

Classification of the materials and their properties



Classification of Engineering Materials:

- **Metals and Alloys**
- **Ceramics, Glasses, and Glass-ceramics**
- **Polymers (plastics), Thermoplastics, Thermosets, Elastomers**
- **Composite Materials**
- **Semiconductors**



Functional Classification of Materials

1-Aerospace

2-Biomedical

3-Electronic Materials

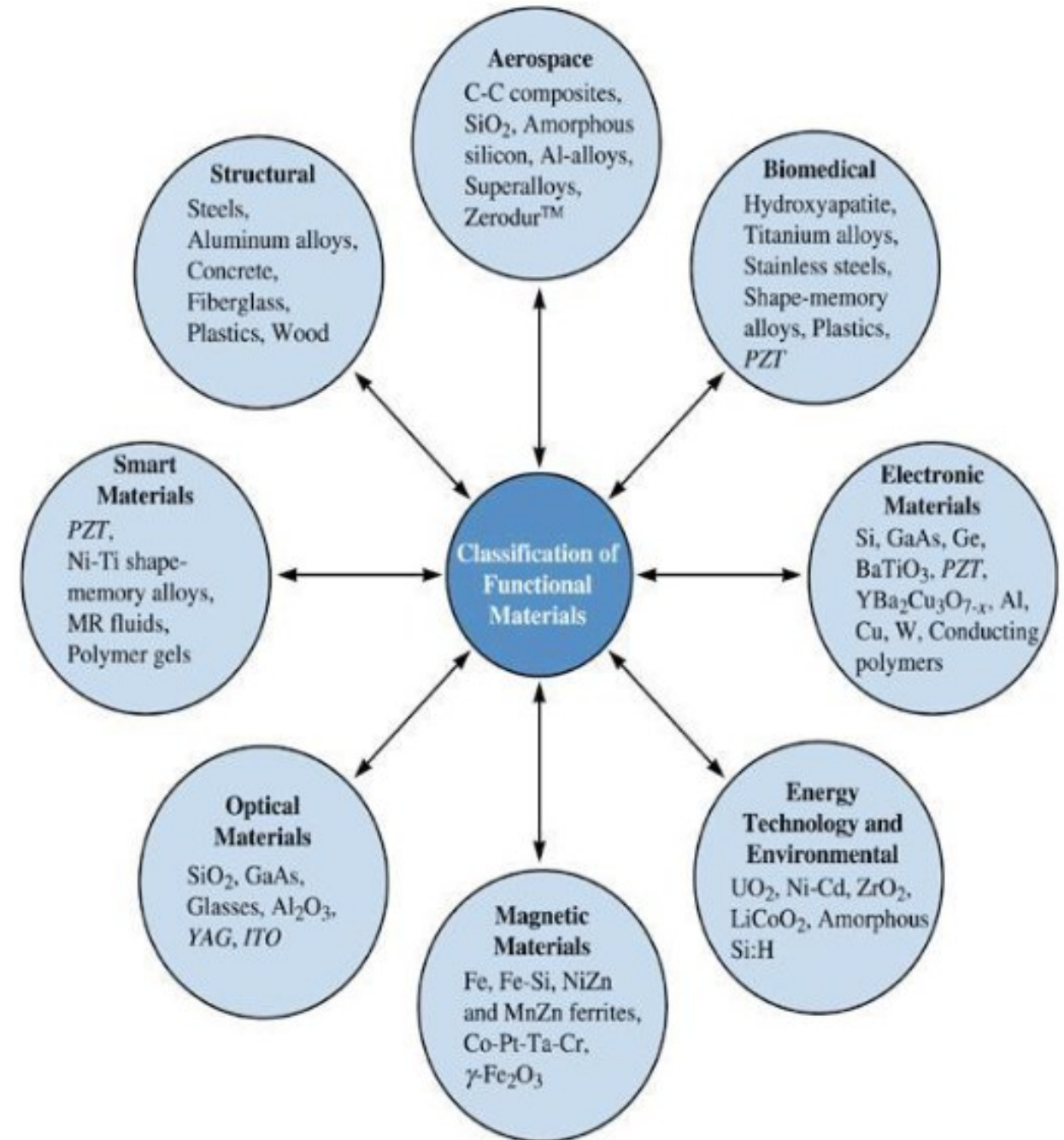
4-Energy Technology and
Environmental Technology

5-Magnetic Materials

6-Photonic or Optical Materials

7-Smart Materials

8-Structural Materials



Materials

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graph TD; Materials --> Metals; Materials --> Polymers; Materials --> Ceramics; Materials --> Composites; Metals --> METALS; Polymers --> POLYMERS; Ceramics --> CERAMICS; METALS --> CERAMICS; CERAMICS --> POLYMERS
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Metals

Polymers

Ceramics

Composites

METALS

High density
Medium to high
melting point
Medium to high
elastic modulus
Reactive
Ductile

CERAMICS

Low density
High melting
point
Very high elastic
modulus
Unreactive
Brittle

POLYMERS

Very low density
Low melting
point
Low elastic
modulus
Ductile and
brittle types

Metals and alloys:

Classification of metals and alloys:

Ferrous: Such as :

- Carbon steels,
- Low alloy steels,
- stainless steels,
- Cast iron,

Nonferrous: Such as :

- Light Alloys(Al, Mg, Ti,)
- Heavy Alloys (Cu, Pb, Ni),
- Refractory Metals (Mo, Ta, W),
- Precious metals (Au, Ag, Pt)

The metals used in product design are, almost without exception, alloys.

Examples:

Pure metal elements (Cu, Ag, Ti, Al, etc.)

Alloys: (bronze =Cu-Sn, brass=Cu-Zn, steel=Fe-C;)

Metals and alloys:

Metals have “free” electrons—electrons that flow in an electric field —so they conduct electricity well, they reflect light, and, viewed with the light behind them, they are opaque.

Compared to all other classes of material, metals are stiff, strong, and tough, but they are heavy.

Metals and alloys:

General properties:

- High electrical conductivity.
- High thermal conductivity.
- Ductile and relatively high stiffness.
- Toughness and strength.
- They are easy to machining, casting, forming, stamping and welding.
- Susceptible to corrosion. Only one metal —gold—is chemically stable as a metal; all the others will, given the chance, react with oxygen, sulfur, phosphorous, or carbon to form compounds that are more stable than the metal itself, making them vulnerable to corrosion.

Metals and alloys:

Applications:

- Structures: buildings, bridges, etc.
- Cars: body, springs, engine block, etc.
- Airplanes: engine components, fuselage, landing gear assembly, etc.
- Trains: rails, engine components, body, wheels
- Machine tools: drill bits, hammers, screwdrivers, saw blades, etc.
- Electrical wiring.
- Magnet

Ceramics:

Ceramics are materials of both the past and the future.

They are the most durable of all materials —ceramic pots and ornaments survive from 5000 BC; Roman cement still bonds the walls of villas.

It is ceramics ' durability, particularly at high temperatures, that generates interest in them today.

Ceramics:

Inorganic, non-metallic crystalline compounds, usually:

- Oxides (SiO_2 , Al_2O_3 , MgO , TiO_2 , BaO),
- Carbides (SiC),
- Nitrides (Si_3N_4),
- Borides (TiB_2),
- Silicides (WSi_2 , MoSi_2).

Glasses are amorphous (non-crystalline) compounds *i.e.* they possess “short range” order of atoms.

Ceramics are hard and brittle and have generally high melting points and low thermal expansion coefficients, and most are good electrical insulators.

Ceramics:

General properties:

- High wear resistance
- Low electrical conductivity
- Low thermal conductivity
- Low thermal expansion
- Poor Thermal shock resistance
- Very brittle
- High elastic modulus
- Low fracture toughness
- High strength at elevated temperature
- Porosity affects properties
- Optical transparent (glass)

Ceramics:

Applications:

- Electrical insulators
- Thermal insulation and coatings
- Windows, television screens, optical fibers (glass)
- Corrosion resistant applications
- Electrical devices: capacitors, varistors, transducers, etc.
- Highways and roads (concrete).
- Building blocks (bricks).
- Building binders (cement, gypsum).
- Biocompatible coatings (fusion to bone)
- Magnetic materials (audio/video tapes, hard disks, etc.)

Comparison Metals/Ceramics

Metals	Ceramics
Crystal structure	Crystal structure
Large number of free electrons	Captive electrons
Metallic bond	Ionic/covalent bonds
Good electrical conductivity	Poor conductivity
Opaque	Transparent (in thin sections)
Uniform atoms	Different-size atoms
High tensile strength	Poor tensile strength
Low shear strength	High shear strength
Good ductility	Poor ductility (brittle)
Plastic flow	None
Impact strength	Poor impact strength
Relatively high weight	Lower weight
Moderate hardness	Extreme hardness
Nonporous	Initial high porosity
High density	Initial low density

Polymers:

A polymer (the name means "many parts") is long chain molecule made up many repeating units, called monomers.

Polymers can be natural (organic) or synthetic:

- Synthetic polymers are derived from petroleum oil, and made by scientists and engineers. Examples of synthetic polymers include nylon, polyethylene, polyester, Teflon, and epoxy.
- Natural polymers occur in nature and can be extracted. They are often water-based. Examples of naturally occurring polymers are silk, wool, cellulose, rubber.

The properties of polymers are linked directly to their structure, which is dictated mostly by intermolecular bonds.

The elements most present are C and H with the presence of O, N, F and Cl, Si.

Types of Polymers

Elastomers	Thermoplastics	Thermosets
Polyisoprene, Neoprene, Spandex or Lycra, Silicones	Polystyrene, Polycarbonate, Polyethylene, Nylon, Polyester	Epoxies, Some urethanes, Cured polyesters, Formaldehyde resins
Properties: Rubbery, Elastic	Properties: Tough, Flexible, Softens with heat	Properties: Strong, Inflexible, Insoluble and does not soften with heat
Usage examples: Tires, gaskets, seals, belts, vibration-damping components	Usage examples: Packaging, appliance components, piping (PE), textile fibers (nylon), bottles (PET)	Usage examples: Structural adhesives, composites (carbon fiber/epoxy), printed circuit boards, automotive and aerospace components

Polymers:

General properties:

- low density,
- amorphous or partially crystalline
- resistant to chemicals.
- thermal and electrical insulators,
- easily modeled,
- low production cost;
- low mechanical strength;
- low melting point.
- soften or burn under the effect of temperature.

The prime weakness is that polymers do not withstand high temperatures.

Polymers:

Applications & Examples

- Adhesives and glues
- Containers
- Moldable products (computer casings, telephone handsets,
- Clothing and upholstery material (vinyls, polyesters, nylon),
- Water-resistant coatings (latex)
- Biomaterials (organic/inorganic interfaces)
- Liquid crystals
- Low-friction materials (Teflon)
- Synthetic oils and greases
- Soaps and surfactants

Composite:

- A combination of two or more materials to achieve better properties than that of the original materials.
- These materials are usually composed of a “Matrix” and one or more of “Filler” material.
- The matrix can be made of a polymeric material (in most cases), metal or ceramic.
- The filler can consist of long fibers, short fibers or particles. Most composites intended for construction have a reinforcement consisting of long fibers of materials such as glass, carbon, boron or Kevlar.
- The primary objective of engineering composites is to increase strength to weight ratio.
- Composite material properties are not necessarily isotropic, i.e., directional properties can be synthesized according to the type of filler materials and the method of fabrication.

Composite:

General properties:

- Low weight,
- High stiffness.
- Brittle.
- Low thermal conductivity.
- High fatigue resistance.
- Their properties can be tailored according to the component materials

Composite:

Applications:

- Sports equipment (golf club shafts, tennis rackets, bicycle frames)
- Aerospace materials
- Thermal insulation
- Concrete
- "Smart" materials (sensing and responding)
- Brake materials

Semiconductors

Semiconductors materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), *have electrical properties somewhere in the middle, between those of a “conductor” and an “insulator”*.

They are not good conductors nor good insulators (hence their name “semi”-conductors).

They have very few “free electrons” because their atoms are closely grouped together in a crystalline pattern called a “crystal lattice” but electrons are still able to flow, but only under special conditions.

The ability of semiconductors to conduct electricity can be greatly improved by replacing or adding certain donor or acceptor atoms to this crystalline structure thereby, producing more free electrons than holes or vice versa.

That is by adding a small percentage of another element to the base material, either silicon or germanium.

Semiconductors

General properties:

- Semiconductor acts like an insulator at Zero Kelvin. On increasing the temperature, it works as a conductor.
- Due to their exceptional electrical properties, semiconductors can be modified by doping to make semiconductor devices suitable for energy conversion, switches, and amplifiers.
- Lesser power losses.
- Semiconductors are smaller in size and possess less weight.
- Their resistivity is higher than conductors but lesser than insulators.
- The resistance of semiconductor materials decreases with the increase in temperature and vice-versa

Semiconductors

Applications:

Uses of Semiconductors in Everyday life

- Temperature sensors are made with semiconductor devices.
- They are used in 3D printing machines
- Used in microchips and self-driving cars
- Used in calculators, solar plates, computers and other electronic devices.
- Transistor and MOSFET used as a switch in Electrical Circuits are manufactured using the semiconductors.

Industrial Uses of Semiconductors

- The physical and chemical properties of semiconductors make them capable of designing technological wonders like microchips, transistors, LEDs, **photovoltaic panels**, solar cells, etc.
- The microprocessor used for controlling the operation of space vehicles, trains, robots, etc is made up of transistors and other controlling devices which are manufactured by semiconductor materials.

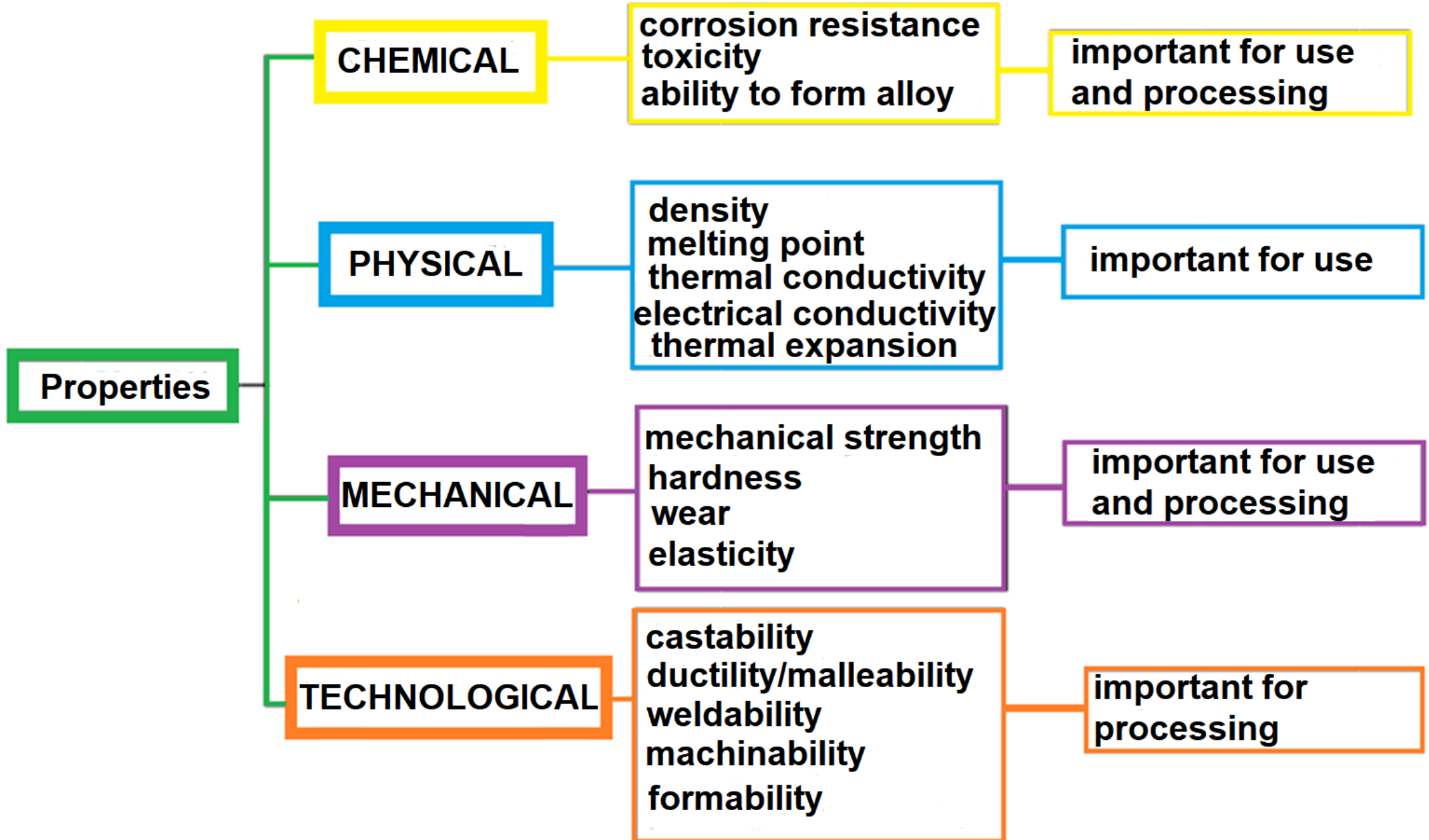
Metals and alloys	Polymers and elastomers	Ceramics and glasses
Aluminum alloys Magnesium alloys Titanium alloys Copper alloys Lead alloys Zinc alloys Nickel-chrome alloys Nickel-based superalloys Low carbon steel Low alloy steel Stainless steel Cast iron	ABS Polyamide PA Polypropylene, PP Polyethylene, PE Polycarbonate, PC PET PVC Polystyrene, PS Polylactide, PLA PHB Epoxy Polyester Phenolic Natural rubber, NR Butyl rubber, BR EVA Polychloroprene, CR	Brick Stone Concrete Alumina Soda-lime glass Borosilicate glass

Material Properties

When selecting a materials for a particular application, there's quite a few factors to consider to find the most suitable option.

These factors include:

- melting point,
- mechanical properties,
- cost,
- ease of machining,
- sufficient safety factor,
- thermal and electrical conductivity,
- density,
- etc.



Material Properties

- Physical: e.g. appearance, weight, boiling point, melting point, freezing point, density, permeability, magnetism, thermal and electrical conductivity, expansion coefficient, resistivity, thermal shock resistance, thermal diffusivity.
- Chemical: e.g.,, corrosion resistance, toxicity, ability to form alloy, composition
- Mechanical: e.g. strength (tensile, compressive, shear, torsion, bending), elasticity, plasticity, rigidity, toughness, hardness, brittleness, fatigue, creep, vibration resistance, wear.

Material Properties

Thermal Conductivity

Thermal conductivity is a measure of the quantity of heat that flows through a material.

Materials with low thermal conductivity may be used as insulators, those with high thermal conductivity may be a heat sink:

- Metals that exhibit high thermal conductivity would be candidates for use in applications like heat exchangers or refrigeration.
- Ceramics that exhibit low thermal conductivity may be used in high temperature applications

The thermal conductivities of some materials at room temperature

Material	k, W/m°C
Silver	430
Copper	390
Gold	320
Aluminium	240
Iron	80
Glass	0.8
Brick	0.7
Water	0.61
Wood	0.17

The thermal conductivities of some materials at room temperature

Type of the material	Material	Thermal conductivity (k) (W/m K)
(i) Metals	Copper	390
	Aluminium	230
	Cast iron	52
	Mild steel	54
	Stainless steel	16
(ii) Ceramics	Alumina	2.0
	Titanium Carbide	3.0
	Glass	1.0
(iii) Polymers	Bakelite	0.23
(iv) Composites	Concrete	1.4
	Wood	0.14

Material Properties

Electrical Conductivity

Electrical conductivity is a measurement of how easily a material allows electric current to flow through it.

Electrical conductivity or specific conductance is the reciprocal of electrical resistivity.

It is commonly signified by the Greek letter σ (sigma),

The SI unit of electrical conductivity is siemens per metre (S/m)

Materials are often selected or discarded for applications due to their electrical conductivity when the passage of electrical current is crucial to the functionality of their application:

- Metals are generally the best conductors of electricity
- Polymers are the least conductors of electricity.

Silver is the best conductor of electricity but it is rarely used for this function due to its scarcity and resultant prohibitive cost.

Resistivity and Conductivity of common materials at 20°C

Material	Resistivity ρ ($\Omega \cdot \text{m}$) at 20°C	Conductivity σ (S/m) at 20°C
Silver	1.59×10^{-8}	6.30×10^7
Copper	1.68×10^{-8}	5.96×10^7
Gold	2.44×10^{-8}	4.10×10^7
Aluminium	2.82×10^{-8}	3.5×10^7
Carbon (diamond)	1×10^{12}	$\sim 10^{-13}$
Silicon	6.40×10^2	1.56×10^{-3}
Glass	$10 \times 10^{10} - 10 \times 10^{14}$	$10^{-11} - 10^{-15}$
Hard rubber	1×10^{13}	10^{-14}
Teflon	$10 \times 10^{22} - 10 \times 10^{24}$	$10^{-25} - 10^{-23}$

Material Properties

Density,

Density expressed grams per cubic centimeter, describes the mass of the alloy per unit volume.

The density of the alloy will determine how much a component of a certain size will weigh.

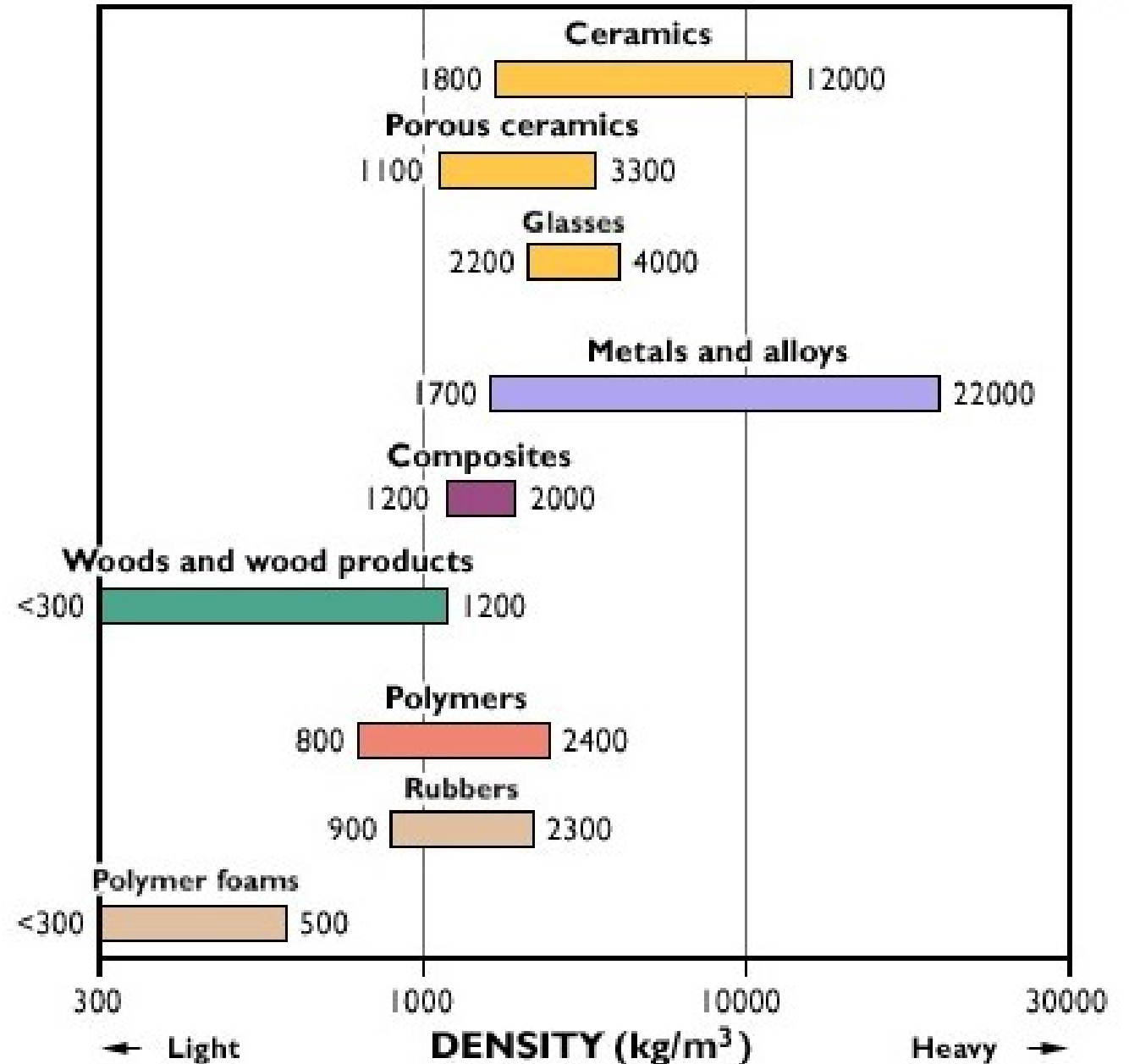
This factor is important in applications like aerospace or automotive where weight is important.

Engineers looking for lower weight components may seek alloys that are less dense, but must then consider the strength to weight ratio.

A higher density material like steel might be chosen, for example, if it provides higher strength than a lower density material.

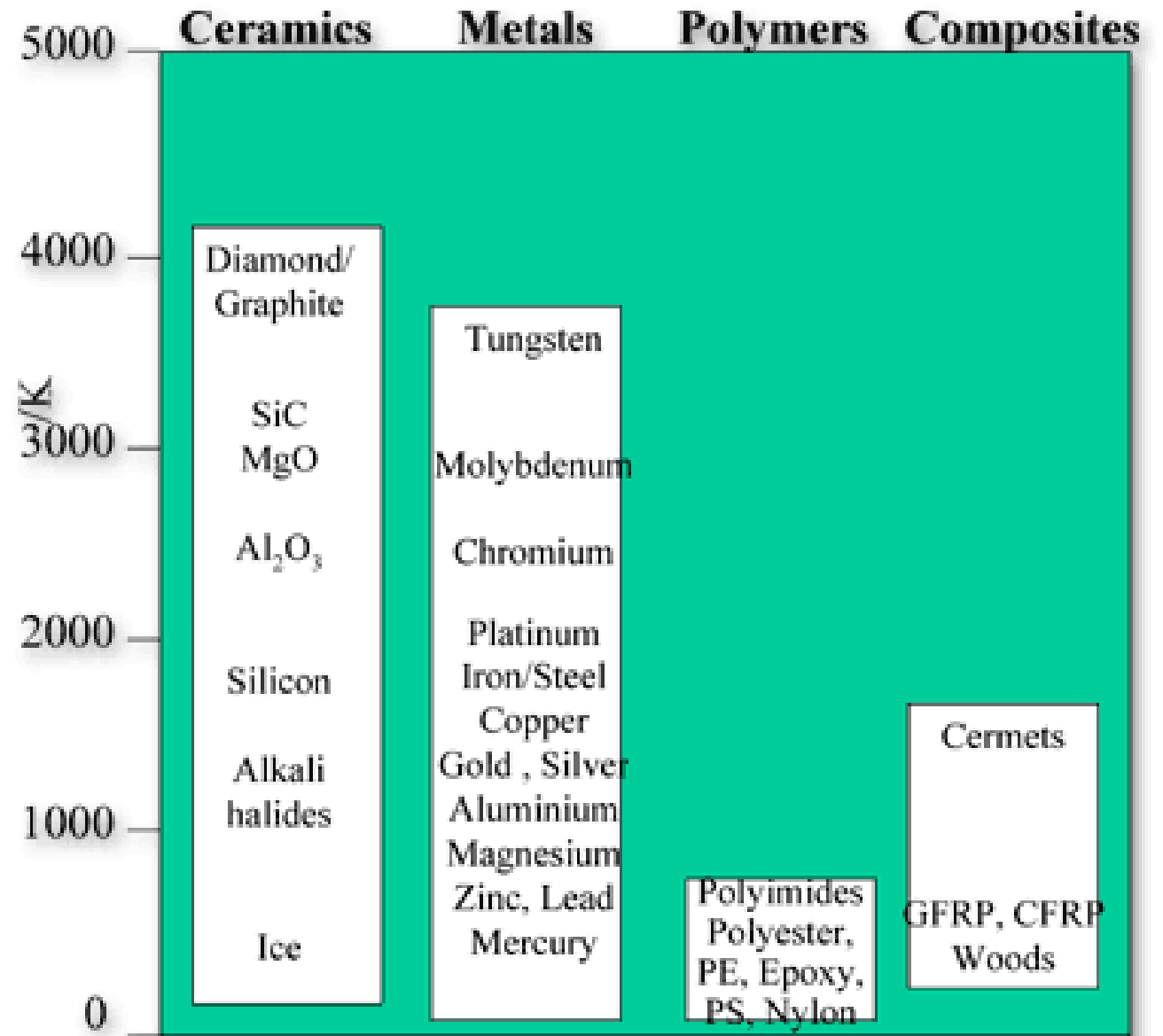
Such a part could be made thinner so that less material could help compensate for the higher density.

Material	(kg/m ³)	(g/cm ³)
Lead	11,300	11.3
Steel	7,800	7.8
Titanium	4,500	4.5
Aluminum	2,700	2.7
Glass	2,700	2.7
Granite	2,600	2.6
Concrete	2,300	2.3
Plastic	2,000	2.0
Rubber	1,200	1.2
Liquid water	1,000	1.0



The melting point

The melting point (or, rarely, liquefaction point) of a substance is the temperature at which it changes state from solid to liquid.



Bar chart of data for melting or softening temperature

Corrosion resistance

Corrosion resistance describes a material's ability to prevent natural chemical or electro-chemical attack by atmosphere, moisture or other agents.

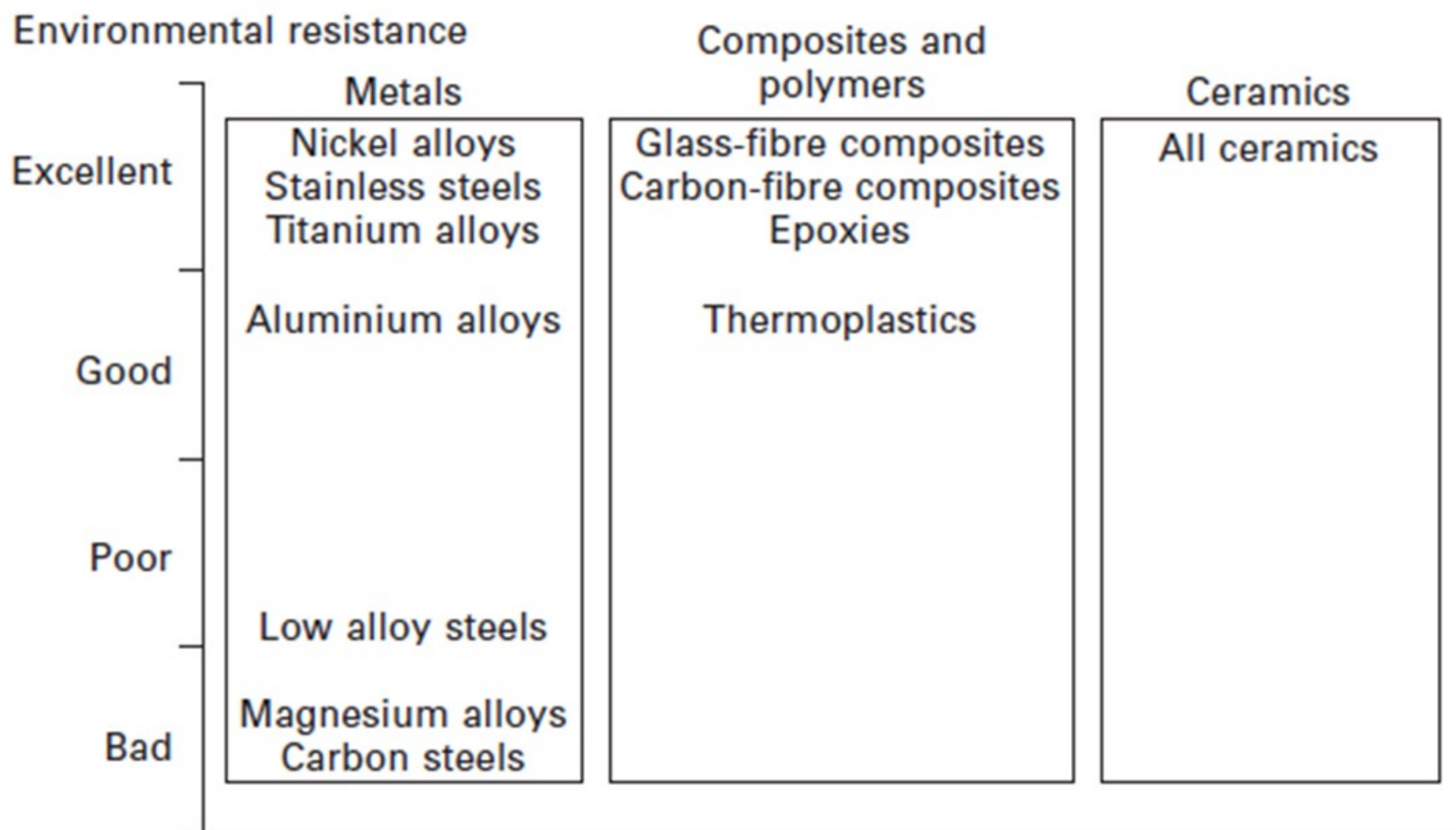
Some materials are intrinsically corrosion resistant, while others benefit from the addition of plating or coatings.

Graphite, aluminosilicates, and pure silica are notable among inorganic nonmetallic corrosion-resistant materials. Quartz glass, in particular, is resistant in many mediums and is widely used in the production of chemical glassware.

Many organic materials, such as polyfluoroethylene resin (Teflon), polyethylene, and polystyrene, are resistant in many aqueous mediums.

The noble metals platinum and gold are resistant to oxidation in gaseous and many liquid mediums.

In acidic oxidizing mediums such as nitric acid, chrome-nickel and chrome stainless steels are corrosion-resistant.



Ranking of the resistance of materials to attack by seawater.

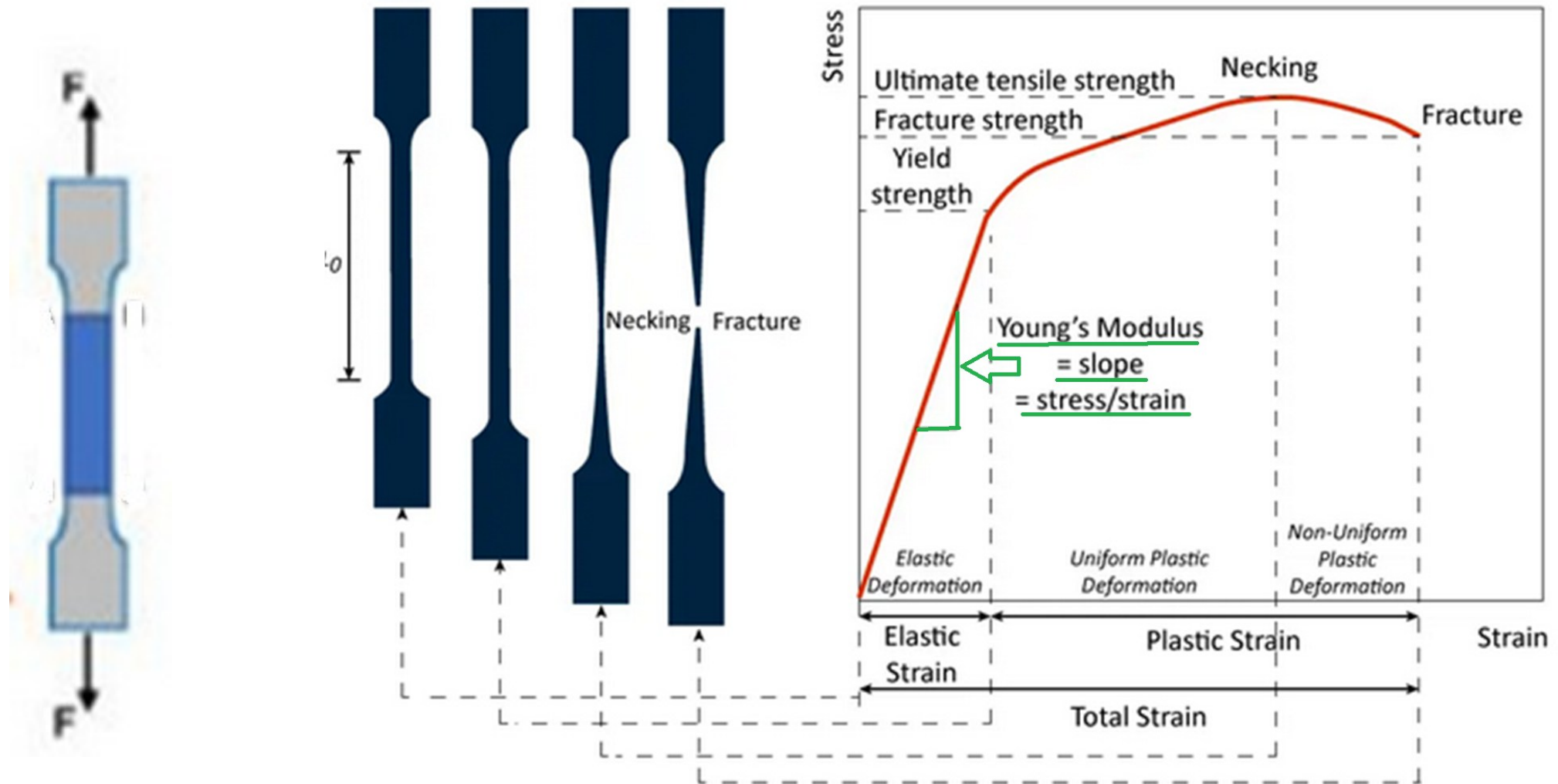
Mechanical properties

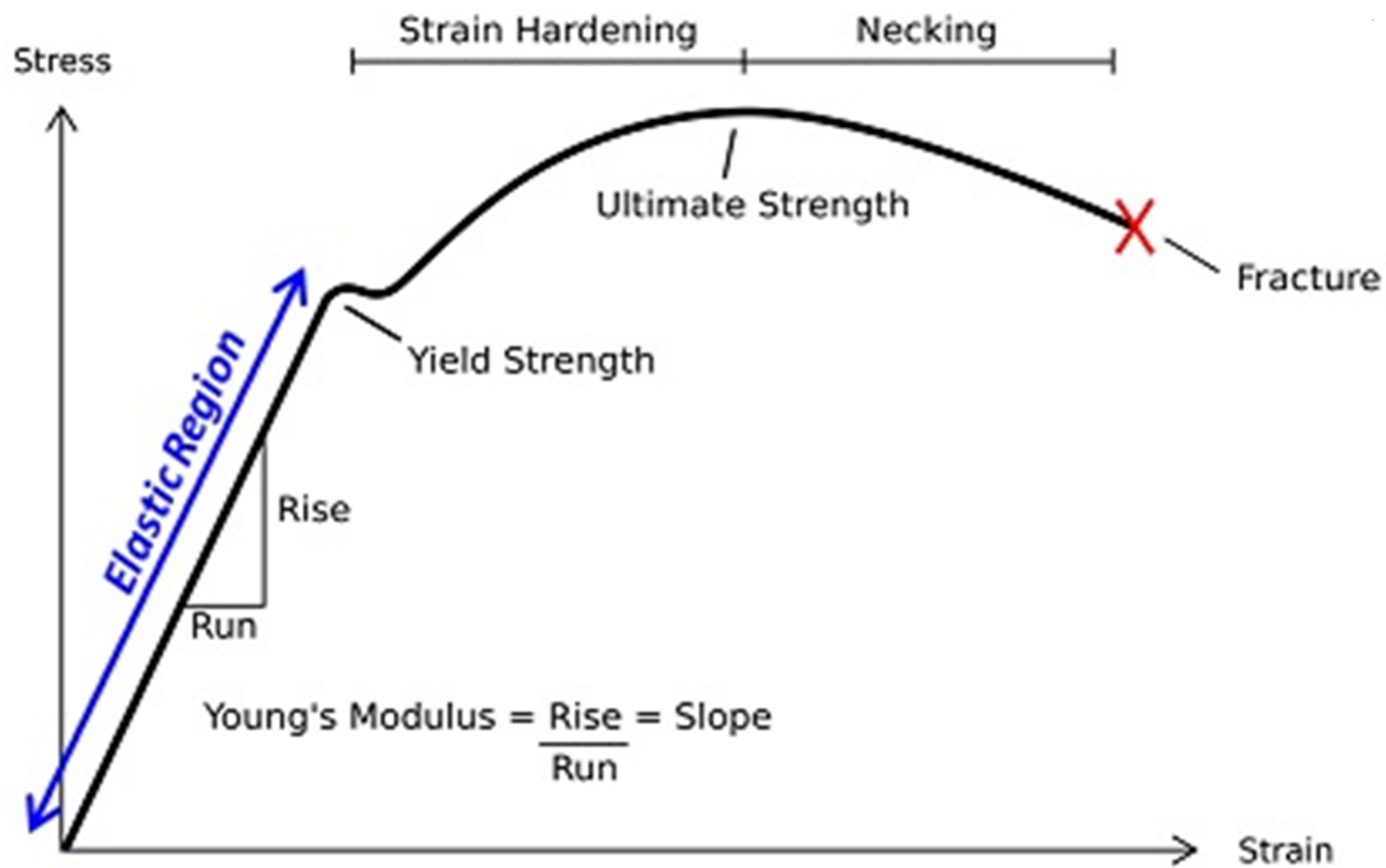
- **Tensile Strength:** The ability of a material to withstand a stretching load without breaking
- **Compressive Strength:** The ability of a material to withstand a squeezing load without breaking
- **Shear Strength:** The ability of the material to withstand loads which have a cutting action
- **Toughness or Impact Strength:** The ability of a material to withstand an impact or hammering load.
- **Elasticity:** The ability of a material to deform under load and return to its original shape when the load is removed. E.g. a spring
- **Hardness.** It is a very important property of the metals and has a wide variety of meanings. It embraces many different properties such as resistance to wear, scratching, deformation and machinability etc. It also means the ability of a metal to cut another metal.

Mechanical properties

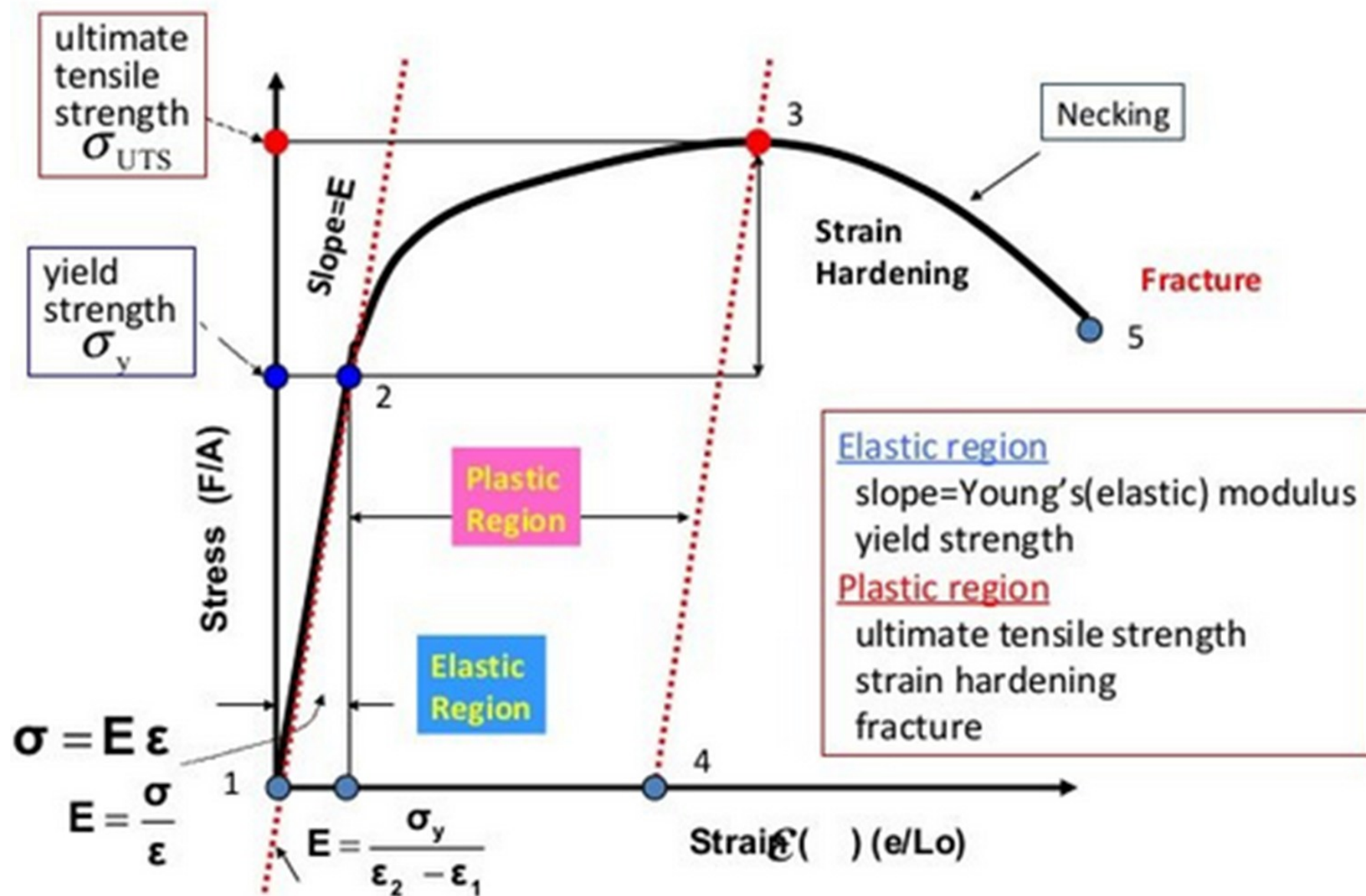
- **Ductility.** It is the property of a material enabling it to be drawn into wire with the application of a tensile force. A ductile material must be both strong and plastic. The ductility is usually measured by the terms, percentage elongation and percentage reduction in area. The ductile material commonly used in engineering practice (in order of diminishing ductility) are mild steel, copper, aluminium, nickel, zinc, tin and lead.
- **Stiffness.** It is the ability of a material to resist deformation under stress. The modulus of elasticity is the measure of stiffness.
- **Brittleness.** It is the property of a material opposite to ductility. It is the property of breaking of a material with little permanent distortion. Brittle materials when subjected to tensile loads, snap off without giving any sensible elongation.

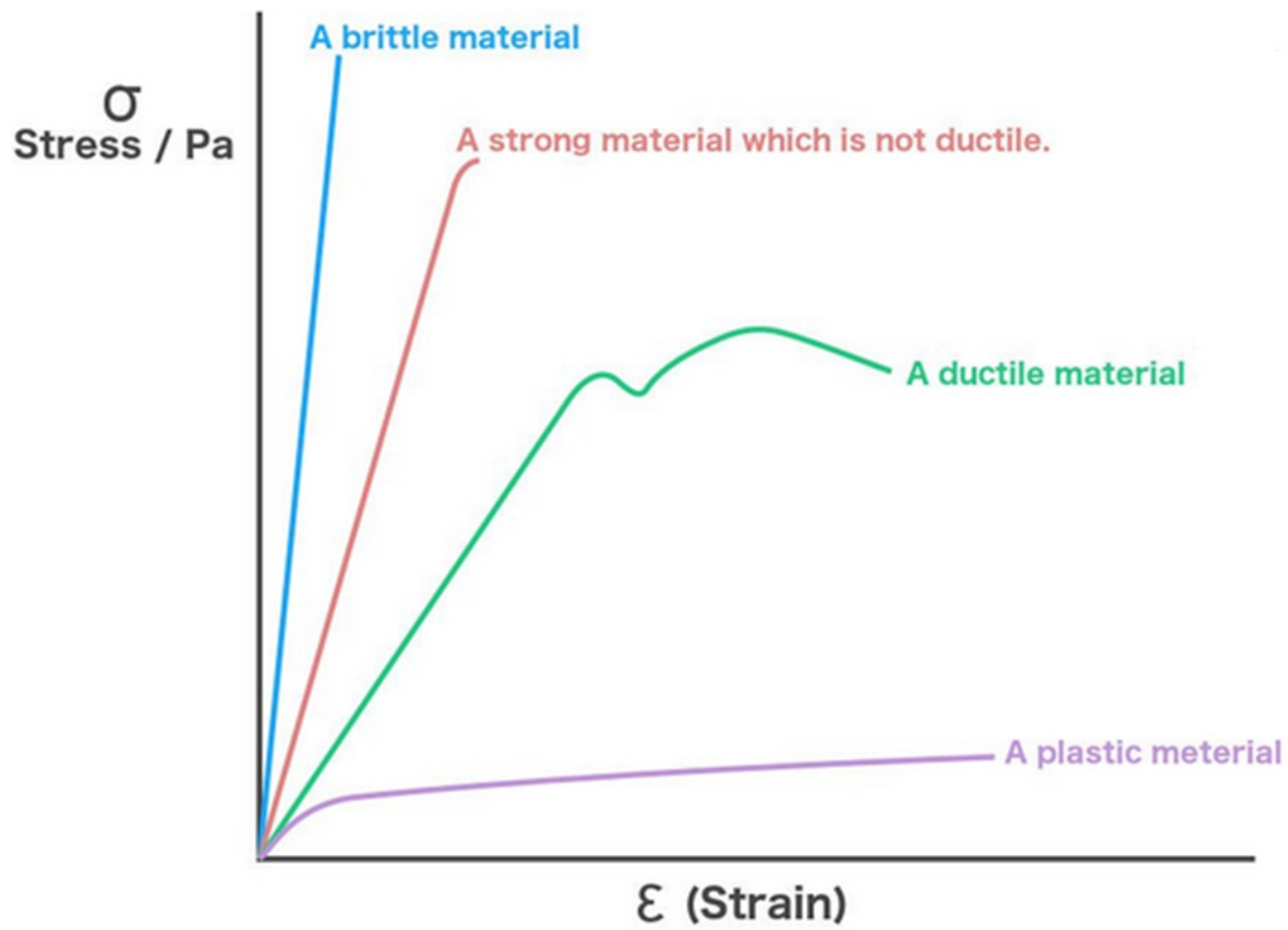
A tensile test, also known as a tension test, is one of the most fundamental and common types of mechanical testing. A tensile test applies tensile (pulling) force to a material and measures the specimen's response to the stress.





Stress-Strain Diagram





Young modulus, or Tensile modulus:

- is a mechanical property that measures the stiffness of a solid material.
- It defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material in the linear elasticity regime of a uniaxial deformation.
- A stiff material has a high Young's modulus and changes its shape only slightly under elastic loads (e.g. diamond).
- A flexible material has a low Young's modulus and changes its shape considerably (e.g. rubbers).
- A stiff material requires high loads to elastically deform it - not to be confused with a strong material, which requires high loads to permanently deform (or break) it.

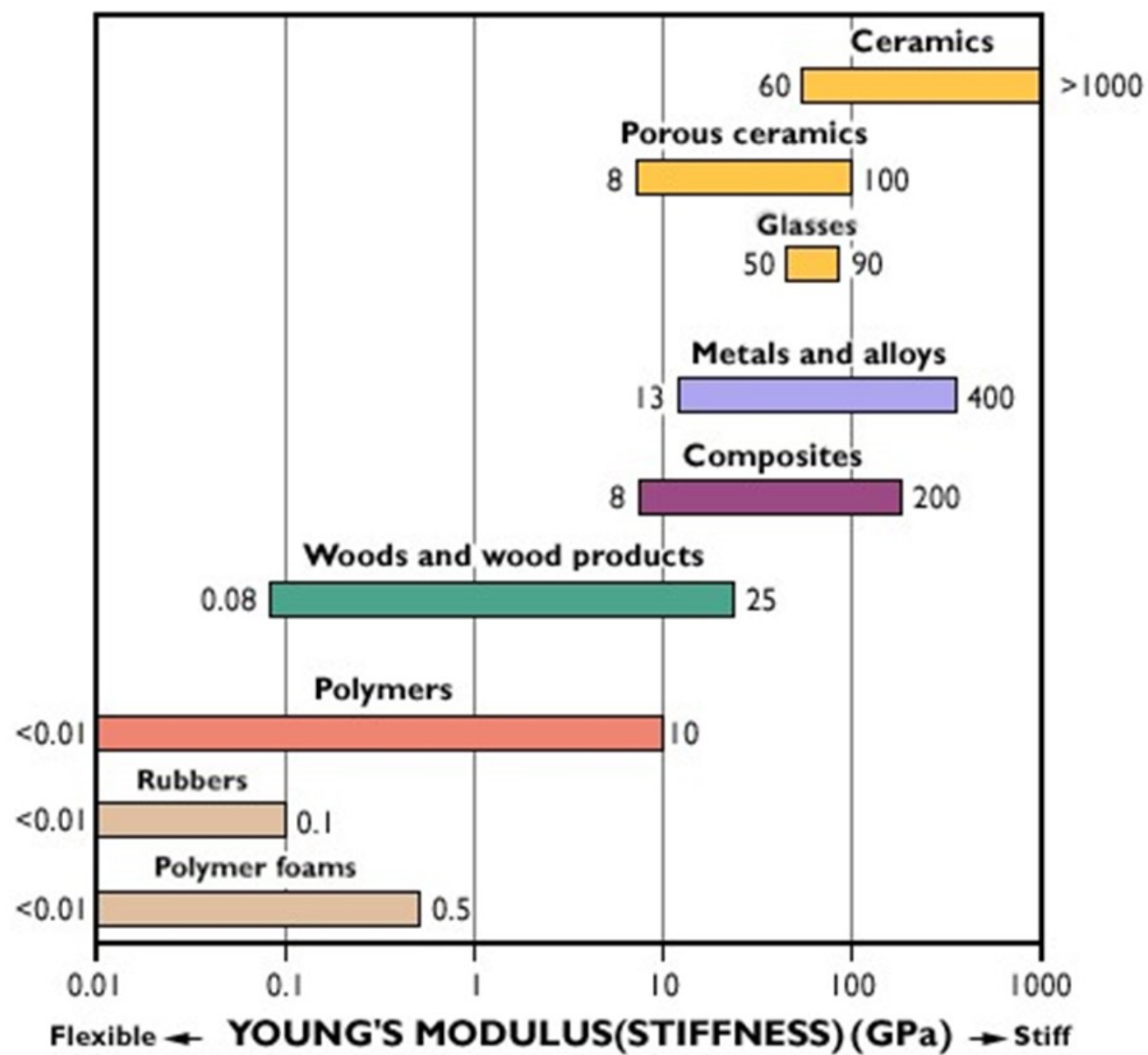
The yield strength or yield stress

- is a material property and is the stress corresponding to the yield point at which the material begins to deform plastically.
- The yield strength is often used to determine the maximum allowable load in a mechanical component
- It represents the upper limit to forces that can be applied without producing permanent deformation.



Ultimate tensile strength (UTS), often shortened to **tensile strength (TS)**,

- is the maximum stress that a material can withstand while being stretched or pulled before breaking.
- In brittle materials the ultimate tensile strength is close to the yield point,
- whereas in ductile materials the ultimate tensile strength can be higher.



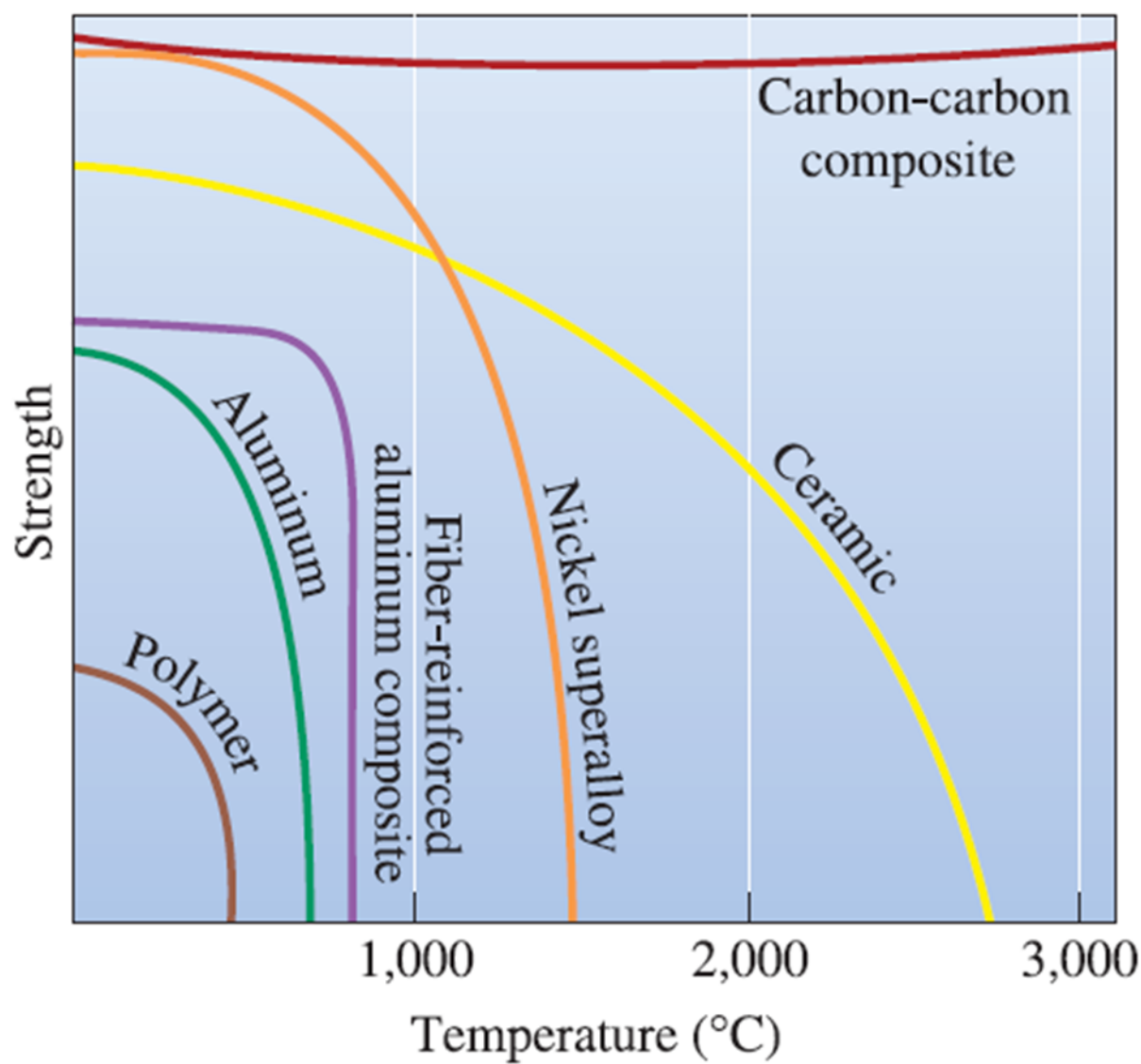
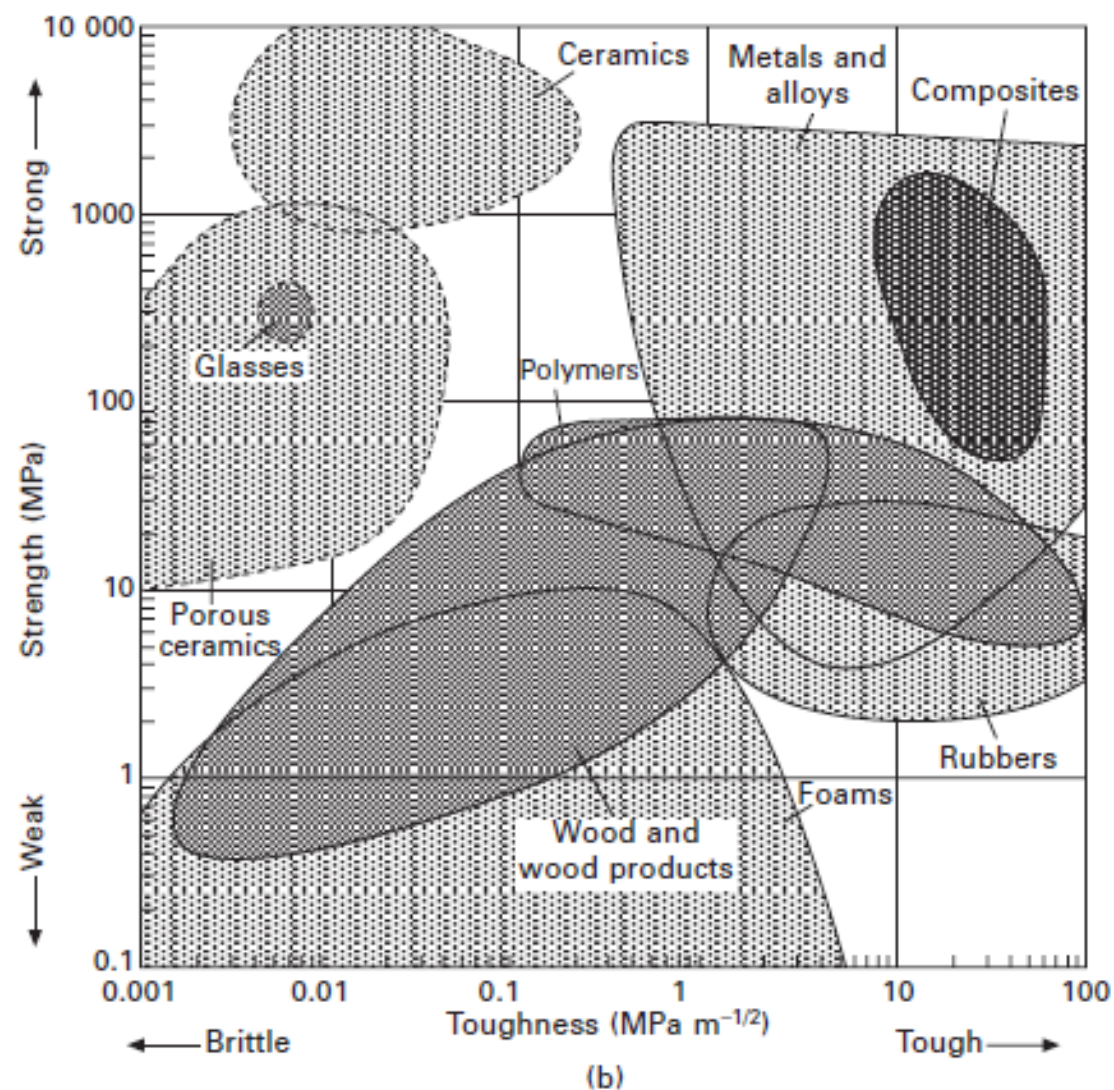
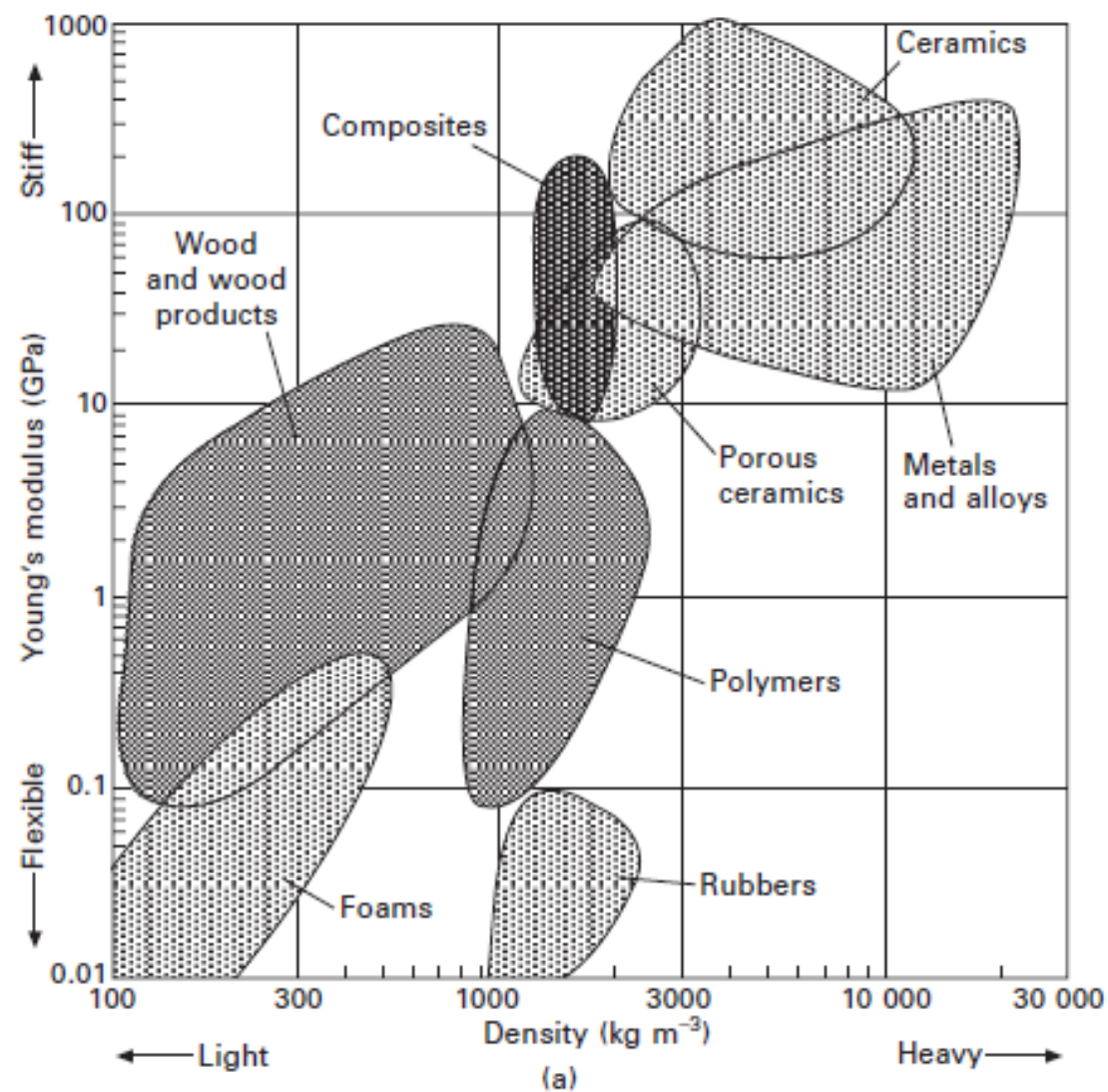


Figure 1-7

Increasing temperature normally reduces the strength of a material. Polymers are suitable only at low temperatures. Some composites, such as carbon-carbon composites, special alloys, and ceramics, have excellent properties at high temperatures.



Examples of material property charts: (a) Young's modulus-density and (b) strength-toughness (provided courtesy of the Department of Engineering, University of Cambridge).

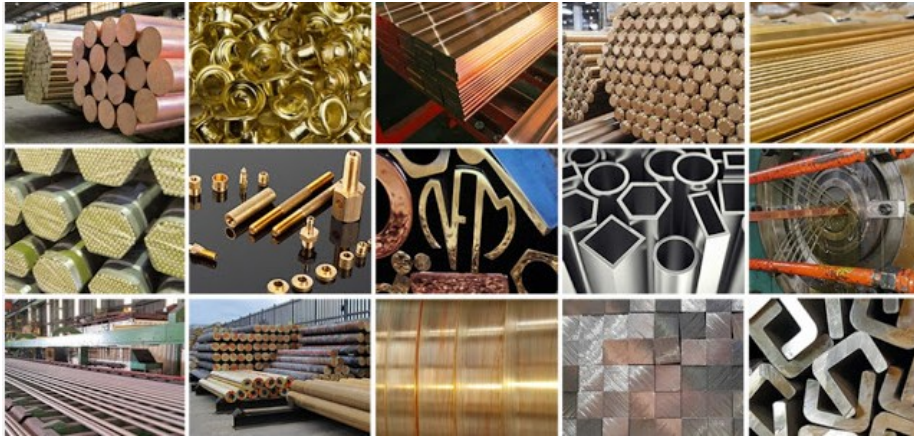
Important properties for different groupings of materials

<i>Property</i>	<i>Metals</i>	<i>Ceramics</i>	<i>Polymers</i>	<i>Composites (wood)</i>
1. Tensile strength (N/mm ²)	200–2000	10–400	30–100	20–110
2. Density (10N/mm ²)	$2-8 \times 10^3$	$2-17 \times 10^3$	$1-2 \times 10^3$	0.5×10^3
3. Hardness	medium	high	low	low
4. Tensile modulus (10 ³ N/mm ²)	100–200	150–450	0.7–3.5	4–20
5. Melting point (°C)	200–3500	2000–4000	70–200	—
6. Thermal expansion	medium	low	high	low
7. Thermal conductivity	high	medium	low	low
8. Electrical conductivity	good conductors	insulator	insulator	insulator

Classification of Materials

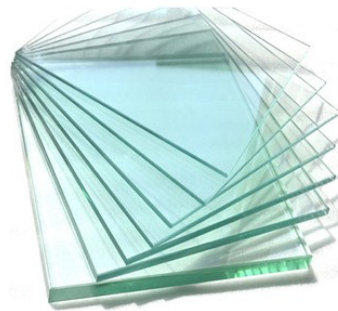
Metals

- good conductors of electricity and heat
- lustrous appearance
- susceptible to corrosion
- strong, but deformable



Ceramics & Glasses

- thermally and electrically insulating
- resistant to high temperatures and harsh environments
- hard, but brittle



Polymers

- very large molecules
- low density, low weight
- maybe extremely flexible



Material	Examples of Applications	Properties
Metals and Alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration-damping
Alloy steels	Wrenches, automobile chassis	Significantly strengthened by heat treatment
Ceramics and Glasses		
$\text{SiO}_2\text{--Na}_2\text{O--CaO}$	Window glass	Optically transparent, thermally insulating
Al_2O_3 , MgO , SiO_2	Refractories (i.e., heat-resistant lining of furnaces) for containing molten metal	Thermally insulating, withstand high temperatures, relatively inert to molten metal
Barium titanate	Capacitors for microelectronics	High ability to store charge
Silica	Optical fibers for information technology	Refractive index, low optical losses

Material	Examples of Applications	Properties
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Epoxy	Encapsulation of integrated circuits	Electrically insulating and moisture-resistant
Phenolics	Adhesives for joining plies in plywood	Strong, moisture resistant
Semiconductors		
Silicon	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, lasers, laser diodes, etc.
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel with the corrosion resistance of titanium