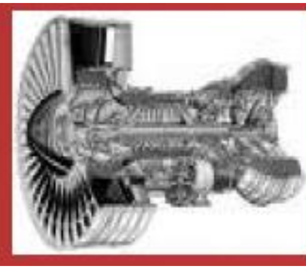
–Very high elastic modulus ~1400MPa

–Easily forged and machined

– High ductility

Applications of Titanium Alloys



- Pure Ti - Jet engine, cases and airframe skins, corrosion-resistance equipment for marines applications, chemical processing industries
- Ti-5Al-2.55Sn –> Gas turbine engine casing
- Ti-6Al-4V –> High strength prosthetic implants, orthopaedics, airframe structured components

Properties and Typical Applications of Selected Wrought Titanium Alloys at Various Temperatures

Nominal composition (%)	UNS	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction of area (%)	Temp. (°C)	Ultimate tensile strength (MPa)	Yield strength (MPa)
99.5 Ti	R50250	Annealed	330	240	30	55	300	150	95
5 Al, 2.5 Sn	R54520	Annealed	860	810	16	40	300	565	450
6 Al, 4 V	R56400	Annealed	1000	925	14	30	300	725	650
		Solution + age	1175	1100	10	20	300	980	900
13 V, 11 Cr, 3 Al	R58010	Solution + age	1275	1210	8	—	425	1100	830

Properties of Copper and its Alloys

Properties of Copper:
- best conductors of electricity and heat
- good corrosion resistance
– difficult to machines

Properties of Cu-alloys:
– its alloys can be processed easily by forming, machining, casting, and joining techniques
- Brass is an alloy of copper and zinc (Zn-Cu)
- Bronze is an alloy of copper and tin (Cu-Sn-Al-Si-Ni)
Beryllium copper (or **beryllium bronze**) and **phosphor bronze** have good strength and hardness

Properties and Typical Applications of Selected Wrought Bronzes

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Architectural bronze (C38500)	57.0 Cu, 3.0 Pb, 40.0 Zn	415 (as extruded)	140	30	Architectural extrusions, storefronts, thresholds, trim, butts, hinges
Phosphor bronze, 5% A (C51000)	95.0 Cu, 5.0 Sn, trace P	325–960	130–550	64–2	Bellows, clutch disks, cotter pins, diaphragms, fasteners, wire brushes, chemical hardware, textile machinery
Free-cutting phosphor bronze (C54400)	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	300–520	130–435	50–15	Bearings, bushings, gears, pinions, shafts, thrust washers, valve parts
Low-silicon bronze, B (C65100)	98.5 Cu, 1.5 Si	275–655	100–475	55–11	Hydraulic pressure lines, bolts, marine hardware, electrical conduits, heat-exchanger tubing
Nickel silver, 65–10 (C74500)	65.0 Cu, 25.0 Zn, 10.0 Ni	340–900	125–525	50–1	Rivets, screws, slide fasteners, hollowware, nameplates

Properties and Typical Applications of Selected Wrought Copper and Brasses

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Electrolytic tough-pitch copper (C11000)	99.90 Cu, 0.04 O	220–450	70–365	55–4	Downspouts, gutters, roofing, gaskets, auto radiators, bus bars, nails, printing rolls, rivets
Red brass, 85% (C23000)	85.0 Cu, 15.0 Zn	270–725	70–435	55–3	Weather stripping, conduits, sockets, fasteners, fire extinguishers, condenser and heat-exchanger tubing
Cartridge brass, 70% (C26000)	70.0 Cu, 30.0 Zn	300–900	75–450	66–3	Radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, locks, hinges, ammunition components, plumbing accessories
Free-cutting brass (C36000)	61.5 Cu, 3.0 Pb, 35.5 Zn	340–470	125–310	53–18	Gears, pinions, automatic high-speed screw machine parts
Naval brass (C46400 to C46700)	60.0 Cu, 39.25 Zn, 0.75 Sn	380–610	170–455	50–17	Aircraft: turnbuckle barrels, balls, bolts; marine hardware: propeller shafts, rivets, valve stems, condenser plates

Applications of Copper and Copper Alloys




Pure Cu:
Electrical and thermal conductors , transistor components, coaxial cables, rectifiers, lead in wires.

Cu alloys:
Cu--Be—Co -> moulds for plastic parts, bearings, valves, gears.

Cu-30Zn & Cu--40Zn (cold40Zn cold--work brass) -> Fasteners, locks, heal exchange components, large nuts and bolts, plumbing accessories, pints and rivets

Cu--4Si -> bearing, belts, marine fittings

Nickel and Nickel Alloys

- **Nickel** (Ni) is a silver-white metal
- A major alloying element that imparts strength, toughness, and corrosion resistance
- Used in stainless steels and in nickel-based alloys (**superalloys**)
- Nickel is magnetic, has high strength and corrosion resistance at elevated temperatures

Properties and Typical Applications of Selected Nickel Alloys (All Are Trade Names)

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Nickel 200 (annealed)	None	380–550	100–275	60–40	Chemical and food processing industry, aerospace equipment, electronic parts
Duranickel 301 (age hardened)	4.4 Al, 0.6 Ti	1300	900	28	Springs, plastics extrusion equipment, molds for glass, diaphragms
Monel R-405 (hot rolled)	30 Cu	525	230	35	Screw-machine products, water meter parts
Monel K-500 (age hardened)	29 Cu, 3 Al	1050	750	30	Pump shafts, valve stems, springs
Inconel 600 (annealed)	15 Cr, 8 Fe	640	210	48	Gas turbine parts, heat-treating equipment, electronic parts, nuclear reactors
Hastelloy C-4 (solution treated and quenched)	16 Cr, 15 Mo	785	400	54	Parts requiring high-temperature stability and resistance to stress-corrosion cracking

Super-alloys

- Superalloys are referred to as *iron-based*, *cobalt-based*, or *nickel-based. Superalloys* are used for high-temperature applications
- Have good resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep, and erosion, at elevated temperatures.

Superalloys

Properties and Typical Applications of Selected Nickel-based Superalloys at 870°C (All Are Trade Names)

Alloy	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Astroloy	Wrought	770	690	25	Forgings for high-temperature use
Hastelloy X	Wrought	255	180	50	Jet engine sheet parts
IN-100	Cast	885	695	6	Jet engine blades and wheels
IN-102	Wrought	215	200	110	Superheater and jet engine parts
Inconel 625	Wrought	285	275	125	Aircraft engines and structures, chemical processing equipment
Inconel 718	Wrought	340	330	88	Jet engine and rocket parts
MAR-M 200	Cast	840	760	4	Jet engine blades
MAR-M 432	Cast	730	605	8	Integrally cast turbine wheels
René 41	Wrought	620	550	19	Jet engine parts
Udimet 700	Wrought	690	635	27	Jet engine parts
Waspaloy	Wrought	525	515	35	Jet engine parts

Refractory Metals and Alloys

- **Refractory metals** are a class of metals that are extraordinarily resistant to heat and wear.
- 4 **refractory metals**: *molybdenum, niobium, tungsten, and tantalum*
- They have high melting points, maintain their strength at elevated temperatures

Refractory Metals and Alloys: Molybdenum

- A silvery white metal
- Has a high melting point, high modulus of elasticity, good resistance to thermal shock, and good electrical and thermal conductivity
- An alloying element in cast and wrought alloy steels and in heat-resistant alloys
- Imparting strength, toughness, and corrosion resistance

Refractory Metals and Alloys: Niobium

- Also referred to as **columbium**
- Has good ductility and formability and greater oxidation resistance than other refractory metals
- Niobium alloys can be produced with moderate strength and good fabrication characteristics

Refractory Metals and Alloys: Tungsten

- **Tungsten** is the most abundant of all the refractory metals
- Has the highest melting point of any metal and high strength at elevated temperatures
- Has high density, brittle at low temperatures, and offers poor resistance to oxidation

Refractory Metals and Alloys: Tantalum

- **Tantalum** is characterized by its high melting point, high density, good ductility, resistance to corrosion and has poor chemical resistance
- Used as an alloying element and processed by techniques similar to those used for processing niobium

Refractory Metals and Alloys: Beryllium

- Steel gray in color
- Has a high strength-to-weight ratio
- An alloying element to copper and nickel
- Beryllium and its oxide are toxic

Refractory Metals and Alloys: Zirconium

- **Zirconium** (Zr) is silvery in appearance
- It has good strength and ductility at elevated temperatures and has good corrosion resistance because of an adherent oxide film

Low-melting Alloys

- Low-melting alloys has relatively low melting points
- Major metals are **lead, zinc, tin**, and **their alloys**

Low-melting Alloys: Lead

- **Lead** has high density, resistance to corrosion, softness, low strength, ductility and good workability
- Also is used for damping sound and vibrations and radiation shielding
- Used as an alloying element in *solders*, steels, and copper alloys for corrosion resistance and machinability

Low-melting Alloys: Zinc

- **Zinc** (Zn) is a bluish white metal
- 3 major uses

1. For galvanizing iron, steel sheet, and wire
2. As an alloy in other metals
3. As a material in castings

- In **galvanizing**, zinc serves as an anode and protects the steel (cathode) from corrosive attack

Low-melting Alloys: Tin

- Most extensive use is as a protective coating on steel sheets
- Used in small amounts
- Low shear strength of the tin coatings on steel sheets improves deep drawability
- Has low friction coefficients

Precious Metals

- Most important *precious* (costly) metals are called **noble metals:**
- **Gold**

  - soft and ductile and has good corrosion resistance at any temperature
- **Silver**

  - ductile and has the highest electrical and thermal conductivity of any metal
- **Platinum**

  - soft, ductile and good corrosion resistance

Shape-memory Alloys (Smart Materials)

- *Shape-memory alloys* after being plastically deformed, they return to their original shape upon heating
- Can be used to generate motion and/or force in temperature-sensitive actuators
- *Reversible* where shape can switch back and forth repeatedly upon application and removal of heat.

Amorphous Alloys (Metallic Glasses)

- It is metal alloys do not have a long-range crystalline structure
- Have no grain boundaries and atoms are packed randomly and tightly
- Amorphous structure obtained by **rapid solidification** of a molten alloy
- Amorphous alloys has excellent corrosion resistance, good ductility, high strength, and very low magnetic hysteresis

Metal Foams

- Metal foams can be produced by blowing air into molten metal, froth solidifies into a foam
- Have unique combinations of strength-to-density and stiffness-to-density ratios