The People's Democratic Republic of Algeria
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الجمهورية الجزائرية الديمقراطية الشعبية
وزارة التعليم العالي و البحث العلمي
جامعة جيلالي ليابس – سيدي بلعباس
كلية التكنولوجيا
قسم الهندسة الميكانيكية

Teaching handout

Materials

Course intended for students:

Field: Mechanical Engineering

Specialization: Mechanical Manufacturing and Production Engineering

Level: Master's Degree

Semester: S1

Teaching Unit: UEF 1.1.1

Course presented by:

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Academic year: 2025/2026

Preamble

The Materials module, intended for students specializing in Mechanical Manufacturing and *Production Engineering* within the Mechanical Engineering program, aims to provide an in-depth scientific and technological foundation for understanding the central role of materials in the design, manufacturing, and performance of mechanical components and systems. The course is designed to equip students with the fundamental knowledge required to analyze the essential relationship between material structure (atomic structure, crystalline arrangement, and microstructure), processing methods, and the resulting properties. Students will learn how factors such as chemical composition, heat treatments, forming processes, and service conditions influence mechanical properties (strength, elasticity, plasticity, toughness, hardness, fatigue, and creep), as well as physical and chemical characteristics.

This module also seeks to develop an integrated understanding of the material–process–product relationship. It connects theoretical knowledge with the industrial realities of mechanical manufacturing by examining the suitability of different materials for various processing techniques such as machining, forming, casting, welding, and advanced manufacturing processes. Students will be trained to interpret standardized mechanical test results (tensile testing, hardness testing, impact testing, fatigue testing) and to use this data to support sound technological decisions. Particular emphasis is placed on understanding material degradation mechanisms, including fracture, wear, and corrosion, in order to prevent service failures and improve the reliability and durability of mechanical components.

Furthermore, the course aims to introduce students to a systematic and rational methodology for material selection based on given design specifications. This includes considering technical requirements, economic constraints, availability, environmental impact, and sustainability. Students will learn to establish an optimal balance between performance, manufacturing cost, process feasibility, and long-term durability. Consideration of material life cycle, recyclability, and sustainable development principles is also integrated into the learning objectives. By the end of the course, students should be able to fully incorporate the “material dimension” into the overall design and manufacturing process and justify their material choices using sound scientific, technical, and engineering arguments within a professional industrial context.

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CHAPTER 1: CRYSTAL STRUCTURES - PERFECT AND REAL (IMPERFECT)

1.1 Introduction

Matter may exist as a gas, a liquid or a solid. The difference between these states is governed by the intensity and spatial organization of the interactions between atoms, ions or molecules. Gases have weakly interacting particles and no fixed shape or volume. Liquids are condensed but remain able to flow. Solids resist deformation because their constituent particles occupy relatively stable positions.

In materials science, solids are divided into amorphous and crystalline solids. Amorphous solids, such as many glasses and some polymers, have only short-range order. Crystalline solids possess long-range periodic order: their atoms repeat in space according to a lattice. This atomic periodicity explains many macroscopic properties, including anisotropy, density, elastic constants, plastic deformation and X-ray diffraction patterns.

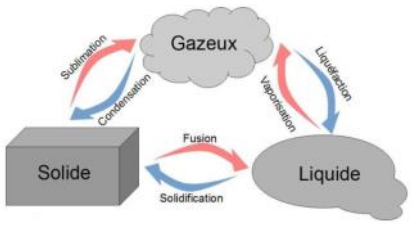


Figure 1.1 — States of matter and phase changes: gas, liquid and solid.

1.2 Definition of Crystallography

Crystallography is the science that studies crystals, their symmetry, their formation, their internal atomic arrangement and the relationship between structure and properties. In modern materials science, crystallography is not limited to mineral crystals; it is essential for metals, ceramics, semiconductors, polymers and many functional materials.

A crystalline state is therefore defined by two conditions: a periodic arrangement repeated through space and an ordered atomic or molecular pattern associated with each lattice point. The role of crystallography is to describe this arrangement using unit cells, lattice vectors, symmetry operations, Miller indices and diffraction methods.

1.3 Definition of a Crystal

1.3.1 Crystal definition

A crystal is a solid in which atoms, ions or molecules are arranged in a regular, repeated pattern. The repeated arrangement can be represented by translations along three non-coplanar vectors. A complete description requires both a lattice, which gives the periodic geometry, and a basis or motif, which gives the atomic content attached to each lattice point.

Crystals may be molecular, ionic, covalent, metallic or macromolecular. Molecular crystals such as iodine or dry ice are held mainly by weak intermolecular forces. Ionic crystals such as NaCl involve electrostatic attraction between cations and anions. Covalent crystals such as diamond involve directional bonds. Metallic crystals are based on metallic bonding and usually show high electrical and thermal conductivity.

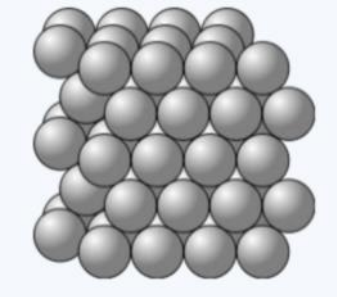


Figure 1.2 — Ordered atomic arrangement in a crystalline solid.

1.3.2 Definition of a Polyhedron

A polyhedron is a three-dimensional solid bounded by plane polygonal faces. In crystallography, ideal external crystal shapes and unit-cell geometries are often described using polyhedra. The five Platonic solids - tetrahedron, cube, octahedron, dodecahedron and icosahedron - are important reference shapes for symmetry and coordination.

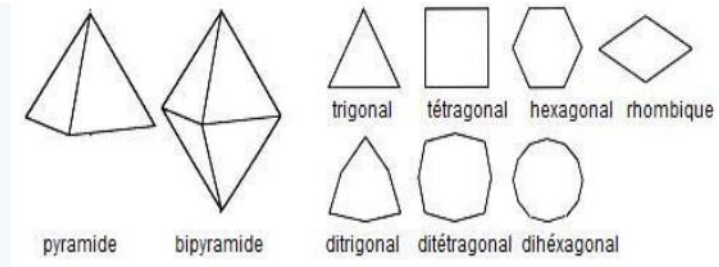


Figure 1.3 — Representative polyhedral shapes used in crystallographic geometry.

1.4 Unit Cell, Basis, Lattice and Crystal Structure

1.4.1 Unit Cell

A unit cell is the smallest repeating volume that can reproduce the entire crystal by translation. In two dimensions, it is a parallelogram; in three dimensions, it is a parallelepiped defined by three vectors a, b and c and three interaxial angles α, β and γ. These six parameters are the crystallographic parameters of the cell.

$$V = abc\,[1 - \cos^2\alpha - \cos^2\beta - \cos^2\gamma + 2\cos\alpha\cos\beta\cos\gamma]^{1/2}$$

A primitive cell contains only one lattice point. Non-primitive or multiple cells contain more than one lattice point and are often chosen because they make the symmetry easier to visualize. In the cubic family, the simplest examples are simple cubic (SC), body-centered cubic (BCC) and face-centered cubic (FCC). SC contains 1 atom per cell, BCC contains 2 atoms per cell and FCC contains 4 atoms per cell when atoms occupy the standard lattice positions.

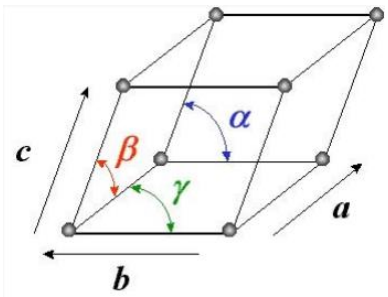


Figure 1.4 — Unit cell parameters a, b, c and interaxial angles α, β, γ.

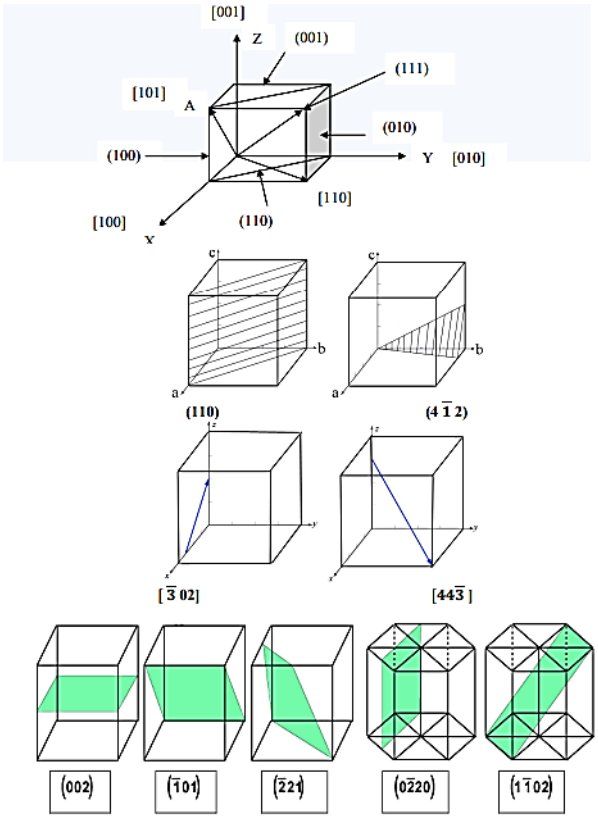


Figure 1.5 — Examples of simple and multiple unit cells, including cubic arrangements.

The Wigner-Seitz cell is a special primitive cell constructed by drawing planes that bisect the lines joining a lattice point to its nearest neighbours. It is useful because it respects the local symmetry around a lattice point.

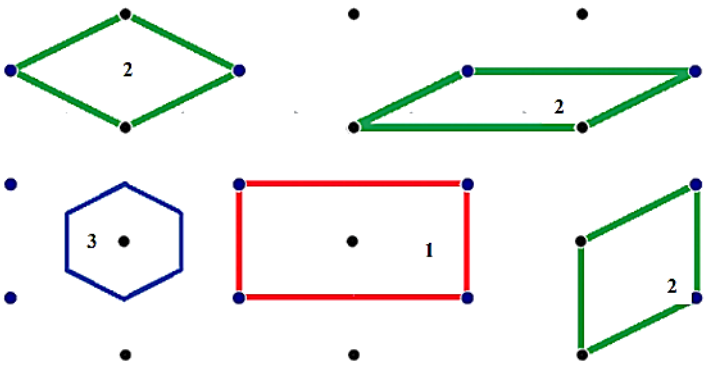


Figure 1.6 — Two-dimensional lattice construction and Wigner-Seitz-type cell concept.

1.4.2 Crystal Lattice

A crystal lattice is an infinite periodic array of mathematical points. Every point has the same environment. If a, b and c are the primitive translation vectors, the position of any lattice point is obtained from the translation vector:

$$T = u\,a + v\,b + w\,c, \text{ where } u, v \text{ and } w \text{ are integers}$$

1.4.3 Basis or Motif

The basis, also called the motif, is the atom, ion, molecule or group of atoms attached to every lattice point. The basis gives the chemical identity and internal arrangement, whereas the lattice gives the periodic geometry.

1.4.4 Crystal Structure = Lattice + Basis

A crystal structure is obtained by placing the same basis at every lattice point. This simple equation is central: lattice plus basis equals crystal structure. Two materials can have the same lattice but different bases, and therefore different crystal structures and properties.

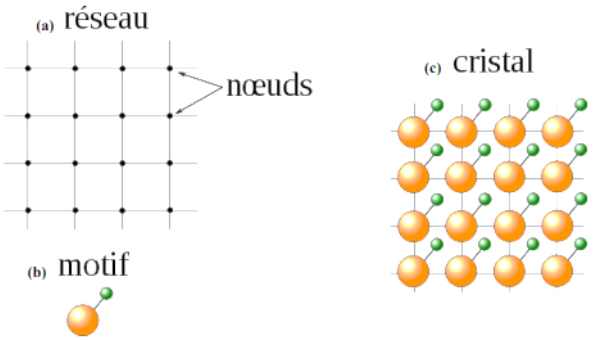


Figure 1.7 — Crystal structure as the combination of a lattice and a basis.

1.5 Seven Crystal Systems and Fourteen Bravais Lattices

Auguste Bravais showed that three-dimensional periodic lattices can be reduced to fourteen distinct lattice types. These are grouped into seven crystal systems according to the relationships between cell lengths and angles: triclinic, monoclinic, orthorhombic, tetragonal, cubic, hexagonal and rhombohedral. The four conventional lattice centering symbols are P for primitive, I for body-centered, F for face-centered and C for base-centered.

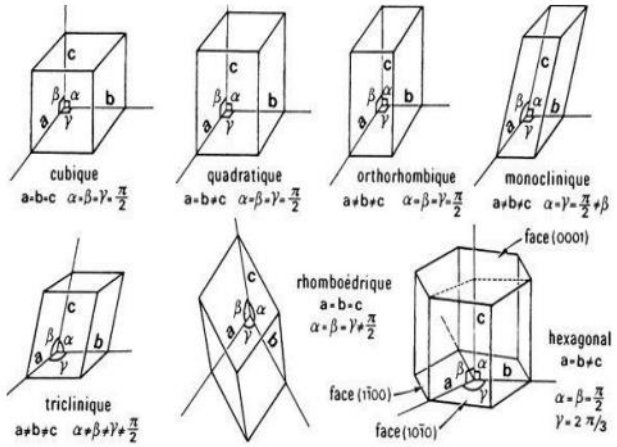


Figure 1.8 — The seven crystal systems and their unit-cell geometries.

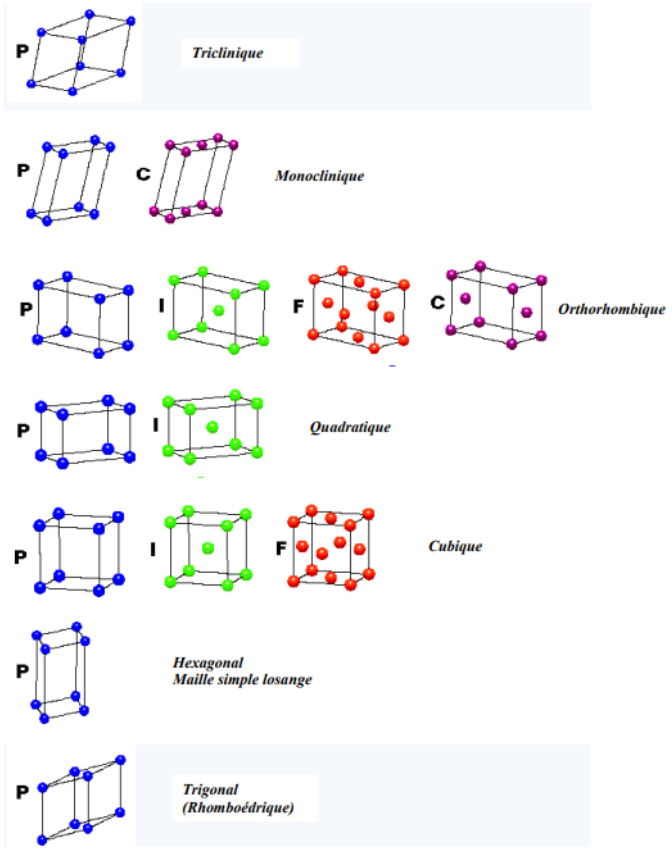


Figure 1.9 — The fourteen Bravais lattices grouped by crystal system.

Crystal system	Cell parameters	Allowed Bravais lattices	Typical examples
Triclinic	$a \neq b \neq c$; $\alpha \neq \beta \neq \gamma \neq 90°$	P	$K_2Cr_2O_7$, $CuSO_4 \cdot 5H_2O$
Monoclinic	$a \neq b \neq c$; $\alpha = \gamma = 90°$, $\beta \neq 90°$	P, C	Gypsum, monoclinic sulfur
Orthorhombic	$a \neq b \neq c$; $\alpha = \beta = \gamma = 90°$	P, C, I, F	Olivine, α-uranium
Tetragonal	$a = b \neq c$; $\alpha = \beta = \gamma = 90°$	P, I	SnO_2, martensite approximation
Cubic	$a = b = c$; $\alpha = \beta = \gamma = 90°$	P, I, F	Fe (BCC), Cu (FCC), NaCl
Hexagonal	$a = b \neq c$; $\alpha = \beta = 90°$, $\gamma = 120°$	P	Mg, Zn, graphite
Rhombohedral	$a = b = c$; $\alpha = \beta = \gamma \neq 90°$	R	Calcite, α-Al_2O_3

1.6 Miller Indices - Directions and Planes

Miller indices provide a compact notation for crystallographic directions and planes. A direction is written [uvw] and represents a vector expressed in lattice-coordinate components. A family of equivalent directions is written <uvw>. A plane is written (hkl), where h, k and l are obtained from the reciprocals of the intercepts made by the plane on the crystallographic axes. A family of equivalent planes is written {hkl}.

For a direction [uvw], the procedure is to draw the vector through the origin or translate it to the origin, express its end-point coordinates in units of a, b and c, then reduce to the smallest integers. For a plane (hkl), the procedure is to find intercepts in units of a, b and c, take reciprocals, clear fractions and reduce to the smallest integers. Negative indices are written with a bar, for example $(\bar{1}10)$.

Notation	Meaning	Example
[uvw]	Single crystallographic direction	[101] direction
<uvw>	Family of symmetry-equivalent directions	<100> cube edges
(hkl)	Single crystallographic plane	(110) plane
{hkl}	Family of symmetry-equivalent planes	{111} close-packed FCC planes
(hkil)	Miller-Bravais plane in hexagonal crystals with i = -(h+k)	(10-10) prism plane

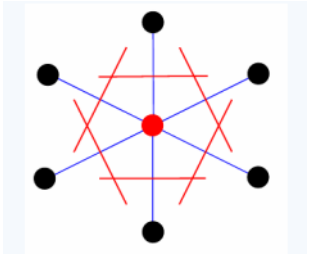


Figure 1.10 — Illustration of crystallographic planes and Miller index construction.

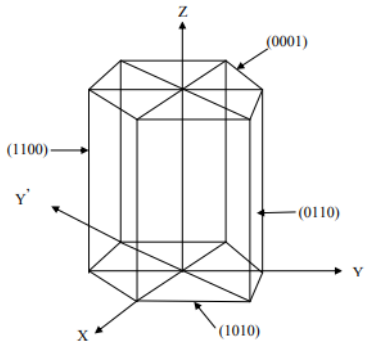


Figure 1.11 — Miller-Bravais indices for planes in the hexagonal system.

1.7 Real Crystal Structures - Crystal Defects

A perfect crystal is an ideal model. Real engineering materials contain defects. This is not a weakness of the theory; it is the reason materials can be processed and strengthened. Diffusion, plastic deformation, precipitation hardening, fracture, corrosion and electrical resistivity are all controlled by defects.

1.7.1 Point Defects (0-D)

Point defects affect only a few atomic positions. A vacancy is a missing atom on a lattice site. A self-interstitial is an atom of the host material placed in an interstitial position. A substitutional impurity replaces a host atom, whereas an interstitial impurity occupies a space between host atoms. In ionic crystals, Frenkel defects combine a vacancy and an interstitial ion; Schottky defects consist of paired cation and anion vacancies that maintain charge neutrality.

$$n_v = N\,exp(-Q_v / kT)$$

The equation shows that the equilibrium vacancy concentration increases strongly with temperature. Point defects increase diffusion rates, alter electrical resistivity and can strengthen metals through solid-solution hardening.

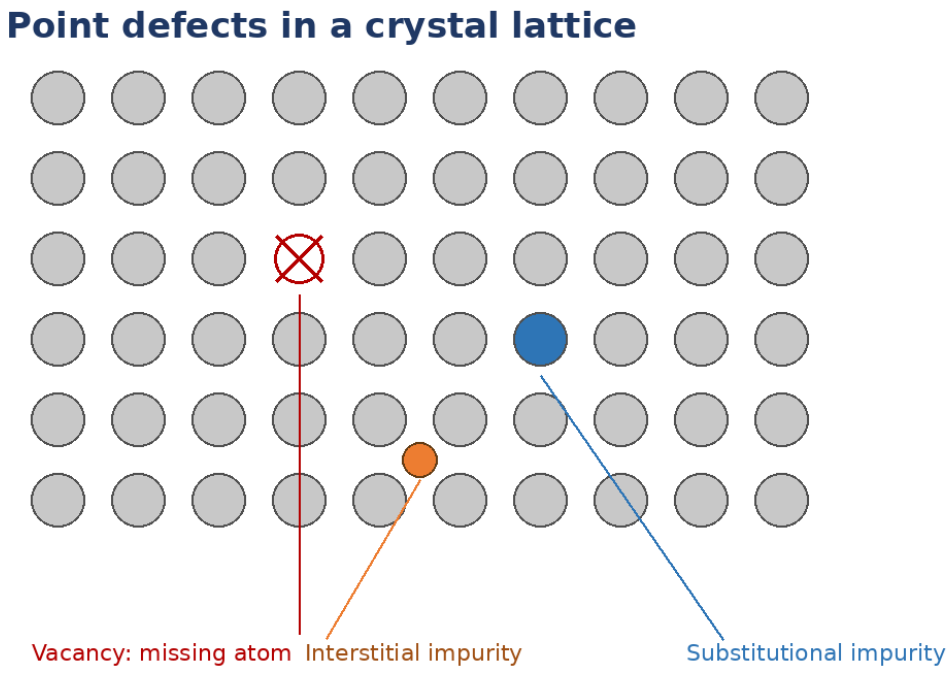


Figure 1.12 — Point defects: vacancy, substitutional impurity and interstitial impurity.

1.7.2 Line Defects - Dislocations (1-D)

Dislocations are line defects that allow crystalline materials to plastically deform at stresses far lower than the theoretical shear strength. An edge dislocation is associated with an extra half-plane of atoms; its Burgers vector is perpendicular to the dislocation line. A screw dislocation creates a helical distortion; its Burgers vector is parallel to the dislocation line. Most real dislocations are mixed.

Dislocation motion occurs mainly by glide on slip planes and, at high temperature, by climb assisted by vacancy diffusion. Work hardening increases strength because dislocations multiply and obstruct one another. Grain boundaries also stop dislocation motion, leading to the Hall-Petch effect.

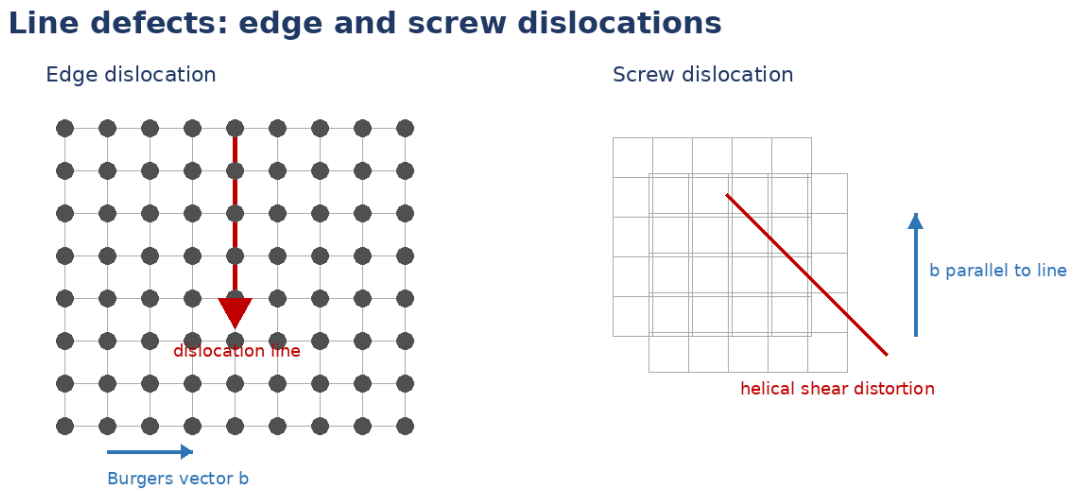


Figure 1.13 — Edge and screw dislocations with Burgers vector orientation.

1.7.3 Planar Defects (2-D)

Planar defects include grain boundaries, twin boundaries and stacking faults. Grain boundaries separate crystals of different orientations in a polycrystalline material. They impede dislocation motion, influence diffusion and can become preferential paths for corrosion or cracking. Stacking faults are local errors in the stacking sequence of close-packed planes, such as a change from ABCABC to ABABC. Twin boundaries are mirror-symmetric interfaces that may form during deformation or annealing.

$$\sigma_y = \sigma_0 + k\, d^{-1/2}$$

The Hall-Petch equation expresses the increase in yield strength as grain size d decreases. Grain refinement is therefore a major strengthening mechanism, but extremely fine grains may affect ductility, creep and thermal stability.

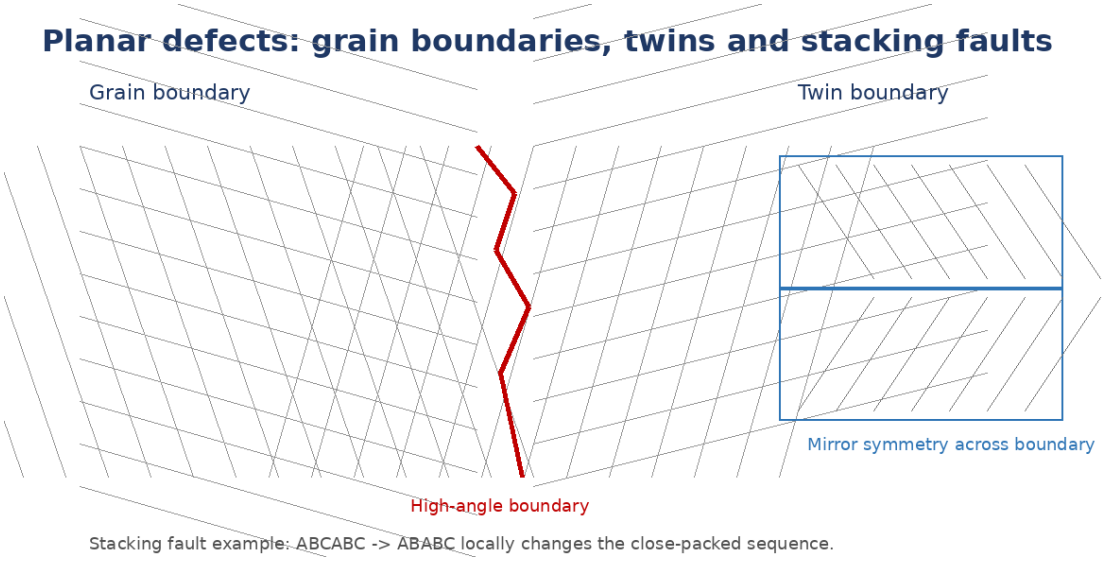


Figure 1.14 — Planar defects: grain boundary, twin boundary and stacking-fault concept.

1.7.4 Volume Defects (3-D)

Volume defects extend over a finite three-dimensional volume. Typical examples are pores, shrinkage cavities, inclusions, second-phase particles and cracks. Pores can originate during casting, welding, powder metallurgy or polymer processing. Inclusions such as oxides and sulfides may act as crack-

initiation sites. Precipitates can either strengthen an alloy or reduce toughness, depending on their size, coherency and distribution.

1.7.5 Summary of Crystal Defects

Defect class	Dimension	Examples	Main property effects
Point defects	0-D	Vacancies, interstitials, substitutional atoms	Diffusion, resistivity, solid-solution strengthening
Line defects	1-D	Edge, screw and mixed dislocations	Plastic deformation, work hardening, yield strength
Planar defects	2-D	Grain boundaries, twins, stacking faults	Strengthening, diffusion paths, corrosion sensitivity
Volume defects	3-D	Pores, inclusions, precipitates, cracks	Fracture initiation, fatigue, toughness, strengthening or embrittlement

CHAPTER 2: METALLIC MATERIALS

2.1 Phase Transformations: Definitions and Fundamental Concepts

A phase is a physically homogeneous region of matter with uniform composition, crystal structure and properties. A component is an independent chemical species needed to describe the composition of all phases. An alloy is a metallic material formed by combining a base metal with one or more elements in order to obtain improved properties.

Phase transformations are changes in the number, type, composition or structure of phases. They may occur by diffusion, by nucleation and growth, by precipitation or by diffusionless shear. The engineering importance is direct: transforming austenite into pearlite, bainite or martensite changes hardness, strength, ductility and toughness.

$$F = C - P + n$$

This is the Gibbs phase rule. F is the number of degrees of freedom, C is the number of components, P is the number of phases and n is the number of external variables considered. For condensed phase diagrams at constant pressure, n is usually 1, so F = C - P + 1.

2.1.1 Binary Solutions and Hume-Rothery Rules

A binary solution contains two components. In substitutional solid solutions, solute atoms replace solvent atoms on lattice sites. In interstitial solid solutions, smaller solute atoms occupy interstitial sites. Extensive solid solubility is favoured when the two elements have the same crystal structure, similar atomic radii, similar electronegativity and compatible valence.

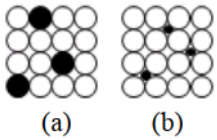


Figure 2.1 — Schematic comparison of ordered and disordered atomic arrangements in alloys.

2.2 Solidification Phenomena

2.2.1 Solidification of a Pure Metal - Nucleation and Growth

Solidification starts when a stable solid nucleus forms inside an undercooled liquid. In homogeneous nucleation, nuclei form inside the liquid without assistance from foreign surfaces. This requires a significant energy barrier because creating a solid-liquid interface costs energy. In heterogeneous nucleation, nuclei form on mold walls, inclusions or inoculant particles, which reduces the energy barrier and is much more common in industrial casting.

$$r^* = 2\gamma T_m / (\Delta H_f \Delta T)$$

The critical radius r* decreases as undercooling ΔT increases. Once the nucleus exceeds this radius, growth becomes energetically favourable. The cooling curve of a pure metal shows a thermal arrest or plateau during solidification because latent heat is released while liquid transforms into solid.

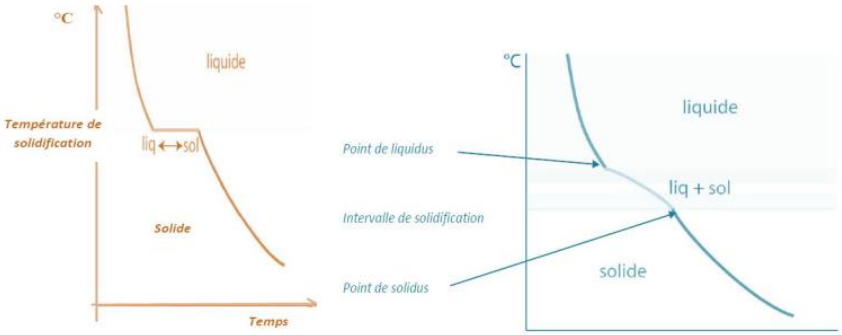


Figure 2.2 — Cooling curve and thermodynamic representation of solidification.

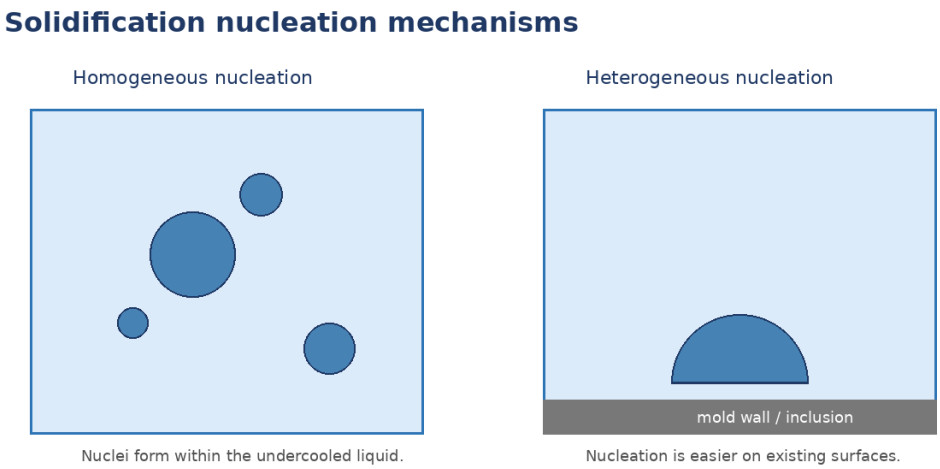


Figure 2.3 — Homogeneous and heterogeneous nucleation during solidification.

2.2.2 Solidification of Alloys - Dendritic Growth

Alloys generally solidify over a temperature interval bounded by the liquidus and solidus lines. In the two-phase region L + S, crystals grow while solute is redistributed between solid and liquid. Constitutional undercooling can destabilize the planar front and produce dendrites. A dendrite contains primary, secondary and sometimes tertiary arms, and chemical segregation may occur between dendrite cores and interdendritic liquid.

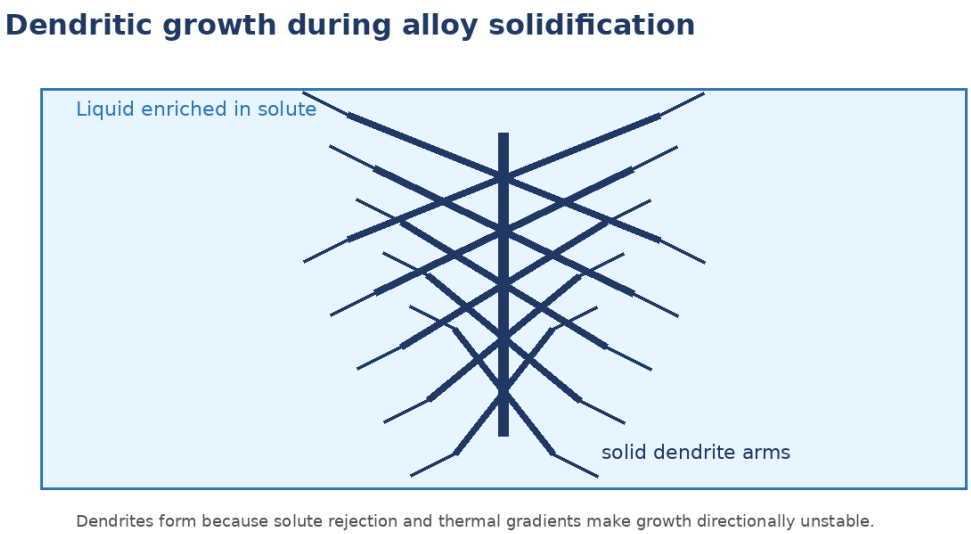


Figure 2.4 — Dendritic growth and solute redistribution in an alloy.

2.3 Binary Alloy Phase Diagrams

2.3.1 Complete Solid Solubility

A binary phase diagram with complete solid solubility contains a liquid phase L, a solid solution α and a two-phase region L + α. The Cu-Ni system is the classical example because both elements have FCC structure, similar atomic radii and compatible chemical behaviour. In the two-phase field, phase compositions are obtained from the tie line, and phase fractions are calculated using the lever rule.

fL = (CS - C0) / (CS - CL), fS = (C0 - CL) / (CS - CL)

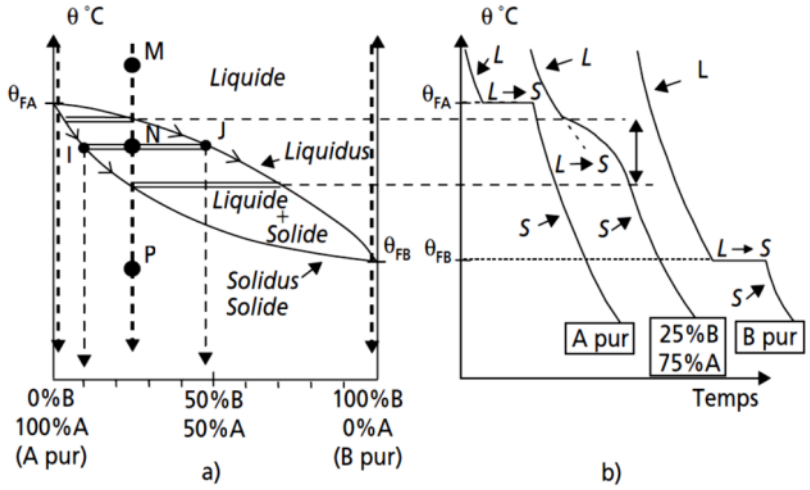


Figure 2.5 — Complete solid-solubility phase diagram and corresponding cooling curves.

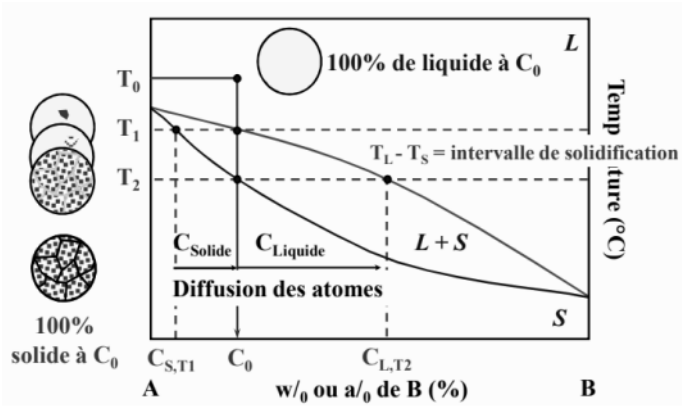


Figure 2.6 — Lever rule applied to a two-phase region.

2.3.2 Partial Solid Solubility

Many alloy systems show partial solid solubility. The eutectic transformation is written L -> α + β and occurs at a fixed temperature and composition. The eutectic microstructure is often lamellar because the two solids grow cooperatively from the liquid. The peritectic transformation is written L + δ -> γ, where a liquid reacts with an existing solid phase to form a new solid phase.

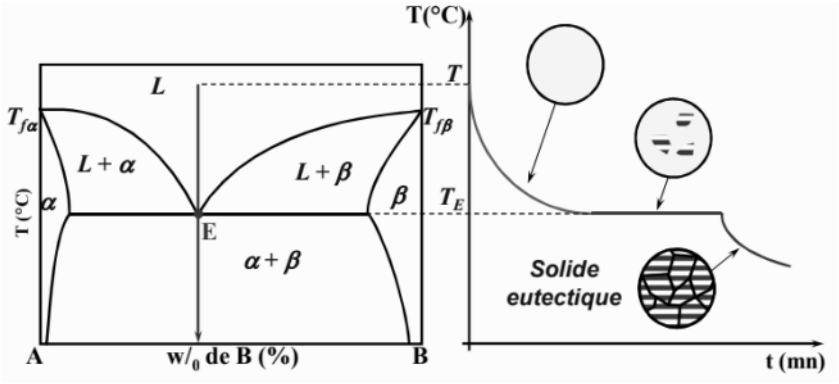


Figure 2.7 — Binary eutectic phase diagram and associated microstructural evolution.

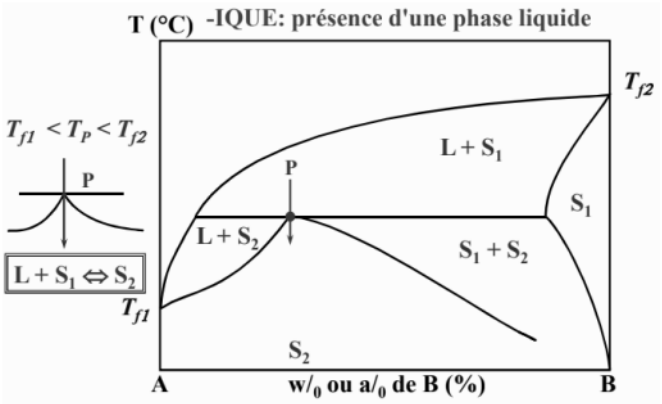


Figure 2.8 — Binary phase diagram showing regions with liquid and two solid phases.

Reaction	General form	Microstructural meaning	Typical relevance
Eutectic	L -> α + β	One liquid transforms into two solid phases	Cast irons, Al-Si alloys, solders
Eutectoid	γ -> α + β	One solid transforms into two solid phases	Pearlite in steels
Peritectic	L + δ -> γ	Liquid and solid react to form a new solid	Fe-C high-temperature region, some bronzes

2.3.3 Iron-Carbon Equilibrium Diagram

The Fe-C diagram is the most important phase diagram for steels and cast irons. Iron has allotropic forms: α-ferrite is BCC at low temperature, γ-austenite is FCC at intermediate temperature and δ-ferrite is BCC near the melting point. Carbon dissolves only slightly in ferrite but more significantly in austenite. Cementite, Fe3C, is a hard metastable carbide containing 6.67 wt% C.

The metastable Fe-Fe3C diagram contains three invariant reactions. The peritectic reaction occurs near 1494 °C and about 0.16 wt% C: L + δ -> γ. The eutectic reaction occurs at 1147 °C and 4.30 wt% C: L -> γ + Fe3C. The eutectoid reaction occurs at 727 °C and about 0.76 wt% C: γ -> α + Fe3C. The eutectoid product is pearlite, a lamellar mixture of ferrite and cementite.

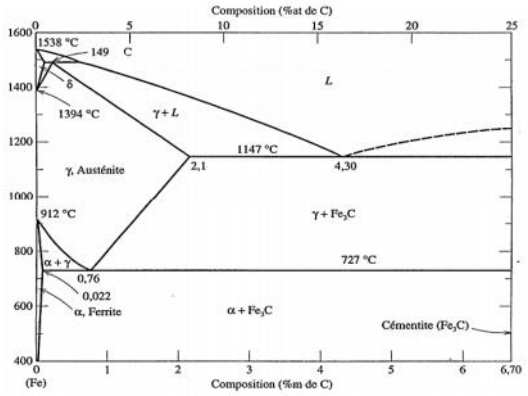


Figure 2.9 — Metastable iron-cementite phase diagram used for steels and white cast irons.

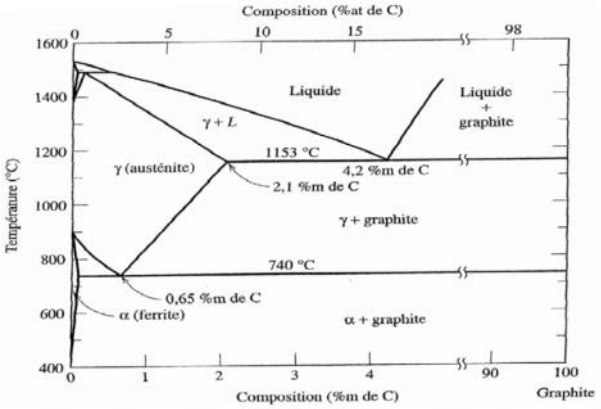


Figure 2.10 — Stable iron-carbon diagram where graphite is the stable carbon-rich phase.

Composition range	Name	Main microstructure after slow cooling	Key feature
< 0.76 wt% C	Hypoeutectoid steel	Proeutectoid ferrite + pearlite	More ductile, lower hardness
≈ 0.76 wt% C	Eutectoid steel	Pearlite	Lamellar ferrite + cementite
0.76-2.11 wt% C	Hypereutectoid steel	Proeutectoid cementite + pearlite	Harder, lower toughness
> 2.11 wt% C	Cast iron	Ledeburite, graphite or cementite depending on system	High castability, brittle unless graphite morphology is controlled

2.3.4 Applications to Light Alloys

Light alloys such as aluminium alloys are selected when low density is essential. The Al-Cu system illustrates precipitation hardening. The decreasing solubility of Cu in Al with temperature makes it possible to solution treat, quench and age the alloy to form fine precipitates. These precipitates obstruct dislocation motion and increase strength.

2.4 Solid-State Transformations

2.4.1 Transformations with Diffusion

Diffusional transformations require atomic migration. Pearlite formation is a cooperative transformation in which ferrite and cementite grow together from austenite. Bainite forms at lower temperatures than pearlite and has a finer morphology; upper bainite generally forms at about 350-550 °C, whereas lower bainite forms at about 270-350 °C. Precipitation hardening also requires diffusion, but the solute moves only short distances to create fine particles.

2.4.2 Transformations without Diffusion - Martensitic Transformation

Martensite forms when austenitized steel is cooled so rapidly that carbon cannot diffuse. The FCC austenite lattice transforms by a coordinated shear into a body-centered tetragonal structure. The transformation begins at Ms and ends at Mf. Increasing carbon content lowers Ms and Mf, increases tetragonality and raises hardness, but it also increases brittleness and retained austenite.

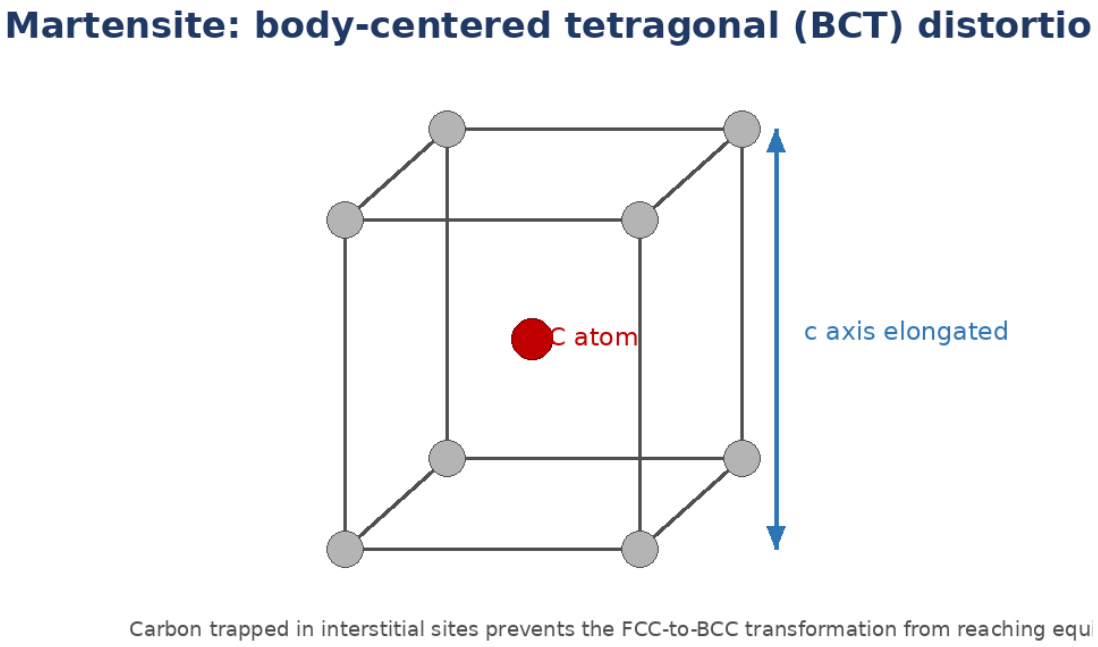


Figure 2.11 — Body-centered tetragonal distortion of martensite caused by trapped carbon.

2.5 Adaptation of Metallic Materials to Their Use

Adapting a metallic material to service means choosing a composition, microstructure, processing route and surface condition that match the functional requirements. A spring needs high elastic limit and fatigue resistance. A gear tooth needs a hard wear-resistant surface and a tough core. A welded structure needs acceptable strength but also weldability and resistance to brittle fracture. No material is universally optimal; the engineering task is to balance strength, ductility, toughness, hardness, fatigue resistance, corrosion resistance, manufacturability and cost.

The central trade-off in steels is strength versus toughness. Hard martensite is strong but brittle; tempered martensite is less hard but much tougher. Fine pearlite is stronger than coarse pearlite, while spheroidized cementite improves machinability and ductility. Grain refinement often improves both strength and toughness, but excessive heat treatment may cause grain growth and reduce performance.

2.6 Heat Treatments of Steels and Light Alloys

According to the engineering definition used in heat-treatment standards, a heat treatment is a sequence of heating, holding and cooling operations applied to a solid metallic product to obtain changes in structure and properties. It does not normally change the chemical composition; it changes the phases, grain size, residual stresses and precipitate state.

The general objectives are: improving mechanical properties, refining grains, homogenizing structure, softening for forming or machining, and relieving internal stresses created by welding, cold working

or casting. A typical cycle contains heating above or below a transformation temperature, holding for thermal and structural homogenization, and controlled cooling.

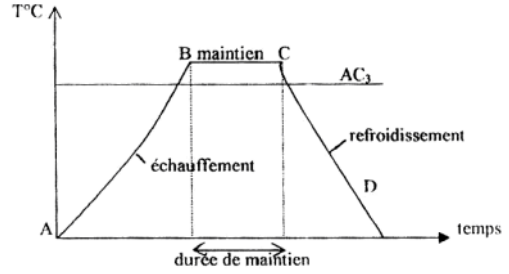


Figure 2.12 — Generic heat-treatment cycle: heating, holding and cooling.

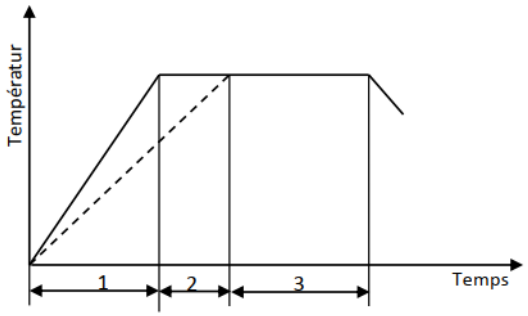


Figure 2.13 — Heating and holding stages used to define heat-treatment time.

2.6.1 TTT Diagrams

A TTT diagram, or Time-Temperature-Transformation diagram, describes isothermal transformation of austenite. The steel is first austenitized, rapidly cooled to a chosen temperature, held isothermally and then the transformation start and finish times are measured. The curves are C-shaped because transformation kinetics depend on both thermodynamic driving force and diffusion rate. The nose of the curve indicates the shortest incubation time and therefore the highest transformation rate.

TTT diagrams identify pearlite, bainite and martensite regions. Above the pearlite nose, coarse or fine pearlite can form depending on the temperature. At lower temperatures, bainite forms. Below Ms, martensite forms by diffusionless transformation. TTT diagrams are excellent for understanding transformation mechanisms and for designing isothermal treatments such as austempering.

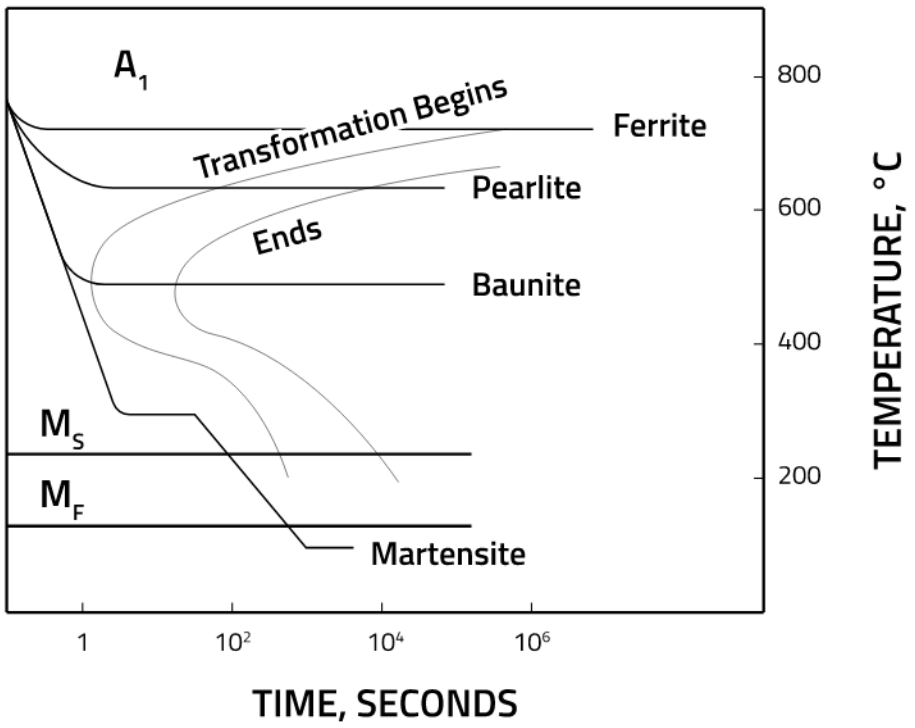


Figure 2.14 — Schematic TTT diagram showing austenite, pearlite, bainite and martensite fields.

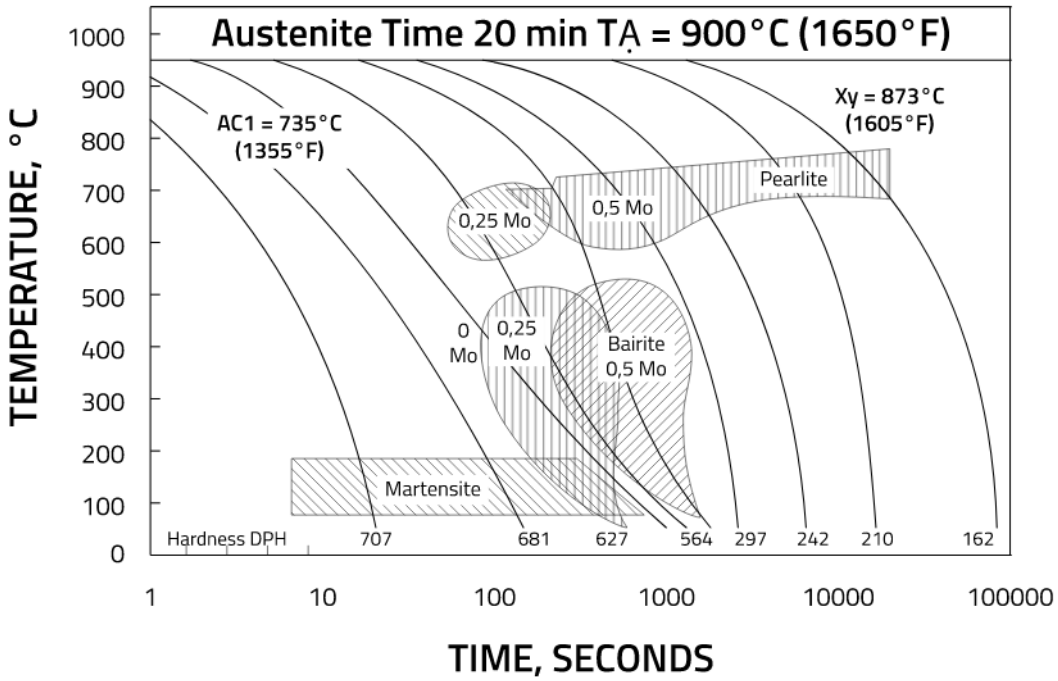


Figure 2.15 — Austenite transformation time diagram used to interpret transformation kinetics.

2.6.2 CCT Diagrams

Industrial quenching rarely uses isothermal holding; the part cools continuously. A CCT diagram, or Continuous Cooling Transformation diagram, is therefore more practical. It is read along cooling curves from high temperature toward low temperature. Compared with a TTT diagram, the transformation start and finish regions are usually displaced to lower temperatures and longer times. The critical cooling rate is the minimum rate required to avoid the pearlite or bainite nose and obtain a fully martensitic structure.

Alloying elements such as Mn, Cr, Mo and Ni often shift transformation curves to the right. This increases hardenability, meaning that martensite can form deeper below the surface and in thicker sections for a given cooling medium.

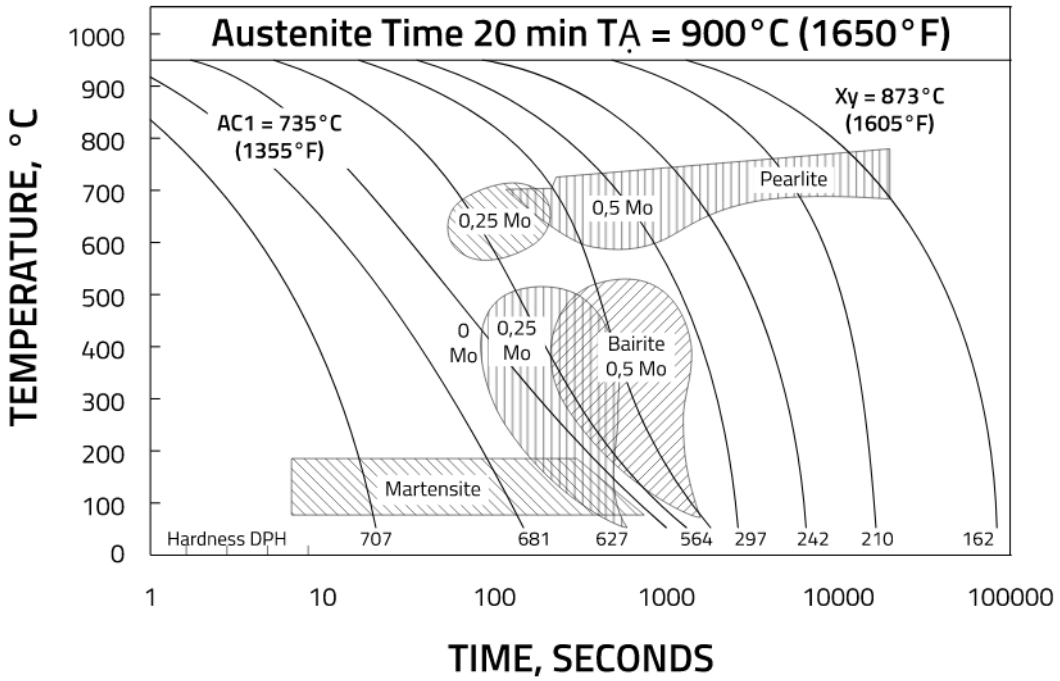


Figure 2.16 — Continuous cooling curves superimposed on transformation domains.

2.6.3 Annealing

Annealing is a softening and homogenizing treatment. Full annealing heats hypoeutectoid steels above Ac3 and cools slowly in the furnace to produce coarse pearlite and ferrite. Process annealing or stress relief is performed below the transformation range to reduce residual stresses. Recrystallization annealing restores ductility after cold working by forming new strain-free grains. Spheroidizing annealing produces globular cementite particles, improving machinability and formability in high-carbon steels.

2.6.4 Quenching

Quenching consists of austenitization followed by rapid cooling in water, oil, polymer solution, air, gas or salt bath. The goal is usually to form martensite. Water gives high cooling severity but also high distortion and cracking risk. Oil is gentler. Air hardening is possible for highly alloyed steels. Because quenched martensite is hard and brittle, quenching is normally followed by tempering.

2.6.5 Tempering

Tempering reheats quenched steel below Ac1. It reduces brittleness, lowers residual stresses and increases ductility and toughness. At low tempering temperatures, internal stresses are relieved and transition carbides may precipitate. At higher temperatures, cementite forms and coarsens. High-alloy steels may show secondary hardening around 500-600 °C because alloy carbides precipitate.

2.6.6 Normalizing

Normalizing heats steel above the austenitization range and cools it in still air. The result is usually a finer pearlitic structure than full annealing. Normalizing refines grain size, homogenizes cast or forged structures and is commonly used as a standard delivery condition for structural steels.

2.6.7 Aging and Precipitation Hardening in Light Alloys

Precipitation hardening is central for aluminium alloys such as 2XXX, 6XXX and 7XXX series. The sequence is solution treatment, quenching to obtain a supersaturated solid solution, and aging. Natural aging occurs at room temperature; artificial aging is performed at controlled temperatures, typically around 120-200 °C. The Al-Cu sequence can be simplified as supersaturated solid solution -> GP zones -> θ" -> θ' -> θ. Peak hardness occurs when fine coherent or semi-coherent precipitates effectively resist dislocation motion. Overaging coarsens precipitates and reduces strength.

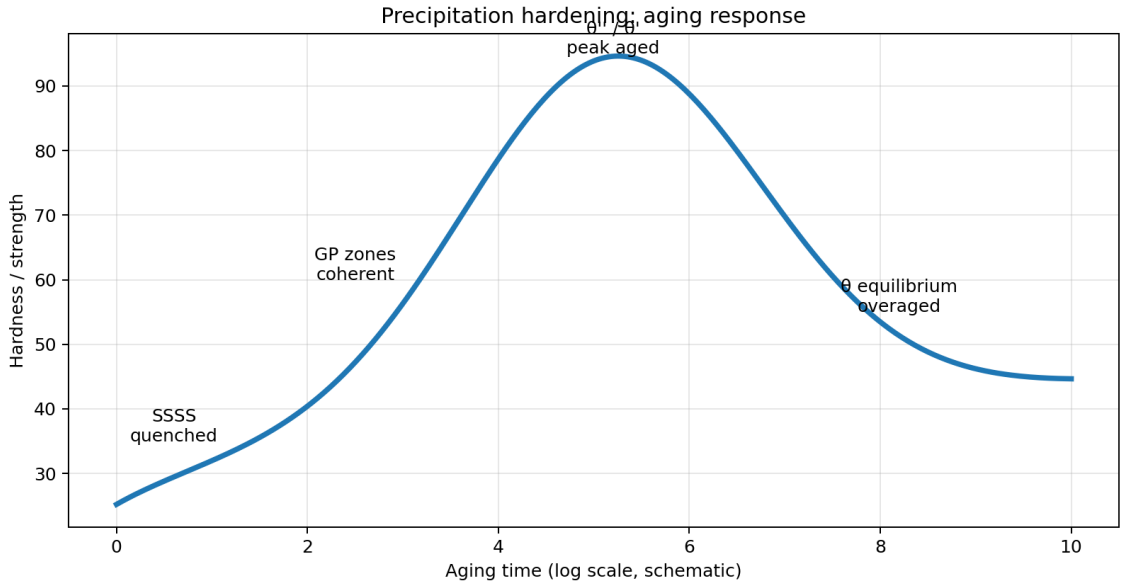


Figure 2.17 — Schematic aging curve for precipitation hardening in an Al-Cu-type alloy.

2.7 Thermochemical and Mechanical Surface Treatments

Surface treatments improve the surface without necessarily changing the entire part. This is essential because many failures begin at the surface: wear, fatigue cracks, corrosion pits and contact damage. A good surface treatment creates a hard and compressively stressed surface while preserving a tough core.

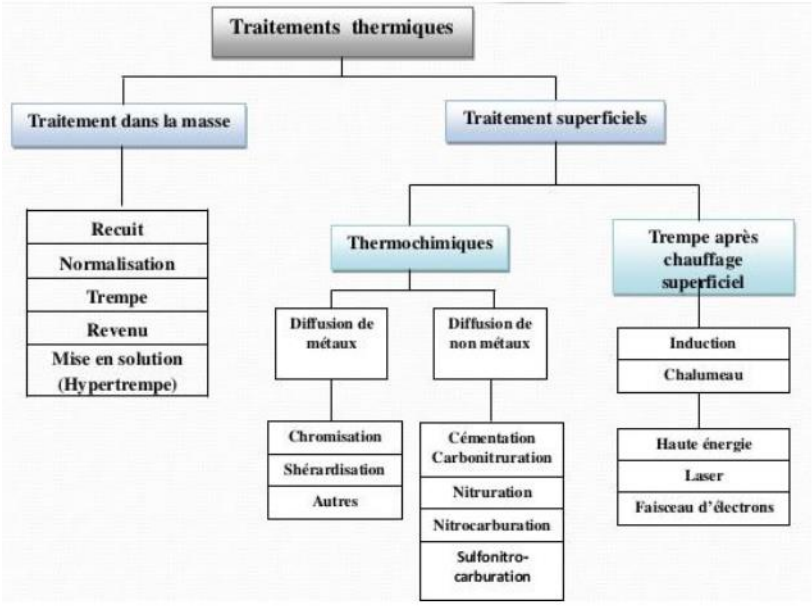


Figure 2.18 — Classification of surface treatments into mechanical, thermal and thermochemical routes.

Treatment family	Principle	Typical effect	Applications
Mechanical	Plastic deformation of surface by contact or impact	Compressive residual stresses, work hardening	Springs, gears, shafts, aircraft parts
Thermal	Localized heating followed by rapid cooling	Surface martensite, hard case	Gears, cams, rails, crankshafts
Thermochemical	Diffusion of carbon, nitrogen or other elements	Hardened chemical case and modified surface composition	Transmission parts, dies, wear components

2.7.1 Mechanical Surface Treatments

Shot peening bombards the surface with small spherical shots. The near-surface layer plastically deforms while the underlying material restrains it, creating compressive residual stresses that improve fatigue resistance. Roller burnishing uses a hard roller or ball to plastically smooth and compress the surface. Hammer peening uses repeated impacts and can produce deeper plastic deformation but is less suitable for complex geometries.

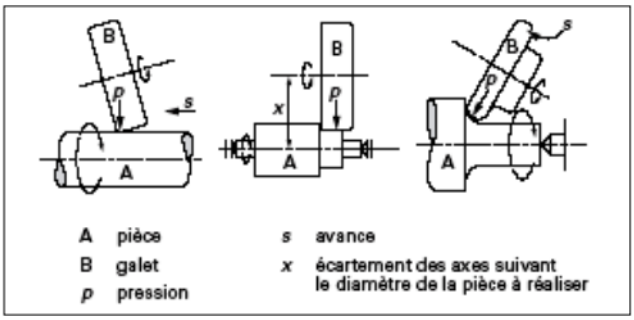


Figure 2.19 — Roller burnishing principle and process parameters.

Treatment	Mechanism	Typical depth	Advantages	Limitations
Shot peening	Impact by high-velocity shots	0.1-0.6 mm	Improves fatigue and stress-corrosion resistance	May increase roughness if poorly controlled
Roller burnishing	Hertzian contact pressure	up to a few mm	Improves roughness and fatigue strength	Requires accessible geometry
Hammer peening	Repeated localized impacts	deeper than shot peening	Useful for weld toes and simple surfaces	Limited automation and geometry

2.7.2 Thermal Surface Hardening

Thermal surface hardening heats only the surface above the austenitization temperature and then quenches rapidly. Induction hardening uses electromagnetic induction; flame hardening uses a controlled flame. Frequency controls the current penetration depth in induction hardening: high frequency gives a shallow case, while low frequency gives deeper heating. The challenge is to obtain a hardened layer without overheating, melting or creating excessive tensile residual stresses.

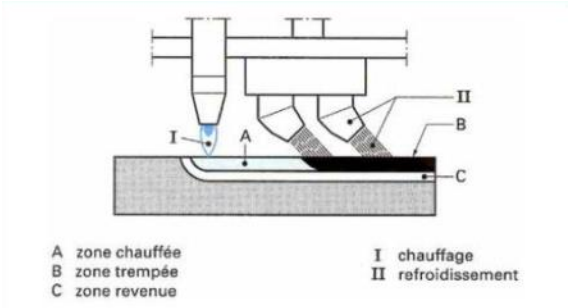


Figure 2.20 — Localized surface austenitization followed by quenching for surface hardening.

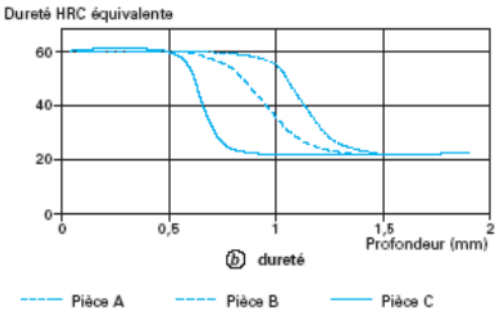


Figure 2.21 — Hardness profiles after different surface-hardening conditions.

2.7.3 Carburizing or Case Hardening

Carburizing enriches the surface of low-carbon steels with carbon at about 900-980 °C in the austenitic region. The target surface carbon is often about 0.7-0.9 wt% C. After carburizing, the part is quenched and tempered. The result is a hard high-carbon martensitic case and a lower-carbon tough core. Conventional case depths are commonly around 0.3-2.5 mm, depending on time, temperature and application.

Carburizing media include gas carburizing, pack carburizing, liquid salt baths and plasma carburizing. Effective case depth is often defined by a specified hardness level, such as the depth to 550 HV.

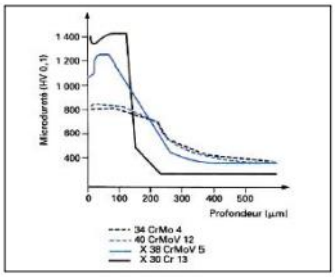


Figure 2.22 — Hardness profile after case-hardening treatments.

2.7.4 Nitriding

Nitriding introduces nitrogen into steel at about 500-575 °C in the ferritic region. Because it is performed below the austenitization temperature, no quench is required, and distortion is low. Alloy steels containing Al, Cr, Mo or V form very hard nitrides, often reaching 900-1200 HV. A nitrided surface typically contains a compound layer, sometimes called the white layer, and a diffusion zone beneath it.

Nitriding methods include gas nitriding using ammonia, salt-bath nitriding and plasma or ion nitriding. Nitriding is selected when high surface hardness, wear resistance, fatigue resistance and dimensional stability are required.

2.7.5 Chromizing

Chromizing is a diffusion treatment that introduces chromium into the surface. In low-carbon steels, the chromium-rich layer improves oxidation and corrosion resistance. In higher-carbon steels, hard chromium carbides may form, providing high wear resistance. It is a more specialized treatment than carburizing or nitriding but important for severe wear and corrosion conditions.

2.8 Corrosion: Mechanisms and Protection

2.8.1 Definition and Economic Impact

Corrosion is the deterioration of a material through chemical or electrochemical interaction with its environment. In metals, electrochemical corrosion is especially important because it couples anodic metal dissolution with cathodic reduction reactions. International corrosion studies estimate the global cost of corrosion at about 3.4 percent of global GDP, demonstrating that corrosion control is an engineering and economic necessity, not a secondary maintenance detail.

2.8.2 Elementary Corrosion Mechanisms

Dry corrosion occurs by direct chemical reaction with gases, such as oxidation in air at high temperature. The general oxidation reaction can be written M + n/2 O2 -> MnOn. Whether the oxide is protective depends on adherence, continuity and the Pilling-Bedworth ratio. Aluminium forms a compact Al2O3 film, while iron oxides often crack and detach.

Wet corrosion requires an anode, a cathode and an electrolyte. At the anode, the metal dissolves: M -> M^n+ + ne-. At the cathode, electrons are consumed by reactions such as oxygen reduction in neutral water or hydrogen evolution in acidic solution. The coupling of these reactions drives corrosion current.

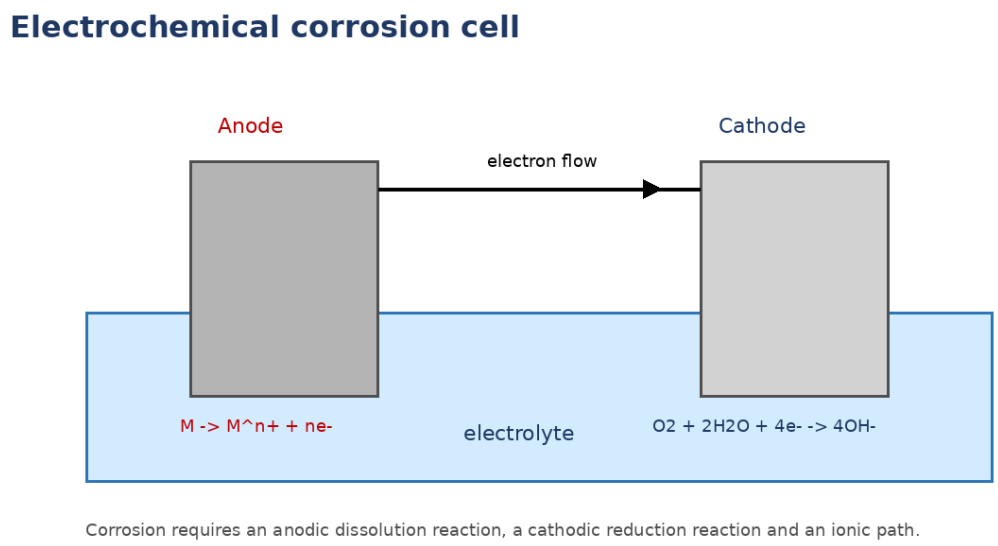


Figure 2.23 — Electrochemical corrosion cell with anodic and cathodic reactions.

Common forms of electrochemical corrosion include galvanic corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, stress corrosion cracking and fretting corrosion. Pitting is especially dangerous because small pits can become crack initiation sites while the surface appears largely intact.

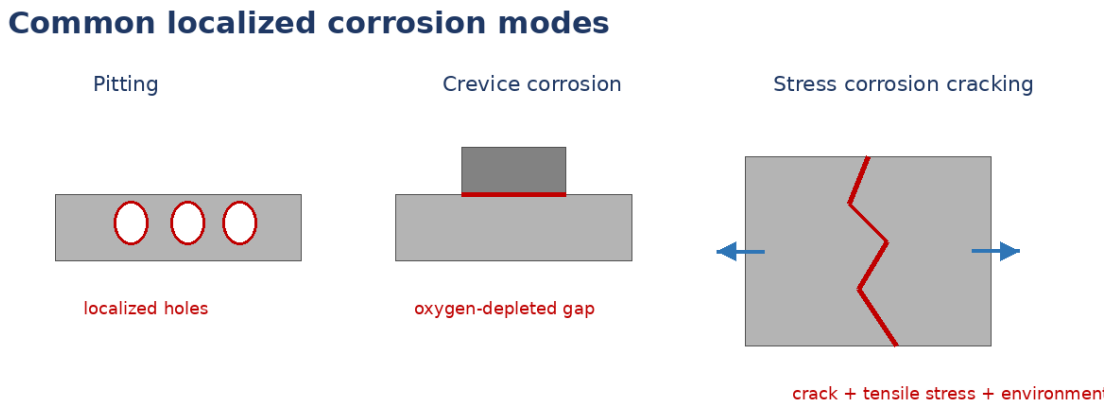


Figure 2.24 — Localized corrosion modes: pitting, crevice corrosion and stress corrosion cracking.

2.8.3 Corrosion Protection Methods

Corrosion protection methods act by changing the material, separating it from the environment, changing the electrochemical potential or modifying the environment. Stainless steels use chromium to form a passive film. Cathodic protection makes the structure the cathode by using sacrificial anodes or impressed current. Galvanizing coats steel with zinc, which acts as both a barrier and a sacrificial anode. Organic coatings, anodizing, electroplating, thermal spray, PVD and CVD coatings are selected according to service temperature, wear conditions, environment and cost.

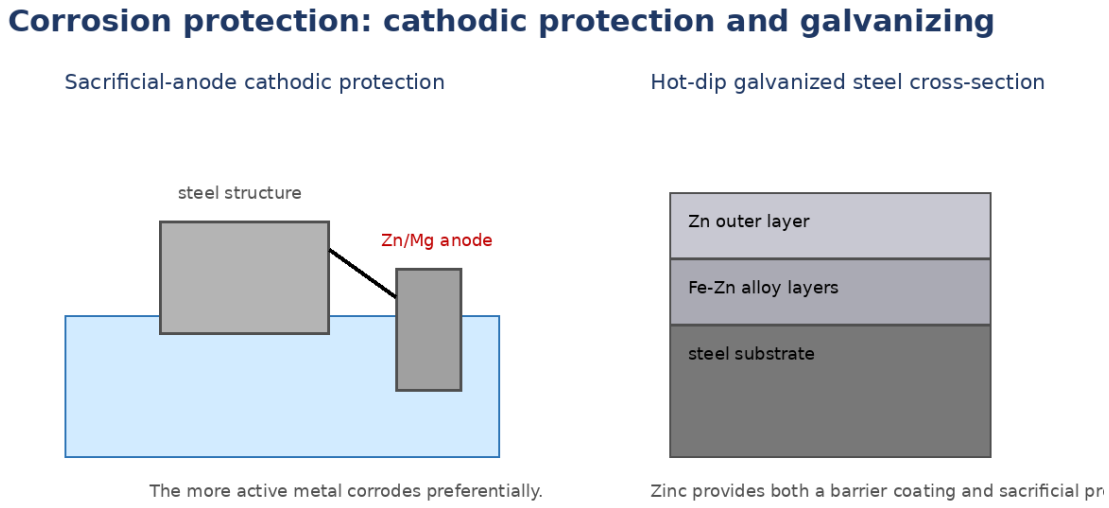


Figure 2.25 — Cathodic protection with sacrificial anode and galvanized coating cross-section.

Protection method	Principle	Typical application
Material selection	Use naturally passive or corrosion-resistant alloys	Stainless steels, Ti alloys, Al alloys
Cathodic protection	Shift metal potential so it acts as cathode	Pipelines, tanks, marine structures
Hot-dip galvanizing	Zinc barrier and sacrificial protection	Structural steel, fasteners, outdoor parts
Anodizing	Thick protective Al2O3 layer on aluminium	Architectural and aerospace aluminium
Organic coatings	Physical barrier with paint or polymer film	Bridges, vehicles, storage tanks
Inhibitors	Chemical species reduce anodic/cathodic reaction rates	Cooling circuits, acid cleaning, closed systems

CHAPTER 3: NON-METALLIC MATERIALS

3.1 Polymeric (Organic) Materials

Polymers are organic engineering materials built from macromolecules. Their apparent simplicity is misleading: the same chemical repeat unit can give a rigid transparent glass, a tough semi-crystalline solid, or a rubber-like material depending on molecular weight, chain architecture, crystallinity and crosslinking. In design, a polymer must therefore be specified not only by name, such as polyethylene or epoxy, but also by grade, additives, processing history and service temperature.

Key Concept — A polymer is a substance composed of very large molecules formed by the repetition of monomer units. Engineering plastics are useful because the chain length, chain regularity, intermolecular bonding and additives can be adjusted to tune stiffness, toughness, chemical resistance, density and processing route.

3.1.1 Molecular structure and specific characteristics of plastics

The first structural parameter is chain length, usually described by molar mass or degree of polymerization. Increasing molar mass improves entanglement density and tends to increase toughness, melt viscosity and resistance to creep, but it also makes processing more difficult. Very low molar mass polymers may be brittle or wax-like because chains slide too easily. Industrial grades often represent a compromise between mechanical performance and processability.

$$DP = M_n / M_0 \qquad (3.1)$$

In Equation (3.1), DP is the number-average degree of polymerization, M_n is the number-average molar mass of the polymer, and M_0 is the molar mass of the repeating unit. A high DP usually increases entanglement and melt viscosity.

The second parameter is chain architecture. Linear chains can pack, entangle and sometimes crystallize. Branched chains usually crystallize less easily and have lower density, as seen in low-density polyethylene compared with high-density polyethylene. Network polymers contain covalent links between chains. If the crosslink density is high, the network behaves as a rigid thermoset. If it is low and the glass transition temperature is below service temperature, the material behaves as an elastomer.

The third parameter is crystallinity. A polymer is rarely fully crystalline. It is commonly amorphous, semi-crystalline or physically mixed between ordered crystalline lamellae and disordered amorphous regions. Crystallinity generally raises density, chemical resistance, stiffness and heat distortion temperature, but it can reduce optical transparency and sometimes reduce impact toughness. Polyethylene, polypropylene, polyamides and PET may be semi-crystalline; PMMA and polystyrene are usually amorphous engineering plastics.

The fourth parameter is crosslinking density. Crosslinks suppress chain flow and prevent remelting. They increase dimensional stability, thermal resistance and solvent resistance, but they also reduce recyclability and often reduce ductility. The designer must not confuse crosslinking with crystallinity:

crystallites are physical ordered regions that may melt; crosslinks are chemical junctions that do not melt under normal processing conditions.

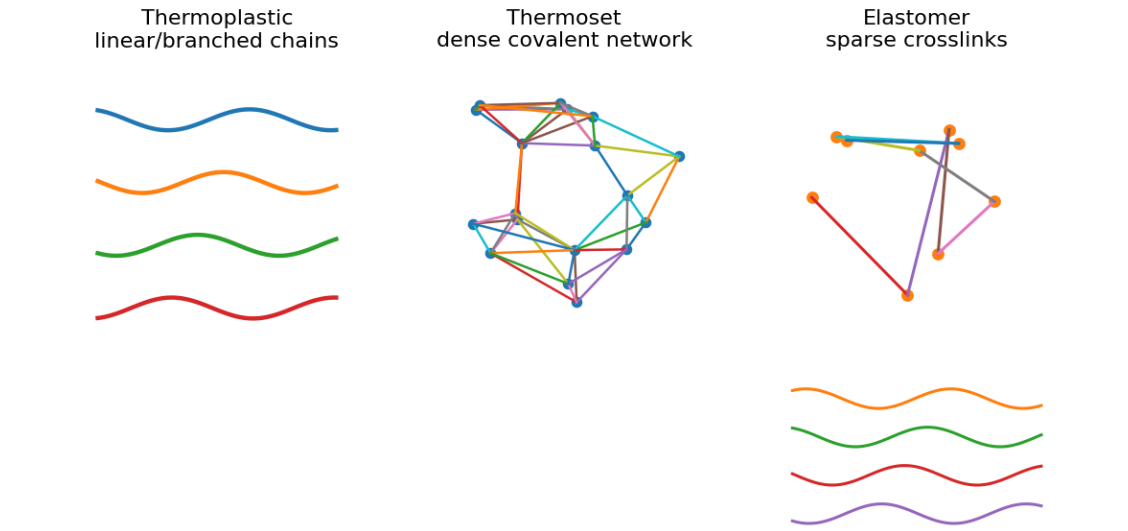


Figure 1.3 — 1 — Schematic relationship between molecular architecture and polymer family. Linear or branched chains favor thermoplastic processing, dense covalent networks produce thermosets, and sparse networks produce elastomeric behavior.

3.1.2 Thermosetting polymers

Thermosetting polymers are formed by irreversible curing reactions that create a three-dimensional covalent network. Before curing, the material may be a low-viscosity resin, a powder or a partially reacted prepolymer. During curing, chemical reactions connect the molecules; after gelation and vitrification the network becomes infusible and insoluble. Heating after cure does not return the material to a processable melt; excessive temperature causes degradation, charring or oxidation.

Epoxy resins, phenolic resins, unsaturated polyester resins, vinyl ester resins and many high-performance polyimides belong to this family. Their useful properties include good dimensional stability, high adhesive strength, low creep at moderate temperature, good chemical resistance and the ability to wet fibers in composite manufacturing. Their weak points are brittleness, difficulty of repair or recycling, and sensitivity to curing cycle, moisture and residual stresses.

Typical applications include electrical encapsulation, printed circuit boards, adhesives, protective coatings, aircraft composite matrices, marine laminates, tooling resins and high-temperature structural components. The practical engineering question is always whether the cure produces the specified network. Under-cured thermosets may retain residual monomer or low glass transition temperature; over-aggressive cure cycles can create thermal gradients and internal stress.

3.1.3 Thermoplastics

Thermoplastics consist mainly of linear or branched macromolecules held together by secondary bonds and physical entanglements. When heated above the relevant transition range, chain mobility increases and the polymer can flow. When cooled, the material solidifies again. This reversibility enables injection molding, extrusion, blow molding, thermoforming and welding. It also permits recycling by remelting, although degradation and contamination limit the number of useful cycles.

Thermoplastics may be amorphous or semi-crystalline. Amorphous grades soften over a glass transition interval and often provide transparency and dimensional accuracy. Semi-crystalline grades

have both a glass transition and a melting point; they usually offer better solvent resistance, fatigue resistance and bearing behavior, but they shrink more during processing. Common examples are PE, PP, PVC, PMMA, PA, PET, POM, PC and PEEK.

The engineer should specify thermoplastics by grade, not only by polymer name. For instance, an unfilled polypropylene, a talc-filled polypropylene and a glass-fiber-reinforced polypropylene have different stiffness, shrinkage, impact resistance, density and processing window. Additives such as stabilizers, plasticizers, flame retardants and pigments are part of the material design.

3.1.4 Elastomers

Elastomers are lightly crosslinked polymers that exhibit rubber elasticity: they can undergo very large reversible deformation because molecular chains uncoil under load and recoil when the load is removed. The glass transition temperature of an elastomer must be well below service temperature; otherwise the material becomes stiff and glassy.

Natural rubber, styrene-butadiene rubber, nitrile rubber, EPDM, butyl rubber, silicone rubber and fluoroelastomers are common examples. Vulcanization, classically using sulfur for diene rubbers, creates sparse crosslinks that prevent permanent flow while maintaining chain mobility. Silicone elastomers use different chemistry and provide useful flexibility over a wide temperature range. Elastomers are used in tires, seals, vibration isolators, flexible couplings, medical devices and electrical insulation.

Table 3.1 — Comparative summary of the main polymer families.

Family	Molecular structure	Thermal behavior	Processing method	Mechanical behavior	Typical applications
Thermoplastics	Linear or branched chains; amorphous or semi-crystalline; physical entanglements.	Reversible softening; amorphous grades soften near Tg; semi-crystalline grades melt at Tm.	Injection molding, extrusion, blow molding, thermoforming, welding, additive manufacturing for some grades.	Modulus from about 0.5 to 4 GPa unfilled; ductile or brittle depending on grade and temperature.	Packaging, pipes, housings, gears, transparent parts, films, electrical insulation.
Thermosets	Densely crosslinked three-dimensional covalent network.	Irreversible cure; cannot be remelted; excessive heat causes degradation.	Compression molding, transfer molding, casting, reaction injection molding, composite impregnation.	Higher dimensional stability; often stiff and brittle; modulus typically 2 to 6 GPa for neat resins.	Adhesives, coatings, electrical encapsulation, composite matrices, tooling, high-temperature parts.
Elastomers	Lightly crosslinked flexible chains; low Tg relative to service temperature.	Do not flow after vulcanization; remain rubbery over service range.	Compression molding, injection molding, extrusion followed by vulcanization, calendaring.	Low modulus; very high reversible strain; strong time- and temperature-dependence.	Tires, seals, hoses, gaskets, vibration mounts, flexible membranes.

Key Points — 1) Polymer properties are controlled by molar mass, architecture, crystallinity, crosslink density and additives. 2) Thermoplastics are process-reversible; thermosets cure into irreversible networks; elastomers are lightly crosslinked rubbery networks. 3) The same polymer name may hide large grade-to-grade differences, so design specifications must include grade, processing route and service conditions.

3.2 Mechanical Behavior of Polymers

Polymer mechanical behavior is governed by molecular mobility. Load, temperature and time cannot be separated. A polymer that is stiff and brittle at low temperature may become ductile near its glass transition and may flow at high temperature. Unlike many metals at room temperature, most polymers show measurable viscoelasticity even under moderate service loads.

3.2.1 Effect of temperature: Tg, rubbery plateau and viscous flow

The glass transition temperature, Tg, marks a broad transition in segmental mobility of amorphous regions. Below Tg, chain segments are largely frozen and the material behaves as a glassy solid. Near Tg, stiffness falls rapidly and damping increases. Above Tg, an uncrosslinked amorphous polymer enters a rubbery or leathery state and can eventually flow. A crosslinked elastomer cannot flow in the same way because the network restricts permanent chain displacement.

> **Engineering Note** — Tg is not a single universal number. It depends on test method, heating rate, frequency, moisture and additives. A design based on a single handbook value without safety margin is weak engineering, especially for parts exposed to heat, solvents or sustained stress.

Dynamic mechanical analysis (DMA) is especially useful because it measures storage modulus, loss modulus and damping as functions of temperature or frequency. The storage modulus represents recoverable elastic response; the loss modulus represents energy dissipation. The tan delta peak is often used to estimate the glass transition region, but it must be interpreted together with frequency and specimen history.

3.2.2 Effect of time: creep, stress relaxation and time-temperature superposition

Creep is the increase of strain with time under constant stress. Stress relaxation is the decrease of stress with time under constant strain. Both arise because chain segments rearrange progressively. A polymer bracket that passes a short tensile test may still fail by creep after months under load; this is a common design blind spot.

$$\varepsilon(t) = \sigma_0 \, J(t) \qquad (3.2)$$

In Equation (3.2), $\varepsilon(t)$ is the creep strain at time t, σ_0 is the applied constant stress, and $J(t)$ is the creep compliance. A rising $J(t)$ indicates increasing deformation under sustained load.

$$E(t) = \sigma(t) / \varepsilon_0 \qquad (3.3)$$

In Equation (3.3), $E(t)$ is the relaxation modulus, $\sigma(t)$ is the stress remaining at time t under constant strain, and ε_0 is the imposed strain.

Time-temperature superposition is based on the idea that raising temperature accelerates molecular motion in a way similar to waiting longer at lower temperature. Master curves are produced by shifting short-time data along the logarithmic time axis. The Williams-Landel-Ferry relation is often used qualitatively near Tg to describe the shift factor. The method is powerful, but it fails when aging, crystallization, moisture uptake, plasticizer loss or chemical degradation occur during the test.

3.2.3 Key mechanical properties and stress-strain curves

The basic mechanical properties used for polymers include Young modulus, tensile strength, elongation at break, yield stress, impact toughness, hardness and heat-deflection temperature. These

properties should always be associated with temperature, strain rate, humidity and specimen preparation. For instance, a notched impact test may reverse the ranking of two polymers that appear similar in tensile strength.

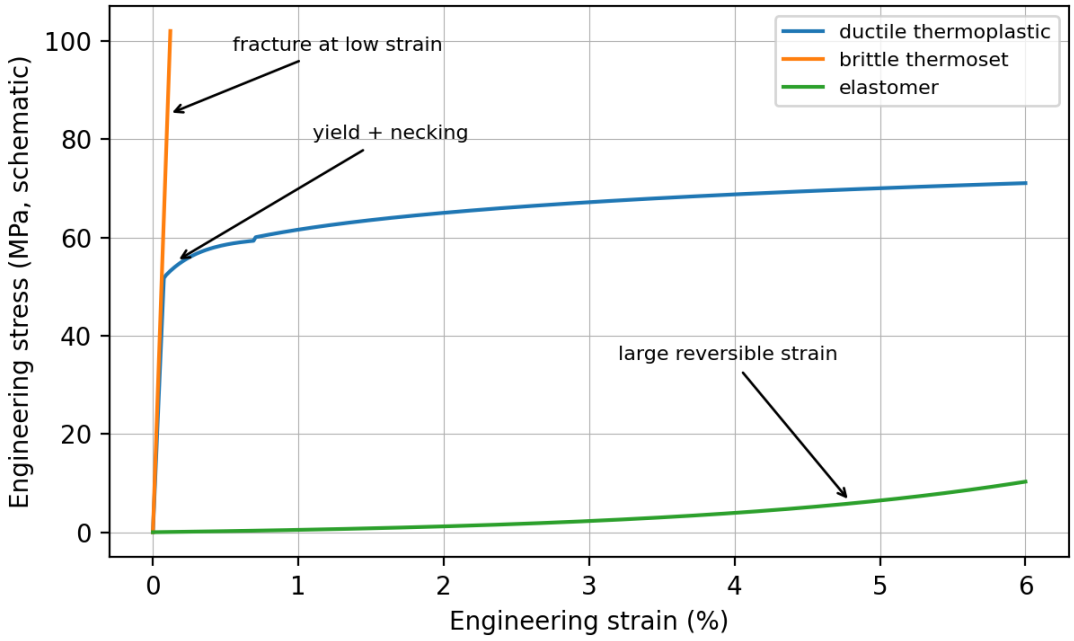


Figure 1.3 — 2 — Representative stress-strain curves for a ductile thermoplastic, a brittle thermoset and an elastomer. The axes are schematic; exact values depend on grade, temperature, strain rate and test method.

Table 3.2 — Typical mechanical property ranges for selected polymers at room temperature. Values are indicative ranges for unfilled or common grades; design must use supplier data and relevant standards.

Material / family	Young modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Impact behavior	Typical notes
LDPE / thermoplastic	0.1-0.3	8-20	100-600	High ductility	Flexible packaging, films, chemical containers.
PP / thermoplastic	1.0-1.8	25-40	50-400	Moderate; notch-sensitive at low temperature	Lightweight molded parts and living hinges.
PMMA / thermoplastic	2.4-3.3	50-80	2-10	Low to moderate	Transparent and stiff but brittle.
PA6 / thermoplastic	2.0-3.0	60-90	20-100	Good when conditioned	Moisture affects dimensions and toughness.
PET / thermoplastic	2.0-3.5	50-80	30-300	Good in oriented products	Fibers, bottles, films and engineering parts.
Epoxy / thermoset	2.5-4.5	40-90	1-6	Often brittle unless toughened	Adhesives and composite matrices.
Phenolic / thermoset	4-8	30-70	0.5-2	Brittle	Heat-resistant molded components.
Natural rubber / elastomer	0.001-0.01	15-30	400-800	Excellent resilience	Tires, mounts, flexible components.
Silicone rubber / elastomer	0.001-0.01	5-12	100-700	Moderate tear without reinforcement	Wide temperature flexibility and seals.

Key Points — 1) Polymer behavior is time-temperature dependent; short tests are insufficient for sustained-load design. 2) Tg marks the onset of large segmental mobility and a strong drop in stiffness. 3) Creep and stress relaxation must be checked for load-bearing polymer components.

3.3 Processing of Polymeric Materials

Polymer processing converts pellets, powders, sheets or reactive resins into useful shapes. The process must be compatible with molecular structure. Thermoplastics are generally processed by melting and solidification; thermosets are processed by shaping a reactive resin and then curing it; elastomers are shaped and vulcanized or crosslinked. Geometry, production volume, tolerances and surface finish then refine the selection.

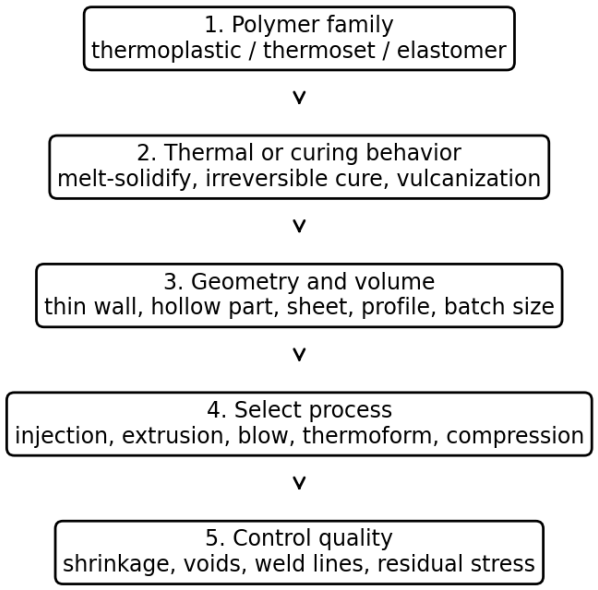


Figure 1.3 — 3 — Simplified logic for selecting a polymer forming process. The process is constrained first by polymer family, then by geometry, production volume, surface quality and property requirements.

3.3.1 Injection molding

Injection molding is the dominant process for complex thermoplastic parts produced in medium to high volume. Pellets are plasticized in a heated screw barrel, injected into a cooled mold, packed to compensate shrinkage and ejected after solidification. It provides high productivity and good dimensional repeatability, but it requires expensive tooling and careful control of shrinkage, weld lines, fiber orientation and residual stress.

3.3.2 Extrusion, blow molding and thermoforming

Extrusion forces a molten thermoplastic through a die to produce continuous sections such as pipe, sheet, film, profiles and cable insulation. Blow molding forms hollow parts by inflating a hot parison or preform inside a mold, as used for bottles and containers. Thermoforming heats a sheet and draws it over or into a mold by vacuum or pressure; it is economical for thin-walled packaging and panels but offers lower detail and property uniformity than injection molding.

3.3.3 Rotational molding, compression molding and reactive processing

Rotational molding heats powder inside a rotating mold, producing large hollow parts with low tooling cost but long cycle time. Compression molding places a charge into a heated mold and compresses it; it is common for thermosets, rubbers and sheet molding compounds. Reactive processes such as reaction injection molding and casting use low-viscosity precursors that polymerize in the mold. They

enable large parts and good wetting of reinforcements but require control of reaction kinetics and exotherm.

Table 3.3 — Mapping polymer families to recommended forming processes.

Polymer family	Recommended processes	Advantages	Limitations / risks
Thermoplastics	Injection molding, extrusion, blow molding, thermoforming, rotational molding, welding, additive manufacturing for selected grades.	Fast cycles, high volume production, recyclability by remelting, complex shapes.	Shrinkage, warpage, thermal degradation, weld lines, anisotropy in filled grades.
Thermosets	Compression molding, transfer molding, casting, reaction injection molding, resin infusion, prepreg cure.	Low resin viscosity before cure, good thermal stability after cure, excellent adhesive behavior.	Irreversible cure, exotherm, voids, cure shrinkage, limited recyclability.
Elastomers	Compression molding, transfer molding, injection molding, extrusion, calendaring followed by vulcanization.	Large elastic strain, sealing capability, vibration isolation.	Vulcanization control, flash trimming, aging, swelling, compression set.

Key Points — 1) Process selection begins with polymer family and thermal behavior. 2) Tooling cost, production volume and part geometry often dominate practical decisions. 3) Processing history controls crystallinity, fiber orientation, void content and residual stresses.

3.4 Degradation, Aging, and Solvent Sensitivity of Polymers

Polymer degradation is not a secondary topic. In many applications the first failure is not overload but aging: embrittlement, cracking, swelling, discoloration, loss of plasticizer, creep rupture or environmental stress cracking. A polymer design is incomplete until exposure conditions and lifetime are considered.

3.4.1 Thermal and thermo-oxidative degradation

Thermal degradation occurs when heat breaks covalent bonds or triggers chemical reactions such as depolymerization, chain scission, side-group elimination or crosslinking. In oxygen, thermo-oxidation often proceeds through radical reactions that create carbonyl groups, reduce molar mass and embrittle the material. The onset temperature depends on polymer chemistry, oxygen access, stabilizers, heating rate and mechanical stress.

Chain scission reduces molar mass and therefore reduces entanglement density and toughness. Crosslinking may initially increase stiffness but often makes the material brittle. The surface may age faster than the core when oxygen diffusion is limiting, producing a brittle skin over a tougher interior. This explains why cracks may initiate at the surface long before bulk properties appear severely degraded.

3.4.2 Photo-oxidation, hydrolysis and chemical attack

Photo-oxidative degradation begins when ultraviolet radiation creates excited states or radicals. Oxygen then participates in oxidation cycles. Symptoms include yellowing, chalking, surface cracking and loss of ductility. Carbon black, UV absorbers, hindered amine light stabilizers and antioxidants are used to delay the process, but they do not make the polymer immortal.

Hydrolysis is important for polymers containing hydrolysable bonds, such as polyesters, polyamides and some polyurethanes. Moisture, acids, bases and elevated temperature accelerate chain cleavage.

Chemical degradation can also involve dehydrochlorination in PVC, solvent-induced crazing in amorphous polymers, oxidation of unsaturated rubbers and extraction of additives.

3.4.3 Solvent sensitivity and service life estimation

Solvent sensitivity is often interpreted using the solubility parameter concept: chemical species with similar cohesive energy density are more likely to swell or dissolve one another. This idea is useful for screening, but it cannot replace chemical resistance testing because crystallinity, additives, residual stress and exposure temperature strongly affect behavior. Environmental stress cracking occurs when tensile stress and a chemical environment act together; each alone may be harmless, while the combination is destructive.

$$\delta = (E_coh / V_m)^{(1/2)} \qquad (3.4)$$

In Equation (3.4), δ is the solubility parameter, E_coh is cohesive energy, and V_m is molar volume. Similar δ values suggest possible swelling or miscibility, but actual compatibility must be verified experimentally.

Service life estimation combines accelerated aging, mechanistic modeling and validation under realistic conditions. Arrhenius extrapolation is common for thermally activated reactions, but it is only defensible when the degradation mechanism remains the same over the tested and service temperature ranges. A false accelerated test can be worse than no test because it creates unjustified confidence.

Engineering Note — A common design mistake is to specify a polymer using only tensile strength. For outdoor, chemical or sustained-load service, the controlling properties may be UV stability, creep resistance, oxidation rate, solvent swelling, glass transition margin or resistance to environmental stress cracking.
Key Points — 1) Degradation may occur by chain scission, crosslinking, oxidation, hydrolysis, depolymerization or additive loss. 2) Solvent compatibility must consider chemistry, stress, crystallinity and exposure temperature. 3) Accelerated aging is useful only if the degradation mechanism remains representative of real service.

3.5 Ceramic Materials - Characteristics and Classification

Ceramics are inorganic, non-metallic materials whose properties arise mainly from ionic, covalent or mixed bonding. Strong directional or electrostatic bonds give high hardness, high melting temperature, chemical stability and low plastic deformability. This combination makes ceramics excellent for severe environments but also makes them vulnerable to brittle fracture from flaws.

3.5.1 Bonding, structure and key properties

Ceramics may be crystalline, amorphous or partly crystalline and partly glassy. Alumina, zirconia, silicon carbide and silicon nitride are crystalline technical ceramics. Silica glass is amorphous. Glass-ceramics are produced by controlled crystallization of a glass. The absence of easy dislocation motion at room temperature explains why ceramics do not yield like ductile metals. Instead, tensile stress concentrates at pores, scratches and microcracks.

Typical ceramic advantages include high hardness, high compressive strength, high melting point, excellent wear resistance, chemical inertness and low density compared with many metals. Electrical behavior varies widely: many oxides are excellent insulators, while some ceramics are semiconducting, piezoelectric, ionic conducting or superconducting. Thermal conductivity also varies:

alumina is moderate, silicon carbide and aluminum nitride are high, and many porous ceramics are insulating.

3.5.2 Classification of ceramics

Table 3.4 — Classification of ceramic materials with examples, key properties and applications.

Category	Examples	Key properties	Main applications
Traditional ceramics	Clay products, brick, tile, porcelain, sanitary ware, cement-based products.	Low cost, formable from plastic clay-water mixtures, high compressive strength, variable porosity.	Construction, domestic ware, refractories, tiles, sanitary components.
Advanced / technical ceramics	Al2O3, ZrO2, SiC, Si3N4, AlN, BN.	High hardness, wear resistance, thermal stability, controlled purity and microstructure.	Cutting tools, bearings, seals, biomedical implants, substrates, engine components.
Glasses	Soda-lime glass, borosilicate glass, fused silica.	Amorphous, transparent grades available, chemically durable, brittle, formable from melt.	Windows, containers, optical fibers, labware, displays.
Glass-ceramics	Lithium aluminosilicate glass-ceramics, machinable mica glass-ceramics.	Controlled crystallization, low thermal expansion possible, good thermal shock resistance.	Cooktops, telescope mirrors, aerospace thermal components, dental restorations.
Functional ceramics	BaTiO3, PZT, ferrites, solid electrolytes, varistors.	Electrical, magnetic, piezoelectric, dielectric or ionic-conducting functions.	Capacitors, sensors, actuators, magnets, fuel cells, surge protection.

Key Points — 1) Ceramics derive high-temperature strength and hardness from strong ionic/covalent bonding. 2) Their low plasticity makes flaw control central to reliability. 3) Traditional, technical, glass, glass-ceramic and functional ceramics serve different performance windows.

3.6 Mechanical Behavior of Ceramic Materials

The most important mechanical fact about ceramics is that they usually fail by brittle fracture in tension. They may show high compressive strength but low tolerance to tensile flaws. Ceramic design is therefore a reliability problem as much as a strength problem: flaw size, surface finish, volume, stress distribution and proof testing matter.

3.6.1 Griffith fracture and fracture toughness

Griffith theory relates fracture to the balance between elastic strain energy released by crack growth and the energy required to create new surfaces. In practical engineering, the concept is expressed through the stress intensity factor and fracture toughness. If the crack-tip stress intensity reaches the material toughness, unstable fracture occurs.

$$K_I = Y \sigma \sqrt{(\pi a)} \qquad (3.5)$$

In Equation (3.5), K_I is the mode-I stress intensity factor, Y is a geometry factor, σ is applied tensile stress, and a is crack length. Failure occurs when K_I reaches K_{IC}, the plane-strain fracture toughness.

$$a_c = (1/\pi) (K_{IC} / (Y\sigma))^2 \qquad (3.6)$$

Equation (3.6) gives the critical flaw size a_c for a tensile stress σ. It shows why small changes in surface finish or defect population can strongly affect ceramic strength.

3.6.2 Weibull statistics and hardness

Because ceramic strength is controlled by the largest dangerous flaw in the stressed volume, measured strength scatters more than for ductile metals. Weibull statistics describe the probability of failure as a function of stress and volume. A high Weibull modulus means less scatter and more predictable strength; a low modulus means that proof testing, conservative design and process control are essential.

$$P_f = 1 - \exp[-(\sigma/\sigma_0)^m] \qquad (3.7)$$

In Equation (3.7), P_f is failure probability, σ is applied stress, σ_0 is a scale parameter, and m is the Weibull modulus. Higher m indicates a narrower strength distribution.

Ceramics rank high on Mohs and Vickers hardness scales because they resist plastic indentation and abrasion. Alumina, silicon carbide and silicon nitride are much harder than most steels. Hardness gives wear resistance, but it also creates machining difficulty: grinding and polishing can introduce surface cracks if not controlled.

3.6.3 Thermal shock sensitivity

Thermal shock occurs when temperature gradients create internal stresses. A hot ceramic suddenly cooled at the surface develops tensile stress at or near the surface; if the induced stress intensity exceeds toughness, cracks form. Low thermal expansion, high thermal conductivity, high strength and high toughness improve resistance. Zirconia transformation toughening and glass-ceramics with very low expansion are examples of strategies used to improve damage tolerance.

Table 3.5 — Indicative property comparison for selected ceramics, metals and polymers.

Material	Density (Mg/m^3)	Young modulus (GPa)	Strength / fracture stress (MPa)	KIC ($MPa\sqrt{m}$)	Hardness / notes
Alumina 99.5%	3.9	350-400	300-600 flexural	3-5	Very hard; excellent wear and electrical insulation.
Zirconia TZP	6.0	200-220	800-1200 flexural	6-10	Transformation toughening; good biomedical use.
Silicon carbide	3.1	400-450	300-600 flexural	3-5	High thermal conductivity and wear resistance.
Silicon nitride	3.2	280-320	700-1000 flexural	5-8	Good thermal shock and bearing applications.
Soda-lime glass	2.5	65-75	30-100 tensile	0.7-0.9	Transparent; flaw-sensitive.
Low-carbon steel	7.8	200-210	250-600 tensile	50-150	Ductile; high toughness.
Aluminum alloy 6061-T6	2.7	68-72	250-320 tensile	25-35	Low density metal; machinable.
PMMA	1.18	2.5-3.3	50-80 tensile	1-2	Transparent polymer; brittle relative to ductile plastics.
Epoxy resin	1.2	2.5-4.5	40-90 tensile	0.5-1.5	Brittle thermoset matrix.

Key Points — 1) Ceramic tensile strength is flaw-controlled, so surface quality and proof testing matter. 2) KIC and Weibull modulus are more informative than a single average strength value. 3) Thermal shock resistance depends on thermal gradients, expansion coefficient, conductivity, strength and toughness.

3.7 Processing of Ceramic Materials

Ceramic processing is mainly a microstructure-control operation. Because most ceramics are too refractory for ordinary melting and casting, many are produced from powders. Powder size, purity,

agglomeration, binder content, packing density, sintering temperature and atmosphere determine porosity, grain size and final reliability.

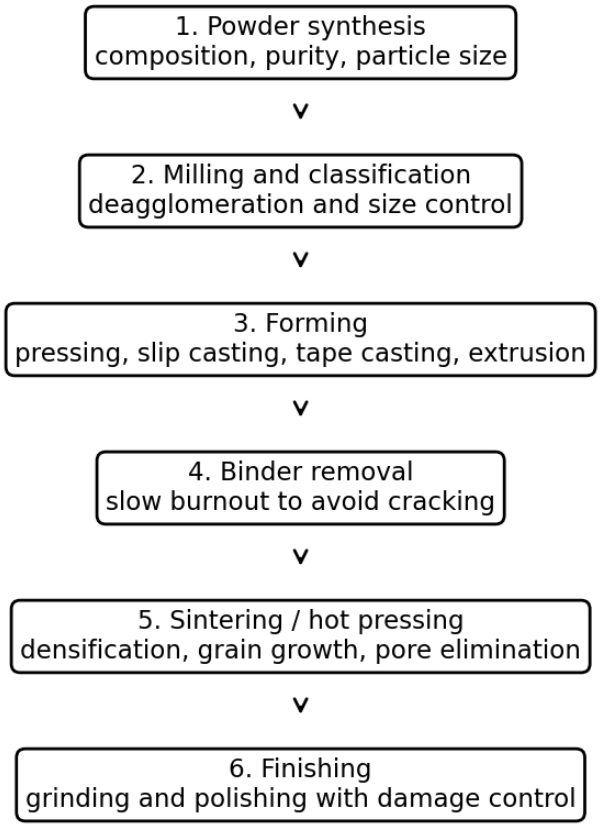


Figure 1.3 — 4 — Typical powder processing route for technical ceramics. Each step controls defect population and therefore strength reliability.

3.7.1 Powder preparation, compaction and sintering

Powder processing begins with synthesis or selection of powder, followed by milling, classification and mixing with binders or sintering aids. Forming may use uniaxial pressing for simple shapes, cold isostatic pressing for more uniform density, injection molding for complex small parts, extrusion for tubes and honeycombs, or tape casting for thin ceramic sheets. Binder burnout must be slow enough to avoid cracking.

Sintering densifies the compact by atomic diffusion. Solid-state sintering occurs without a liquid phase; liquid-phase sintering uses a transient or persistent liquid to accelerate densification. Hot pressing and hot isostatic pressing apply pressure during high-temperature exposure to reduce porosity. Spark plasma sintering uses pulsed current and pressure to obtain rapid densification and fine microstructures, although scale and cost can limit industrial use.

3.7.2 Casting, glass forming and coatings

Slip casting uses a stable ceramic suspension poured into a porous mold; water removal deposits a powder layer. Tape casting produces thin sheets for electronic substrates and multilayer components. Gel casting uses polymerization of a monomer solution to form a strong green body with complex geometry.

Glasses are processed from melts by casting, pressing, blowing, drawing or float glass production. Float glass forms a flat ribbon on molten tin, providing excellent surface quality for windows and displays. Chemical vapor deposition is used for ceramic coatings and thin films such as SiC, diamond-like carbon or protective oxides. Post-processing by grinding, lapping and polishing is common, but expensive because hardness and brittleness demand diamond tools and careful damage control.

Key Points — 1) Powder route ceramics are highly sensitive to green density, pore distribution and sintering schedule. 2) Glass forming differs from ceramic powder processing because a viscous melt is shaped directly. 3) Finishing can improve dimensional accuracy but can also introduce critical surface flaws.

3.8 Composite Materials - Definition and Classification

A composite material combines at least two distinct phases to obtain a property profile that cannot be achieved as efficiently by either phase alone. The matrix binds and protects the reinforcement, transfers load and defines many environmental limits. The reinforcement provides stiffness, strength, toughness, wear resistance or thermal function. The interface or interphase controls stress transfer and damage evolution; it is often the difference between a strong composite and a weak mixture.

Key Concept — A composite is a designed multiphase material. In fiber composites, the material and the structure are partially created at the same time; fiber orientation, stacking sequence, fiber volume fraction, void content and cure history are part of the material definition.

3.8.1 Classification by matrix and reinforcement geometry

Polymer matrix composites include glass-fiber-reinforced polymers (GFRP), carbon-fiber-reinforced polymers (CFRP), aramid-fiber composites and short-fiber thermoplastics. Metal matrix composites include aluminum reinforced with silicon carbide particles or fibers. Ceramic matrix composites such as SiC/SiC are developed for high-temperature applications where monolithic ceramics would be too brittle.

Reinforcement geometry may be continuous unidirectional fibers, woven fabrics, braided preforms, chopped fibers, particles, flakes or whiskers. Continuous fibers provide the highest directional stiffness and strength, but properties transverse to the fibers and through thickness remain much weaker. Particulate composites are more isotropic but usually provide lower reinforcement efficiency.

3.8.2 Anisotropy and micromechanics

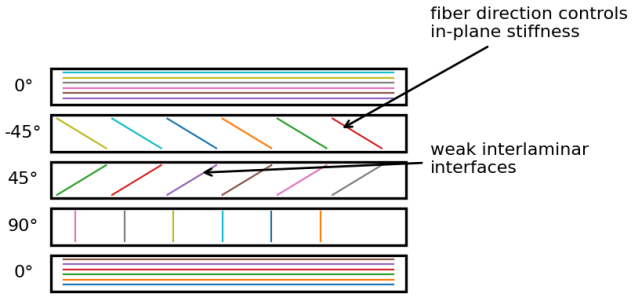
Anisotropy means that properties depend on direction. A unidirectional carbon/epoxy ply may be very stiff along the fibers and much less stiff transverse to them. The designer uses laminate stacking sequence to distribute stiffness and strength in the required directions. This creates opportunity and risk: composites can outperform metals in specific stiffness, but only when load paths and damage modes are understood.

$$E_L = V_f E_f + V_m E_m \tag{3.8}$$

Equation (3.8) is the longitudinal rule of mixtures for a continuous fiber composite loaded parallel to the fibers. E_L is longitudinal modulus, E_f and E_m are fiber and matrix moduli, and V_f and V_m are their volume fractions.

$$1/E_T = V_f/E_f + V_m/E_m \tag{3.9}$$

Equation (3.9) is the inverse rule of mixtures for transverse modulus in a simplified iso-stress model. It illustrates why transverse stiffness is dominated by the matrix and interface when fibers are much stiffer than the matrix.



Cross-ply and angle-ply stacking creates tailored anisotropy; the laminate is a designed material, not merely a shaped material.

Figure 1.3 — 5 — Schematic of a laminated composite. Fiber direction in each ply controls in-plane stiffness, while interlaminar interfaces are common paths for delamination.

Table 3.6 — Typical properties of common reinforcing fibers.

Fiber	Density (Mg/m^3)	Tensile modulus (GPa)	Tensile strength (GPa)	Failure strain (%)	Design notes
E-glass	2.55	70-80	2.0-3.5	2.5-4.5	Low cost, good electrical insulation, used in GFRP.
S-glass	2.49	85-90	4.0-4.8	4-5	Higher strength and cost than E-glass.
Carbon, standard modulus	1.75-1.85	230-250	3.5-5.5	1.5-2.2	High specific stiffness; electrically conductive; galvanic issues with metals.
Carbon, high modulus	1.85-1.95	350-600	2.0-4.5	0.5-1.2	Very high stiffness but lower strain to failure.
Aramid / Kevlar	1.44	70-130	2.8-3.6	2-4	Excellent toughness and impact resistance; moisture and compression limitations.

Key Points — 1) Composite properties depend on constituents, fiber volume fraction, architecture and interface. 2) Continuous fibers are efficient parallel to their axis but create anisotropic design constraints. 3) Rule-of-mixtures models are useful first estimates, not substitutes for laminate testing and allowables.

3.9 Processing of Composite Materials

Composite processing must place reinforcement, impregnate it with matrix, remove voids, consolidate the laminate and cure or solidify the matrix without damaging fibers. The process determines fiber volume fraction, void content, fiber waviness, residual stresses and therefore mechanical performance.

3.9.1 Open-mold and liquid composite molding

Hand lay-up is simple and flexible: dry fabric or mat is placed in a mold and impregnated manually with resin. Spray-up uses chopped fibers and resin sprayed onto a mold. These processes are low cost and suitable for large parts, but fiber volume fraction, void content and surface quality are less controlled than in closed-mold processes.

Resin transfer molding places dry reinforcement in a closed mold and injects resin under pressure. Vacuum-assisted resin infusion uses vacuum to draw resin through a dry preform under a flexible bag.

Both methods improve surface quality and emissions control compared with open molding. Their success depends on permeability, resin viscosity, injection strategy, vacuum integrity and cure cycle.

3.9.2 Prepreg autoclave, filament winding and pultrusion

Prepregs are reinforcements pre-impregnated with a controlled amount of partially cured resin. Autoclave processing uses vacuum, heat and external pressure to consolidate the laminate and cure the resin, producing high fiber volume fraction and low void content for aerospace structures. The price is high equipment cost, freezer storage, labor-intensive lay-up and long qualification cycles.

Filament winding places continuous fibers under tension onto a rotating mandrel. It is efficient for pressure vessels, pipes, rocket motor cases and tanks where fibers follow hoop and helical load paths. Pultrusion pulls fibers through a resin bath and heated die to create continuous constant-section profiles such as rods, beams and channels. Both processes show how composite processing and structural design are inseparable.

Engineering Note — Void content is not a cosmetic defect in structural composites. Voids reduce matrix-dominated properties, fatigue resistance and interlaminar strength; they can also act as moisture pathways and crack initiation sites.
Key Points — 1) Composite processing controls fiber placement, impregnation, consolidation and cure. 2) Autoclave prepreg processing gives high performance but high cost. 3) Filament winding and pultrusion are efficient when geometry and load paths are compatible with continuous fibers.

3.10 Joining and Machining of Composite Materials

Machining and joining composites are difficult because the material is heterogeneous and anisotropic. A cutting tool may meet hard abrasive fibers and soft matrix in the same operation. Heat cannot always dissipate quickly, and local damage may be hidden below the surface. Design must minimize secondary machining where possible, but holes and joints remain unavoidable in many assemblies.

3.10.1 Machining and drilling challenges

Common machining defects include delamination, fiber pull-out, matrix smearing, uncut fibers, burrs, thermal damage and rapid tool wear. Carbon and glass fibers are abrasive, so carbide or diamond-coated tools are often required. Drilling is particularly critical because holes introduce stress concentrations and can create entry or exit delamination. Feed rate, spindle speed, drill geometry, backup support and tool wear must be controlled. Dust extraction and personal protection are essential, especially for carbon and glass fiber particles.

3.10.2 Adhesive bonding, mechanical fastening and co-curing

Adhesive bonding distributes load over an area and avoids drilling holes, but it requires surface preparation, contamination control, adhesive selection and joint design that reduces peel stress. Scarf and stepped joints are more efficient than simple butt joints. Mechanical fastening is familiar and inspectable, but holes cut fibers and create bearing, net-tension, shear-out and delamination risks. Hybrid bonded-bolted joints are sometimes used to combine load transfer with damage tolerance.

Co-curing bonds uncured composite parts in the same cure cycle. Co-bonding joins a cured part to an uncured part. Secondary bonding joins cured parts with a separate adhesive. CFRP joined to aluminum or steel can suffer galvanic corrosion if the carbon fibers electrically contact the metal in the presence of an electrolyte; isolation layers, sealants and compatible fasteners are therefore important.

Key Points — 1) Composite machining creates mechanical and health risks that must be designed and controlled. 2) Adhesive bonding avoids holes but demands excellent surface preparation and joint geometry. 3) Bolted joints are inspectable but weaken laminates through stress concentration and fiber interruption.

3.11 Specific Mechanical Behavior of Composite Materials

Composite failure is usually progressive rather than a single yielding event. Matrix cracks, fiber breaks, interface debonding and delamination may appear in sequence. A laminate can retain some stiffness after initial damage, but hidden damage may reduce compression strength or fatigue life severely.

3.11.1 In-plane and out-of-plane behavior

In-plane properties are controlled mainly by fiber orientation and stacking sequence. Along fibers, continuous-fiber composites can reach very high specific stiffness and strength. Transverse and interlaminar properties are controlled more by matrix and interface; they are usually much weaker. Out-of-plane loading, impact, free-edge stresses and bolted joints therefore need special attention.

3.11.2 Failure modes, fatigue and impact

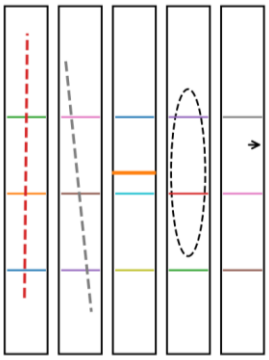


Figure 1.3 — 6 — Typical damage mechanisms in fiber-reinforced composites. Real failures often combine several mechanisms, making inspection and damage tolerance essential.

Main failure modes include fiber breakage, matrix cracking, delamination, interfacial debonding and fiber pull-out. Fiber breakage is critical for longitudinal tensile strength. Matrix cracking reduces transverse stiffness and opens paths for moisture. Delamination separates plies and can grow under compression, bending or fatigue. Interface debonding and fiber pull-out can absorb energy but may also reduce load transfer.

Fatigue in composites differs from metals. Metals often initiate a crack that grows as a dominant defect; composites accumulate distributed damage. The S-N curve may not show a classical endurance limit, and stiffness reduction can be a useful damage indicator. Impact damage is especially dangerous for CFRP because barely visible impact damage can create internal delamination. Compression-after-impact testing evaluates residual compressive strength after a controlled impact event.

Table 3.7 — Summary comparison of composites, metals and polymers for structural design.

Criterion	Fiber composites	Metals	Unreinforced polymers
Specific strength	Very high when fibers aligned with load; poor transverse performance if not designed.	Moderate to high; more isotropic and ductile.	Low to moderate; highly grade-dependent.
Specific stiffness	Excellent for CFRP; good for GFRP; direction-dependent.	Good but density penalty for steels and titanium.	Low except highly filled or reinforced grades.
Fatigue resistance	Good when strain levels and defects are controlled; damage	Well-characterized; crack growth methods mature.	Creep and thermal effects often dominate.

Criterion	Fiber composites	Metals	Unreinforced polymers
	is progressive and inspection is difficult.		
Impact and damage tolerance	GFRP/aramid good; CFRP may hide delamination and needs CAI checks.	Often ductile with visible plastic deformation.	Varies widely; notches, temperature and rate are critical.
Cost and manufacturing	High for aerospace-grade prepregs; lower for glass/polyester and pultrusion.	Mature supply chains and fast forming for many alloys.	Low to moderate; high productivity in injection molding.
Design challenge	Anisotropy, joints, inspection, allowables, repair.	Corrosion, fatigue cracks, mass, forming limits.	Creep, aging, low stiffness, temperature limits.

Key Points — 1) Composite design must consider directional properties and progressive damage. 2) Delamination and impact damage are central risks in laminated composites. 3) Specific stiffness and strength advantages are real only when load paths, joining and manufacturing quality are controlled.

CHAPTER 4: MATERIALS SELECTION CRITERIA

4.1 Introduction to Materials Selection

Materials selection is a central engineering decision because it links function, geometry, process, cost, durability, safety and environmental impact. A technically strong design can fail commercially if the material is too expensive, unavailable or difficult to process. Conversely, a cheap material can become costly if it causes warranty failures, excessive weight, corrosion, machining problems or short service life.

The modern selection process is systematic rather than intuitive. It does not begin by asking, "Which material do I like?" It begins by asking what the component must do, what it must never fail to satisfy, what should be optimized and what variables remain free. The Ashby approach expresses this logic as translation, screening, ranking and documentation.

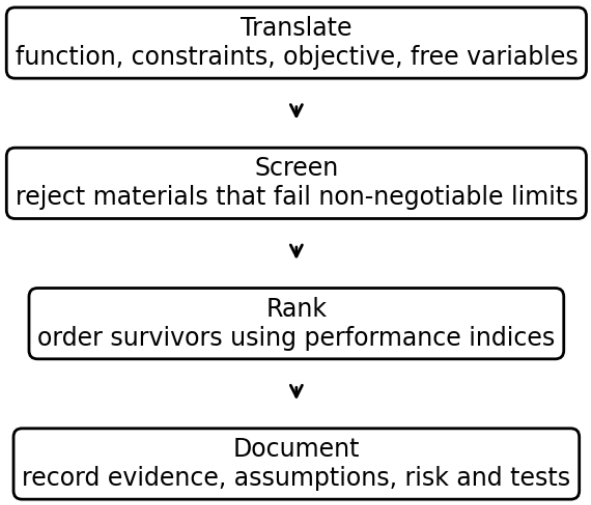


Figure 1.4 — 1 — Structured materials selection sequence. Translation defines the problem; screening removes unacceptable candidates; ranking orders survivors; documentation records evidence and risk.

4.1.1 The four stages: translation, screening, ranking and documentation

Translation converts the design problem into engineering language: function, constraints, objectives and free variables. Screening eliminates materials that cannot meet non-negotiable constraints such as maximum service temperature, minimum fracture toughness, corrosion resistance, electrical insulation, food-contact approval or manufacturing route. Ranking orders the remaining candidates using performance indices, cost models or weighted criteria. Documentation records data sources, assumptions, risks, standards and reasons for rejection or selection.

Key Concept — A constraint is a pass/fail requirement. An objective is a quantity to maximize or minimize among candidates that pass the constraints. Treating an objective as a constraint, or a constraint as an objective, is a common source of poor material decisions.

4.1.2 Material properties and component performance

A component does not experience a material property in isolation. It experiences a combination of material, shape, manufacturing defects, environment and loading history. Stiffness depends on E and geometry. Mass depends on density and volume. Cost depends on material price, process yield, tooling, finishing, inspection and lifetime. Therefore, material choice must be coupled with process and geometry rather than made from a property table alone.

$$P = f(F, G, M) \qquad (4.1)$$

In Equation (4.1), P is the performance measure to be optimized, F represents functional requirements and loading, G represents geometry, and M represents material properties. Materials selection seeks the material-property group that improves P while satisfying constraints.

Key Points — 1) Materials selection is an engineering decision linking product, material and process. 2) The Ashby sequence is translation, screening, ranking and documentation. 3) A high property value is not enough; the property must improve the component-level performance index.

4.2 Functional Analysis of a Component

Functional analysis identifies what the component must do before deciding what it should be made from. The discipline here is important: premature attachment to a familiar material prevents better solutions from emerging. A mature engineer separates function from solution. “A steel bracket” is not a function; “support a static load with limited deflection in a corrosive environment at minimum mass and cost” is closer to a functional statement.

4.2.1 Required qualities and quantitative requirements

Required qualities may be mechanical, thermal, electrical, chemical, aesthetic, acoustic, tactile, regulatory or environmental. Mechanical requirements include stiffness, strength, fatigue resistance, fracture toughness, wear resistance and creep resistance. Thermal requirements include conductivity, expansion, maximum service temperature and thermal shock. Chemical requirements include corrosion, oxidation, solvent resistance and moisture uptake. Aesthetic requirements include color, surface finish, transparency and perceived quality.

The task is to translate each requirement into measurable material properties or tests. “Strong” becomes minimum yield strength, tensile strength, fatigue limit or fracture toughness depending on failure mode. “Lightweight” becomes low density combined with stiffness or strength index. “Works outdoors” becomes ultraviolet resistance, water absorption, temperature range and chemical resistance. Vague requirements should be challenged until they become testable.

4.2.2 Deriving performance indices

A performance index is derived by writing a model for the component and isolating the material-property group that controls the objective. For a light beam of fixed length and specified stiffness in bending, mass decreases when the ratio E^(1/2)/rho increases. The exact index depends on loading

mode, geometric freedom and objective. A tension tie, a beam, a pressure vessel and a spring do not share the same best material index.

$$P = f_1(F)\, f_2(G)\, f_3(M) \qquad (4.2)$$

Equation (4.2) expresses separability: if performance can be separated into functional, geometric and material groups, material ranking can be based on f_3(M), the material index.

$$M = E^{(1/2)} / \rho \qquad (4.3)$$

Equation (4.3) is a common index for a minimum-mass beam in bending with stiffness constraint, where E is Young modulus and ρ is density. Materials with higher M are better for that simplified objective.

Worked Example — Lightest beam in bending. For a rectangular beam of fixed length with free section scale, bending stiffness is proportional to E I. If stiffness is fixed, required section size decreases as E increases. Mass is proportional to ρ times area. Eliminating the area scale gives a material ranking proportional to E^(1/2)/ρ. This is why a material with lower E can still compete if its density is much lower.
Key Points — 1) Functional analysis must define function, constraints, objective and free variables. 2) Performance indices come from structural models, not from preference. 3) Different loading modes lead to different material rankings.

4.3 Drawing up a Material Requirements Specification

A material requirements specification, or materials cahier des charges, is the document that converts the design intent into material selection criteria. It prevents informal decisions, exposes missing data and provides a record for later design review. It should be concise but complete enough that another engineer can reproduce the candidate list.

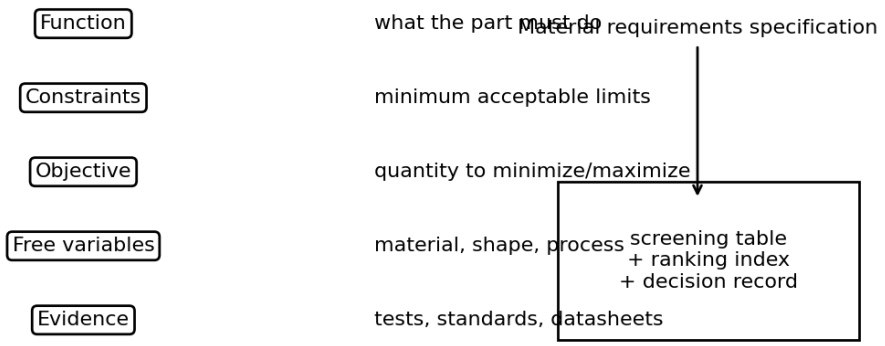


Figure 1.4 — 2 — Elements of a material requirements specification. A good specification links function, constraints, objectives, free variables and evidence.

4.3.1 Structure of a complete specification

The specification begins with component function and operating principle. It then states geometry and loading: static, cyclic, impact, contact, pressure, bending or torsion. It defines the service environment: temperature range, humidity, ultraviolet exposure, chemicals, corrosion, radiation, wear and cleaning agents. It records processing constraints: allowable processes, tolerances, surface finish, joining, repair and inspection. Finally, it records economic, regulatory and sustainability constraints.

Requirements should distinguish threshold values and target values. A threshold is the minimum acceptable value, such as service temperature above 120 °C or density below 2.0 Mg/m³. A target

expresses the preferred direction, such as minimize mass, minimize cost or maximize fatigue life. Without this distinction, the selection becomes subjective.

Table 4.1 — Template for a material requirements specification document.

Item	Questions to answer	Example entries
Component function	What does the part do? What load or energy does it carry?	Support a sensor module under vibration; protect electronics from dust and splash water.
Geometry and loading	What dimensions are fixed? What loads, moments, pressure, impact or cycles occur?	Wall thickness 2-4 mm; random vibration; accidental drop from 1 m.
Mechanical constraints	What minimum stiffness, strength, toughness, fatigue or wear values are required?	No brittle fracture at -10 °C; deflection < 1 mm under service load.
Thermal constraints	What operating and peak temperatures occur? Are thermal gradients present?	Continuous 80 °C, short peak 110 °C; thermal cycling daily.
Chemical/environmental constraints	What fluids, UV, humidity, corrosion or radiation exposures occur?	Outdoor UV, rainwater, detergent wipe-down, salt spray risk.
Processing constraints	Which processes and tolerances are feasible?	Injection molded; annual volume 50,000; textured surface; snap-fits required.
Economic constraints	What cost, availability and supply-chain limits apply?	Material cost target < 4 USD/kg; at least two suppliers.
Regulatory/standards constraints	Which standards or approvals apply?	RoHS, REACH, UL flammability rating, food or medical approval if applicable.
Objective and index	What should be minimized or maximized after screening?	Minimize cost at required impact resistance; minimize mass under stiffness constraint.
Evidence required	Which data sources, tests or prototypes are needed?	Supplier datasheets, ISO tensile tests, impact tests, aging test, pilot molding trial.

4.3.2 Worked example: structural bracket

Consider a small bracket that supports an instrument inside a machine. The function is to carry static load with limited deflection and survive vibration. Constraints include maximum deflection of 0.5 mm, yield safety factor of 2, service temperature from -20 °C to 80 °C, compatibility with light oil mist, machinability or castability, and no brittle fracture under handling impact. The objective is minimum mass at acceptable cost. Free variables include material family, cross-section details and manufacturing process.

The initial screening may remove unreinforced low-stiffness polymers if deflection cannot be met, remove brittle ceramics because impact and fastening are required, and remove expensive titanium if cost is too high. Candidate families may include aluminum alloys, glass-fiber-reinforced polyamide and low-carbon steel. Ranking then depends on whether mass, cost, stiffness or fatigue is most important.

Key Points — 1) A specification converts vague design language into measurable material criteria. 2) Threshold values are pass/fail; target values guide optimization. 3) A good specification records environment, process, economics and evidence, not only mechanical strength.

4.4 Mechanical Characteristics in Materials Selection

Mechanical selection requires more than choosing the strongest material. Yield strength, ultimate tensile strength, fatigue resistance, fracture toughness, hardness, creep resistance, wear resistance and ductility answer different failure questions. The relevant property depends on whether the part will yield, break, buckle, wear, creep, vibrate or crack.

4.4.1 Key mechanical properties

Yield strength σ_y controls permanent deformation in ductile materials. Ultimate tensile strength is useful for comparison but may be less relevant than yield for design. Fatigue limit or fatigue strength controls cyclic loading. Fracture toughness K_IC controls crack tolerance and damage tolerance. Hardness often correlates with wear resistance but cannot replace tribological testing. Creep resistance becomes critical at high homologous temperature for metals and at moderate temperature for polymers.

Specific stiffness E/ρ and specific strength σ/ρ are useful when mass matters. However, they are not universal answers. A slender compression member may be controlled by buckling and require an index involving E and density. A pressure vessel may be controlled by strength/density. A spring may require high $\sigma_y^2/E\rho$. The correct property group must be derived from the design model.

4.4.2 Ashby property charts

Ashby charts plot material properties on logarithmic axes, grouping material families and allowing performance index lines to be drawn. An E-ρ chart helps identify materials that maximize stiffness per unit mass. A σ_y-ρ chart helps identify high specific strength materials. A K_IC-σ_y chart helps compare strength and crack tolerance. Charts are most powerful during early design, when the aim is to compare families and eliminate weak candidates.

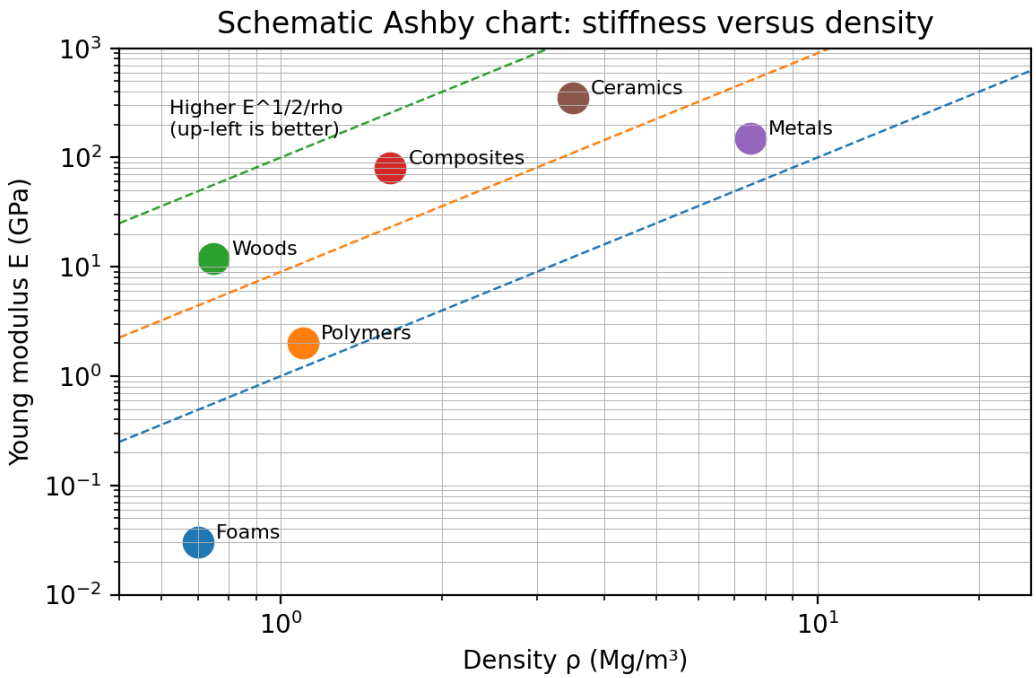


Figure 1.4 — 3 — Annotated schematic Ashby E-ρ chart. Material families occupy fields; dashed lines represent constant E^(1/2)/ρ for a simplified light beam in bending.

Key Points — 1) Mechanical properties must match the failure mode. 2) Specific properties are useful for lightweight design but must be tied to a performance model. 3) Ashby charts help screen and rank material families visually.

4.5 Sources of Materials Data

Material data are never neutral. They depend on composition, processing history, heat treatment, moisture, temperature, strain rate, surface finish, specimen size and test standard. A datasheet value is

usually a typical value, not a guaranteed design allowable. The reliability of the source and the relevance of the test conditions must be evaluated before using the data in design.

4.5.1 Textbooks, handbooks and databases

Textbooks such as Callister and Rethwisch, Ashby and Jones, and Shackelford are excellent for principles and broad property ranges. ASM Handbooks provide authoritative engineering data on metals, non-metallic materials, processing and failure analysis. Online databases such as MatWeb provide searchable datasheets, while Ansys Granta EduPack and Granta Selector support systematic selection using property charts, filters and process data. NIST materials repositories and databases provide research-grade datasets for selected material systems.

Table 4.2 — Comparison of major materials data sources used in selection.

Source	Coverage	Access type	Reliability level	Best use
Callister, Ashby, Shackelford textbooks	Principles and representative ranges for metals, polymers, ceramics and composites.	Books / institutional libraries.	High for fundamentals; approximate for detailed design values.	Teaching, first estimates, understanding trends.
ASM Handbooks / ASM Digital Library	Processing, properties, performance, failure analysis and material families.	Subscription / institutional access.	High; authoritative handbook source.	Engineering reference and failure analysis.
MatWeb	Searchable datasheets for metals, plastics, ceramics and composites.	Free web access with optional registration features.	Moderate to high depending on datasheet source; verify grade and supplier.	Early screening and quick property lookup.
Ansys Granta EduPack / Selector	Curated materials and process database with charts and selection tools.	Educational or commercial license.	High for selection workflow; verify final values with standards and suppliers.	Teaching, systematic screening, ranking and eco-audits.
NIST Materials Data Repository / JARVIS	Research datasets and computational or experimental materials data.	Open web access for many datasets.	High for documented datasets; scope depends on dataset.	Research, data-driven materials design, benchmarking.
Supplier datasheets	Specific commercial grades and processing recommendations.	Public or request from supplier.	Useful but often typical, not allowable; marketing bias possible.	Final candidate verification and processing window.
Standards and design codes	Test methods and allowable design rules.	Standards organizations / code bodies.	High for regulated design when current and applicable.	Qualification, compliance and safety-critical design.

4.5.2 Critical evaluation of data

Good practice requires checking whether the value is minimum, typical or guaranteed; whether the material condition matches the candidate; whether the test temperature and strain rate match service; whether aging, moisture and processing are included; and whether scatter or confidence bounds are provided. For composites and ceramics, statistical allowables may be necessary because defects and manufacturing variability strongly affect strength.

Engineering Note — Do not mix data from different conditions without tracking them. A yield strength from a heat-treated bar, a fatigue strength from polished laboratory specimens and a cost from a different country do not automatically describe the same manufacturable product.

Key Points — 1) Material data must be relevant to grade, processing history and service conditions. 2) Typical values are not design allowables. 3) Final selection should combine databases, supplier data, standards and verification tests.

4.6 Selection Criteria and Trade-offs

Real material choices are multi-criteria decisions. Strength, stiffness, density, corrosion resistance, processability, cost, availability and environmental impact rarely point to the same candidate. A disciplined decision method makes trade-offs explicit and prevents a single attractive property from dominating the decision irrationally.

4.6.1 Cost, availability, service and manufacturing criteria

Cost should be measured per function, not only per kilogram. A more expensive material can reduce total cost if it lowers mass, simplifies assembly, eliminates coating, increases life or reduces machining time. Availability matters when supply chains are unstable, materials are strategic or lead times are long. Service conditions can dominate: temperature, corrosion, radiation, cyclic loading and contact wear may eliminate otherwise attractive candidates.

Manufacturing constraints include formability, castability, machinability, weldability, joinability, heat treatability, surface treatability and compatibility with production volume. A material that looks excellent on a property chart may be impractical if it cannot be formed to tolerance, joined reliably or inspected economically.

4.6.2 Weighted property index method

A weighted property index is a simple multi-criteria method. Each criterion receives a weight according to importance. Each material receives a normalized score for each criterion. The total score is the sum of weight multiplied by score. This method is transparent, but it is only as good as the chosen weights and normalization. It should be used after pass/fail screening, not to hide a failed constraint.

$$WPI_j = \Sigma\, w_i\, s_{ij} \qquad (4.4)$$

In Equation (4.4), WPI_j is the weighted property index of material j, w_i is the weight assigned to criterion i, and s_{ij} is the normalized score of material j on criterion i. The weights should sum to 1.

Table 4.3 — Worked WPI example for an automotive support bracket after screening.

Criterion	Weight	Aluminum alloy score	HSLA steel score	GF-PA66 score	Rationale
Low mass	0.30	9	5	10	Density favors polymer composite and aluminum over steel.
Stiffness / deflection	0.25	8	10	5	Steel highest E; aluminum acceptable; polymer needs ribs.
Fatigue and durability	0.20	7	9	6	Steel strong in fatigue; polymer sensitive to moisture and temperature.
Manufacturing cost	0.15	7	8	8	Steel stamping and GF-PA injection can be economical at volume.
Corrosion resistance	0.10	8	5	9	Polymer and aluminum better without coating.
Total WPI	1.00	7.85	7.35	7.45	Aluminum ranks first in this weighting; sensitivity analysis is required.

The example ranks aluminum slightly above glass-fiber-reinforced polyamide and steel. However, the ranking is not an absolute truth. If cost weight increases or stiffness becomes stricter, steel may win.

If mass and corrosion dominate and the geometry can be ribbed, GF-PA66 may win. A mature decision reports this sensitivity instead of pretending that one table has solved the whole problem.

Key Points — 1) Cost must be evaluated at component and lifecycle level, not only price per kilogram. 2) Manufacturing and availability can eliminate materials that look excellent mechanically. 3) WPI is useful for transparent trade-offs but cannot override mandatory constraints.

4.7 Computer-Aided Materials Selection Tools

Computer-aided selection tools implement the same logic at larger scale. They allow the engineer to search thousands of materials, plot property charts, apply screening limits, draw performance index lines and inspect datasheets. They are especially useful in education and early design, where broad comparison across families is needed.

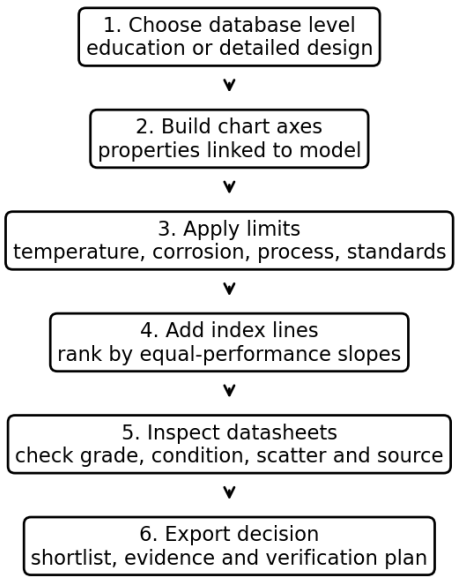


Figure 1.4 — 4 — Typical workflow in a computer-aided materials selection tool such as Granta EduPack or Selector.

4.7.1 CES / Granta methodology

The CES method follows translate, screen, rank and support. The user first chooses a database level suitable for the design stage. Screening may be done by tree selection, property limits, process filters or environmental restrictions. Ranking may use chart selection, index lines or tabular comparison. Supporting information includes datasheets, process notes, sustainability data and references.

4.7.2 Constructing charts and using filters

A selection chart must use axes that correspond to the problem. For lightweight stiffness, E versus density is useful. For strength-limited tension, strength versus density is useful. For thermal management, thermal conductivity versus electrical resistivity may be more relevant. Index lines show equal performance; moving the line in the favorable direction identifies better candidates. Filters should then remove materials that fail temperature, corrosion, process or regulatory constraints.

The strongest criticism of software-based selection is overconfidence. Databases simplify reality. They may not include local availability, exact supplier grade, forming defects, weld quality, moisture

conditioning, anisotropy, repair constraints or certification costs. Software should accelerate reasoning, not replace it.

Key Points — 1) Computer tools accelerate selection across large material/process databases. 2) Charts and filters must be chosen from the engineering model. 3) Software output must be verified against supplier data, standards, prototypes and local manufacturing constraints.

4.8 Case Studies in Materials Selection

4.8.1 Case Study 1 - Lightweight structural component: bicycle frame

Functional analysis: a bicycle frame supports rider loads, transmits pedaling and braking forces, resists fatigue and impact, and provides acceptable ride feel at low mass. Constraints include sufficient stiffness, fatigue resistance, joint reliability, crash tolerance, manufacturability and corrosion resistance. The objective for a performance frame is usually low mass at acceptable cost and durability. Free variables include tube geometry, material, joining process and lay-up if composite is used.

Screening removes brittle ceramics and low-stiffness unreinforced polymers. Candidate materials include steel, aluminum alloys, titanium alloys and CFRP. For bending-dominated tubes with strength constraints, indices such as σ^(2/3)/ρ and E^(1/2)/ρ guide early ranking, but fatigue, joining and crash damage must also be checked.

Table 4.4 — Bicycle frame selection summary.

Candidate	Strength/stiffness potential	Mass potential	Manufacturing and joining	Final assessment
Steel alloy	High strength and fatigue resistance; high density.	Moderate to heavy unless thin tubes are used.	Welded or brazed; mature and repairable.	Excellent durability and cost; not lowest mass.
Aluminum alloy	Good specific stiffness with larger tube diameters; fatigue design important.	Low mass.	Welded, heat treatment and corrosion control needed.	Strong mainstream choice for cost-performance.
Titanium alloy	Good corrosion resistance and fatigue; lower modulus than steel.	Low to moderate mass.	Difficult welding and high material cost.	Premium durable choice; cost limits use.
CFRP	Very high directional specific stiffness and strength.	Very low mass possible.	Lay-up, curing, joints and impact inspection critical.	Best for high-performance low mass when cost and damage tolerance are managed.

Final selection: for a high-performance racing frame, CFRP is selected because fiber orientation can be tailored to bending, torsion and ride compliance at very low mass. For a robust low-cost commuter bicycle, aluminum or steel may be more rational. The “best” material changes with objective and market position.

4.8.2 Case Study 2 - Pressure vessel

Functional analysis: a pressure vessel stores fluid safely at internal pressure. Constraints include burst pressure, leak-before-break or fracture control, corrosion resistance, joining reliability, inspection access, code compliance and service temperature. For a thin-walled vessel, hoop stress is proportional to pressure times radius divided by wall thickness. Minimum mass for a strength-limited vessel favors high σ_y/ρ.

$$M = \sigma_y / \rho \qquad (4.5)$$

Equation (4.5) is the simplified material index for a thin-walled pressure vessel controlled by yield strength, where σ_y is allowable yield strength and ρ is density. In real vessels, fracture toughness, corrosion, weld efficiency and design codes also enter.

Table 4.5 — Pressure vessel selection summary.

Candidate	Screening result	Ranking considerations	Final comment
Low-carbon steel	Passes strength and cost; corrosion protection needed.	High density but cheap, weldable and code familiarity high.	Often best for stationary low-cost vessels.
Aluminum alloy	Good density and corrosion resistance; lower modulus and strength than high-strength steels.	Good σ/ρ for some applications; welding and fatigue need attention.	Useful for lightweight moderate-pressure vessels.
Austenitic stainless steel	Excellent corrosion resistance and toughness; high cost and density.	Chosen when corrosion or hygiene dominates.	Best when environment is severe.
CFRP overwrapped vessel	Excellent σ/ρ in fiber direction; liner and impact issues.	Very low mass; high qualification cost.	Best for high-pressure lightweight gas storage when certified.

Final selection: for an industrial compressed-air receiver, low-carbon steel may be selected because weldability, cost, inspection and code compliance dominate. For a portable hydrogen or breathing-air cylinder, a composite overwrapped pressure vessel may be justified by mass reduction despite higher cost and stricter inspection.

4.8.3 Case Study 3 - Automotive component substitution for weight reduction

Functional analysis: replace a cast iron bracket or housing to reduce vehicle mass without sacrificing stiffness, fatigue life, dimensional stability, thermal resistance, noise-vibration behavior or cost target. Candidates include aluminum alloy, magnesium alloy and short-fiber-reinforced polymer. Constraints include service temperature, bolt loads, creep, chemical exposure, crash requirements and production volume.

Table 4.6 — Automotive substitution summary.

Candidate	Advantages	Risks	Best use condition
Aluminum alloy	Good mass reduction, mature casting and machining, good thermal conductivity.	Galvanic corrosion, fatigue detail sensitivity, casting porosity.	Structural housings and brackets where stiffness and temperature are moderate.
Magnesium alloy	Very low density and good castability.	Corrosion protection, flammability concerns in processing, lower modulus.	Weight-critical die-cast parts with controlled environment.
Short-fiber-reinforced polymer	Low density, integrated functions, corrosion resistance, high-volume injection molding.	Creep, moisture, anisotropic shrinkage, lower temperature limit, fiber orientation.	Complex shapes with ribbing where loads and temperature are within polymer limits.

Final selection: if stiffness and temperature are strict, aluminum is the safest replacement for cast iron. If geometry allows ribbing and loads are moderate, glass-fiber-reinforced polyamide can reduce mass and part count. Magnesium is attractive for weight but requires stronger corrosion and process control. The final decision should include tooling cost, cycle time, joining, recycling and warranty risk.

4.8.4 Cross-case lessons and sensitivity check

The three case studies expose a useful discipline: the selected material is not simply the material with the best single property. CFRP is attractive in a racing bicycle because directional stiffness and low mass dominate, but the same material may be irrational for a low-cost commuter frame. Steel is heavy in a pressure vessel, but it remains strong when weldability, code familiarity, inspection and price dominate. A reinforced polymer can replace metal in an automotive bracket only when the geometry can be redesigned around ribs, inserts and fiber orientation.

A final selection should therefore include a sensitivity check. The engineer deliberately changes the weights, the cost estimate, the safety factor, the annual production volume or the environmental exposure and observes whether the ranking changes. If a small change reverses the decision, the result is fragile and requires additional testing or a more conservative choice. If the same candidate remains first under plausible variations, the decision is more robust.

Table 4.7 — Final decision record template for materials selection case studies.

Decision item	Minimum content to record	Why it matters
Chosen material and condition	Alloy/polymer grade, heat treatment, reinforcement, fiber orientation or ceramic processing route.	Prevents ambiguity between material family and actual purchasable grade.
Rejected alternatives	One sentence explaining why each serious candidate was rejected.	Shows that the decision was comparative, not biased toward a familiar material.
Controlling constraint	The requirement that most strongly limits the design: stiffness, fatigue, corrosion, creep, temperature, cost or process.	Identifies where future redesign could create the largest improvement.
Main risk	The most credible failure or supply risk remaining after selection.	Guides prototype tests, inspection plan and supplier qualification.
Verification plan	Tests, standards, supplier certificates, prototype trials and environmental aging checks.	Transforms a calculated selection into an engineering decision ready for validation.

Key Points — 1) Case studies show that material choice changes when objective, constraints or market position changes. 2) Performance indices guide ranking but do not replace fatigue, corrosion, joining and regulatory checks. 3) The final selection must explain rejected candidates, not only defend the chosen one.

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