Technology of Metallic Materials

Table of Contents

Alloy Formation

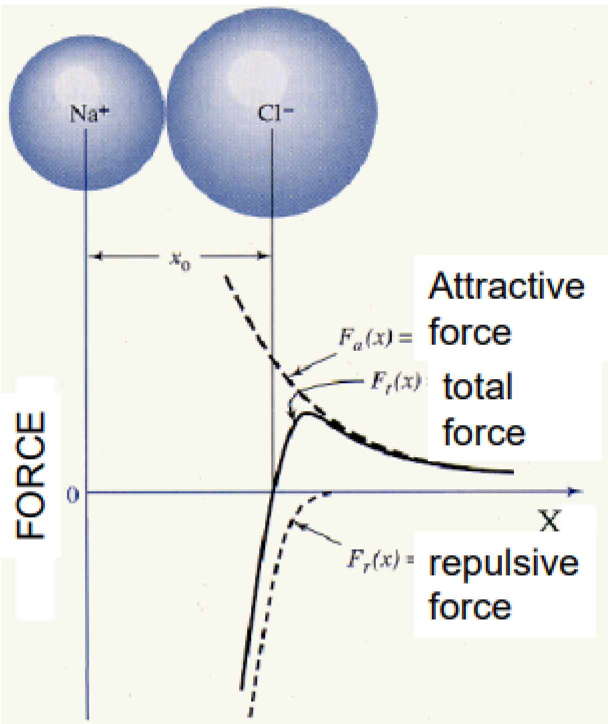
Alloy Formation

Humé-Rothery Rules for Alloy Formation

- **Dimensional Factor**
  - Atoms tend to pack $\implies$ Atomic radii of solvent atoms must stay within 15% of solutes'
- **Identical crystal** structure of solute and solvent (e.g. BCC, FCC)
- **Similar electronegativity** of solute and solvent
- **Valence Factor**
  - A solute will enter into a solution if its valence is greater that of the solvent's

Condon-Morse Model

> **Important**
>
> The Condon-Morse model describes the relationship between intermolecular distance and their forces and potential energy.



When $x = x_0 : F(x_0) = 0$ we have an equilibrium, where there is no net force between the particles and we therefore have stability. As we increase distance above this point, intermolecular forces begin to pull the particles together (such as Van der Waals, ionic bonds, covalent bonds, external stress etc.), but if the particles get too close, we get overlapping electron clouds which cause repulsive forces.

Remember

$$U = \int_{\infty}^{r} F\,dx = U_A + U_R$$

Where:

- r is the atomic distance
- U_A is the attractive potential energy
- U_R is the repulsive potential energy

Bonding energy is the energy required to separate two atoms:

$$U \equiv E$$

Aluminium Alloys

Aluminium Alloys

Quick Stats

- **Melting Point:** $660°C$ (Softens at $150 - 200°C$)
- **Crystal Structure:** FCC (Face Centered Cubic) $\rightarrow$ **No ductile-to-brittle transition** (remains ductile at low temps)
- **Density:** 2.7 g/cm^3 (vs 7.7 for Fe) - *It is light!*
- **Young's Modulus (E):** 70 GPa (vs 210 GPa for Fe) - *It is 1/3 as stiff as steel.*

Why Aluminium? (Pros & Cons)

The Good

- **Conductivity:** High electrical conductivity (62% IASC). Good heat conductor.
- **Formability:** Easily formed by extrusion, forging, rolling. Can make intricate shapes due to FCC structure.
- **Corrosion Resistance:** Excellent due to a thin, strong oxide coating.
- **Machinability:** Good.

The Bad

- **Fatigue Strength:** Low. Be careful with cyclic loading.
- **Cost:** Sheet form is $\sim 4.5\times$ mild steel cost.
- **Temperature:** Low melting point limits high-temp applications.

Critical Exam Concept: SCC

Precipitation-hardened alloys can suffer from **Stress-Corrosion Cracking** (SCC) due to precipitate-free zones near grain boundaries. Do not forget this.

Strengthening Mechanisms

How do we make soft aluminium strong?

- **Solid Solution Hardening:** Adding atoms that distort the lattice.

- **Cold Work (Strain Hardening):** Dislocation tangles.
- **Age Hardening (Precipitation):** The big one. Requires heat treatment.

$$\sigma_{ys} = \sigma_o + kd^{-1/2}$$

(Hall-Petch relation: Smaller grains = Higher strength)

The Designation System (Wrought & Cast)

Memorize the Series Logic

The first digit tells you the **principal alloying element**.

Wrought Alloys (4 Digits: xxxx)

Series	Element	Treatable?	Main Characteristic
1xxx	Pure Al $(99\%+)$	No	Foil, electrical conductors. Weak.
2xxx	**Copper (Cu)**	**YES**	**Aircraft.** High strength, age-hardened. Not weldable.
3xxx	Manganese (Mn)	No	**Drink cans.** Ductile, good formability.
4xxx	Silicon (Si)	Some	**Pistons.** Forgeable, lowers melting point.
5xxx	**Magnesium (Mg)**	No	**Marine.** Best corrosion resistance. Weldable.
6xxx	**Mg + Si**	**YES**	**Structural.** Window frames. Good medium alloy, weldable.
7xxx	**Zinc (Zn)**	**YES**	**High Stress Aircraft.** Highest strength. Not weldable.
8xxx	Other (Li)	**YES**	Specialist (e.g., Al-Li for aerospace).

> **Cast Alloys** use a decimal point (e.g., `3xx.x`). Most common is **Al-Si** eutectic for automotive castings.

Practical Naming Examples

How to read the code on the exam:

Example 1: AA 7075-T6 (Common aircraft alloy)

- **7:** Principal element is **Zinc**.
- **0:** No major modification to the original alloy limits (0 = original).
- **75:** Identifies the specific alloy in the 7xxx series.

- **T6:** Solution heat treated + **Artificially Aged** (Furnace).

Example 2: AA 5083-H116 (Marine/Shipbuilding)

- **5:** Principal element is **Magnesium**.
- **0:** Original alloy limits.
- **83:** Specific alloy ID.
- **H1:** Cold worked only (Strain hardened).
- **16:** Specific degree of hardness/processing.

Example 3: AA 1050 (Electrical wiring)

- **1:** Pure Aluminium (99.00% min).
- **0:** Original impurity limits.
- **50:** Indicates purity of 99.50%. (Last two digits in 1xxx series = decimal percentage above 99%).

Temper Designations (The Suffixes)

This tells you the **history** of the metal.

- **F:** As Fabricated (Raw output).
- **O:** Annealed (Softest, lowest strength).

H - Cold Worked (Strain Hardened)

Used for Non-Heat Treatable alloys (1xxx, 3xxx, 5xxx)

- **H1:** Cold worked only.
- **H2:** Cold worked + partially annealed.
- **H3:** Cold worked + stabilized.
- **Second Digit:** Indicates hardness (2 = 1/4 hard ... 8 = Hard).

T - Heat Treated (The Important Ones)

Used for Heat Treatable alloys (2xxx, 6xxx, 7xxx)

Don't mix these up!

- **T4:** Solution Heat Treated + **Natural Ageing** (Room temp).
- **T6:** Solution Heat Treated + **Artificial Ageing** (Furnace).
- **T3:** Solution + **Cold Work** + Natural Ageing.

Age Hardening (Precipitation Hardening)

Focus: 2xxx Series (Al-Cu)

This is the primary way we strengthen high-performance aluminium. It is a process over time:

1. **Solid Solution Treatment:** Cu is in solid solution.
2. **GP Zones:** Cu forms clusters. Strain fields created.
3. θ'' **Precipitates:** *Coherent* precipitates. **PEAK AGED condition.** Maximum hardness.
4. θ' **and** θ **($CuAl_2$):** *Incoherent* precipitates. **Overaged.** Hardness drops.

> **The Curve**
>
> The Yield Stress rises to a peak and then falls. Overaging (holding it in the oven too long) ruins the material strength.

Applications Cheat Sheet

Application	Series	Why?
Cooking Foil	1xxx	Pure, ductile, corrosion resistant.
Drink Cans	3xxx	Deep drawing capability (ductile).
Airplane Fuselage	2xxx	High strength (but needs Alclad for corrosion).
Airplane Wing Structures	7xxx	Highest strength available.
Car Pistons	4xxx	Low thermal expansion, wear resistance (Si).
Window Frames	6xxx	Extrudable, good corrosion resistance.
Ship Hulls	5xxx	Saltwater corrosion resistance.

Cast Iron

Cast Iron

What is it?

Think of Cast Iron as steel that ate too much Carbon.

- **Composition:** Iron + **2-4.5% Carbon** + **1-3% Silicon**.
- **The Matrix:** Usually Ferrite or Pearlite (like steel).
- **The Difference:** The excess Carbon cannot remain dissolved, so it precipitates out as a second phase: Graphite or **Iron Carbide** (Cementite) (Fe_3C).

- **Pros:**
  - Low melting point (easy to cast)
  - High fluidity (fills complex moulds)
  - Low shrinkage
  - Easy to machine.
- **Cons:**
  - Generally brittle
  - Has low impact resistance compared to steel.

Type	Carbon Form	Silicon Content	Key Property
White	**Iron Carbide (Fe_3C)**	Low (0.5-1.5%)	Hard, Wear Resistant, Brittle
Gray	**Flakes**	High (1-3%)	Vibration Damping, Brittle in Tension
Ductile	**Spheres (Nodules)**	Med-High (1.8-2.8%) + **Mg**	Tough, Ductile, Strong
Malleable	**Clusters (Rosettes)**	Med (1.1-1.6%)	Good Toughness (Heat Treated)

White Cast Iron

This is the “primitive” form. It forms when cooling is rapid or Silicon is low.

- **Composition:** Low C (2.5-3%) and **Low Si (0.5-1.5%)**.
- **Structure:** Carbon does not create graphite. Instead, it forms Cementite.
- **Appearance:** Fracture surface looks white/shiny (crystalline).

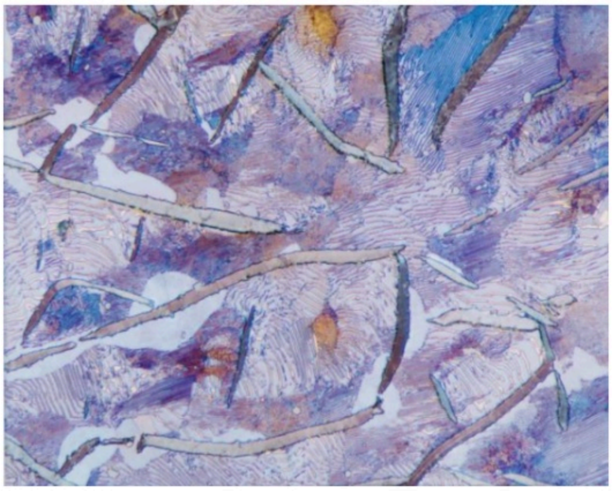
- **Properties:**
  - Extremely hard and wear-resistant (due to carbides).
  - **Extremely brittle.** You cannot machine this; you must grind it.
- **Use:** Rock crushers, slurry pumps, grinding balls.

Gray Cast Iron

This is the most common type. It forms when cooling is slow and Silicon is high (Si is a graphite stabilizer).

- **Composition:** C (2.5-4%) and **High Si (1-3%)**.
- **Structure:** Carbon precipitates as **Graphite Flakes**.
- **Appearance:** Fracture surface looks gray (due to the graphite).
- **Properties:**
  - **Weak in Tension:** The sharp tips of the flakes act as stress concentrators (pre-existing cracks).
  - **Strong in Compression.**
  - **Vibration Damping:** The internal graphite flakes absorb energy. This is why heavy lathe beds and engine blocks are made of Gray Iron.
  - Excellent machinability (graphite acts as a lubricant).

Gray cast iron with pearlitic matrix: color etching



Beraha Etchant 500x

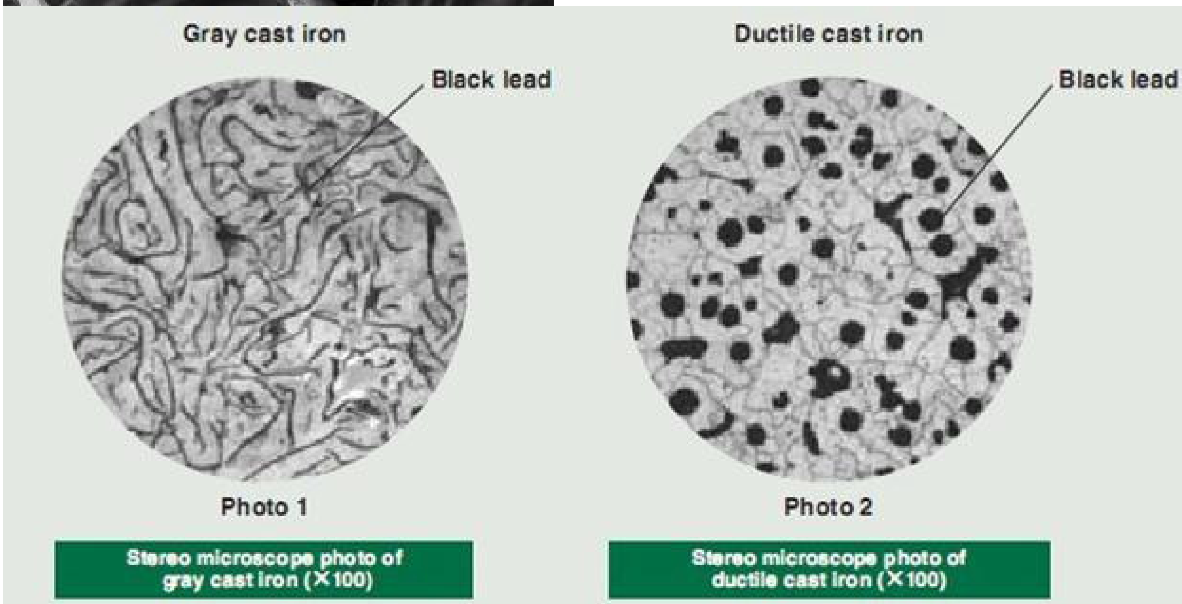
> Above is the result of chemical etching on a sample of cast iron.

Ductile (Nodular) Cast Iron

The "We want the graphite, but we hate the flakes" cast iron.

- **The Trick:** We add a "nodulizing agent" (usually Mg or Ce) to the molten mix.
- **Structure:** The graphite forms into **Perfect Spheres (Nodules)** rather than flakes. This is often called a Bull's eye microstructure (Graphite sphere surrounded by ferrite/pearlite).
- **Composition:** C (3-4%) and Si (1.8-2.8%).
- **Properties:**

    - The spheres *do not* concentrate stress.
    - Result: High strength, **High Toughness**, and **Ductility**.
    - It behaves much more like steel but retains the castability of iron.
- **Use:** Crankshafts, gears, heavy-duty suspension parts.



Malleable Cast Iron

- **Process:**
    1. Cast the part as **White Iron** (hard, brittle).
    2. Heat treat it (Annealing/Malleablizing) for a long time.
    3. The Iron Carbide decomposes into **Irregular Graphite Clusters** (Rosettes).
- **Composition:** C (2-2.6%) and Si (1.1-1.6%).
- **Properties:** Good toughness and ductility (hence "Malleable").
- **Use:** Pipe fittings, tools, railway parts.

Classification of Metals

Classification of Metals

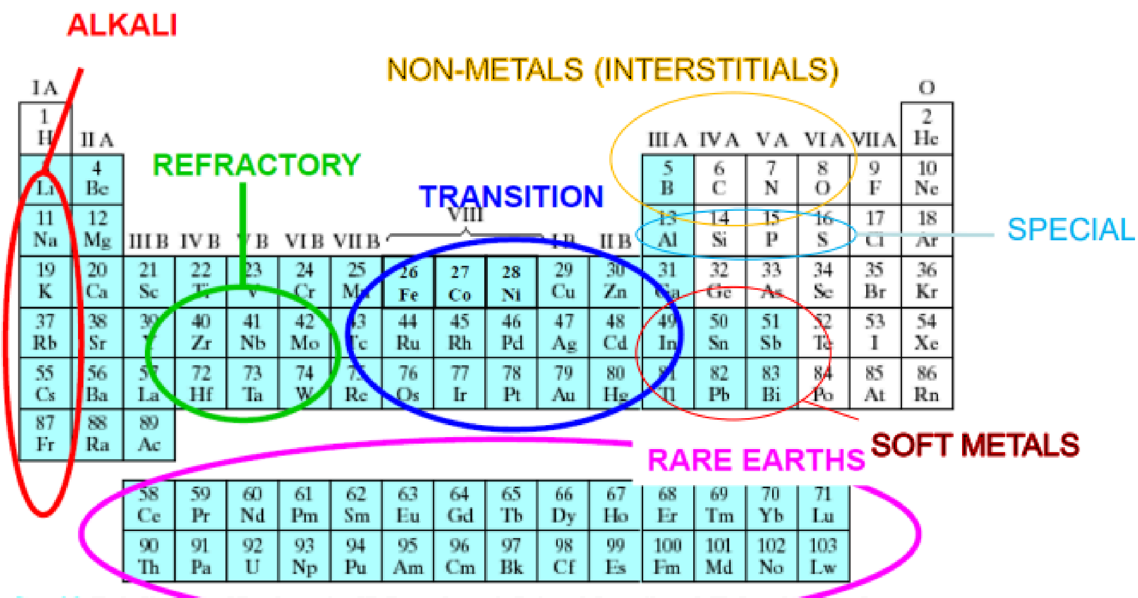


Figure 1-3 *Periodic table of the elements with those elements that are inherently metallic in nature in color.*

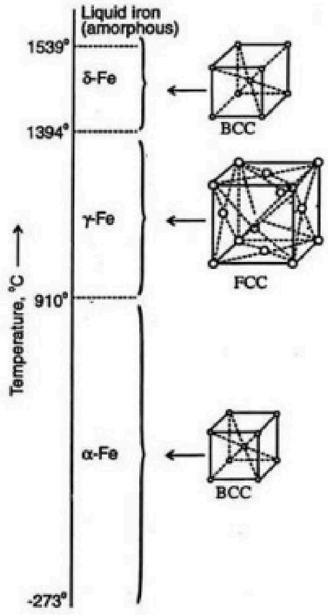
Electronegativity Table

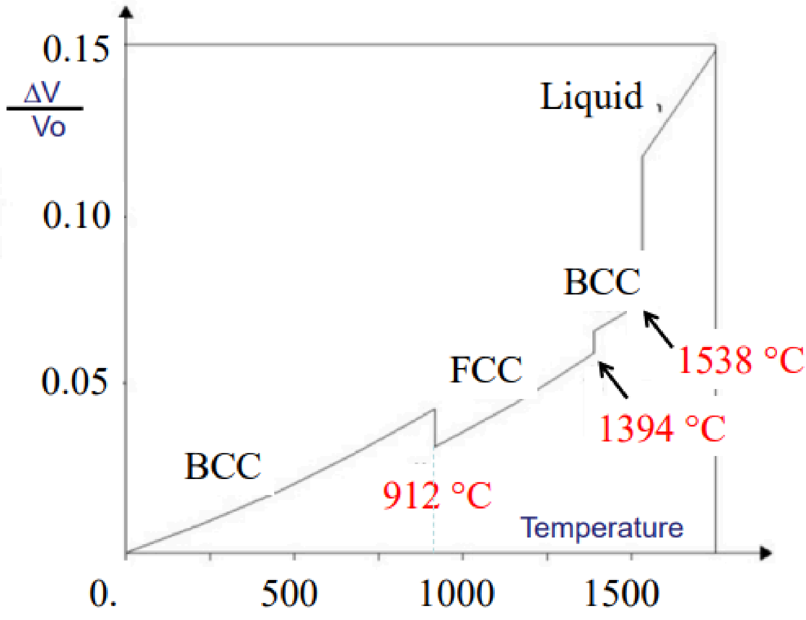
	Group																	
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 2.1																	He 0
2	Li 0.98	Be 1.57											B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne 0
3	Na 0.93	Mg 1.31											Al 1.61	Si 1.9	P 2.19	S 2.58	Cl 3.16	Ar 0
4	K 0.82	Ca 1	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.9	Zn 1.65	Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr 0
5	Rb 0.82	Sr 0.95	Y 1.22	Zr 1.33	Nb 1.6	Mo 2.16	Tc 1.9	Ru 2.2	Rh 2.28	Pd 2.2	Ag 1.93	Cd 1.69	In 1.78	Sn 1.96	Sb 2.05	Te 2.1	I 2.66	Xe 2.6
6	Cs 0.79	Ba 0.89	La 1.1	Hf 1.3	Ta 1.5	W 2.36	Re 1.9	Os 2.2	Ir 2.2	Pt 2.28	Au 2.54	Hg 2	Tl 2.04	Pb 2.33	Bi 2.02	Po 2	At 2.2	Rn 0

White= No data	0-.66	.66-1	1-1.33	1.33-1.66	1.66-2	2-2.33	2.33-2.66	2.66-

Allotropy

Allotropy, Polymorphism: Fe





Corrosion

Corrosion

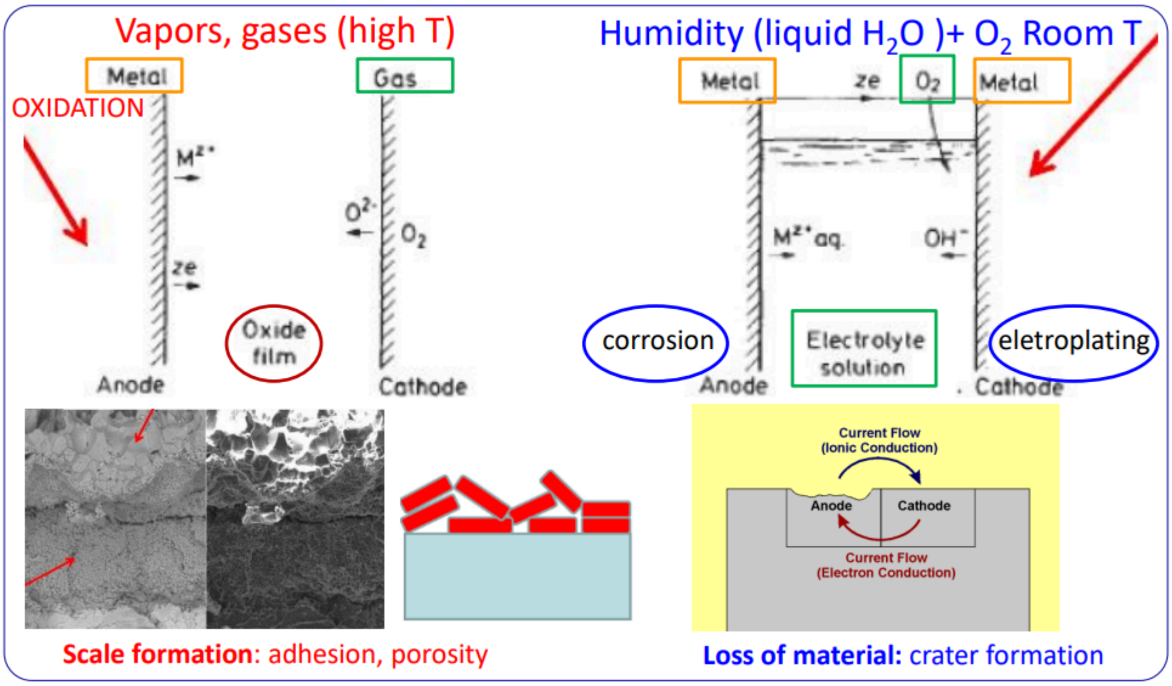
Dry vs. Wet Corrosion

Dry Corrosion (High Temperature Oxidation)

- **Environment:** Vapours and gases at **High Temperatures**.
- **Mechanism:** Direct chemical reaction between the metal and the gas (usually O_2).
- **Process:** $M + O_2 \rightarrow Oxide$.
- **Outcome:** Formation of an oxide film (scale).
  - Adhesion and porosity of the scale determine if it protects the metal or allows further attack.

Wet Corrosion (Electrochemical)

- **Environment:** Humidity (liquid H_2O) + Oxygen at **Room Temperature**.
- **Mechanism:** Electrochemical process involving an electrolyte.
- **Components Required:**
  1. **Anode:** Gives up electrons (Corrodes).
  2. **Cathode:** Accepts electrons (Protected).
  3. **Electrolyte:** Conducts ions (M^{2+}).
  4. **Electrical Connection:** Conducts electrons (e^-).
- **Outcome:** Loss of material (crater formation) at the anode; often electroplating or byproduct formation at the cathode.



The Electrochemical Reactions

Stopping Wet Corrosion

For wet corrosion to occur, two simultaneous reactions must happen. If you stop one, you stop the corrosion.

The Anodic Reaction (Oxidation)

This is where the metal is lost. The metal dissolves into the electrolyte as ions.

$$M \rightarrow M^{n+} + ne^-$$

Examples:

- $Fe \rightarrow Fe^{2+} + 2e^-$
- $Zn \rightarrow Zn^{2+} + 2e^-$

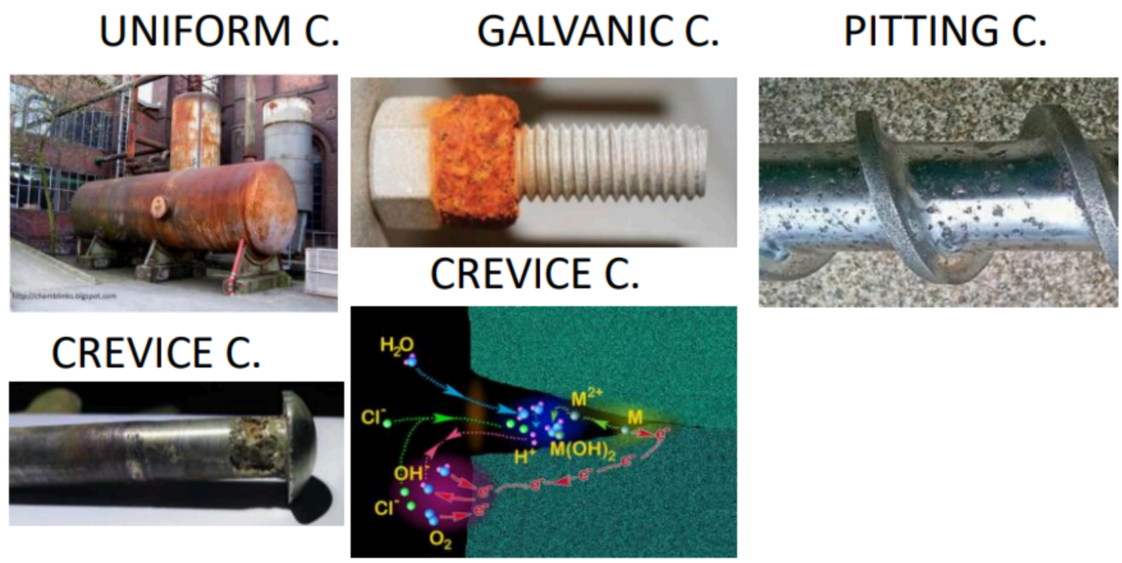
The Cathodic Reaction (Reduction)

This occurs at the surface that *does not* corrode. The specific reaction depends on the environment's pH and oxygen content.

Environment	Condition	Reaction
Acidic	High H^+ ions	$2H^+ + 2e^- \rightarrow H_2$
Acidic	Dissolved O_2	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Neutral/Basic	Dissolved O_2	$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$

Note: Metal ions can also be reduced (Electroplating): $M^{n+} + ne^{-} \rightarrow M$.

Classification of Corrosion Phenomena



1. Uniform Corrosion

- **Appearance:** Even removal of metal across the surface.
- **Mechanism:** Micro-corrosion cells shift randomly over time.
- **Risk:** Greatest destruction by mass, but **least dangerous** technically because it is predictable and easy to measure.

2. Galvanic (Bimetallic) Corrosion

- **Mechanism:** Two dissimilar metals in electrical contact in an electrolyte.
- **The Law:** The **less noble** (anodic) metal corrodes; the **more noble** (cathodic) metal is protected.
- **Driving Force:** The difference in electrical potential (Voltage) between the metals.

The "Area Ratio" Effect

The rate of corrosion is determined by the current density ($i = I/Area$).

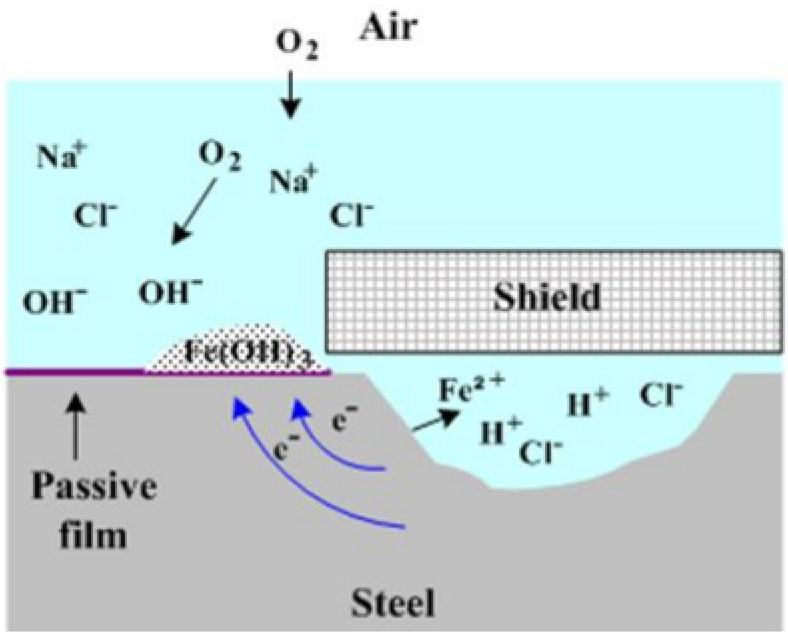
- **Big Cathode + Small Anode = DISASTER.**
  - The massive cathode demands a huge flow of electrons. The tiny anode must corrode furiously to supply them.
  - *Example:* Steel rivets in a Copper plate $\rightarrow$ Rivets disintegrate rapidly.
- **Small Cathode + Large Anode = Safe.**
  - The corrosion is spread out over a large area and is sluggish.

3. Localized Corrosion

These are dangerous because the overall mass loss is low, but the structural damage is high.

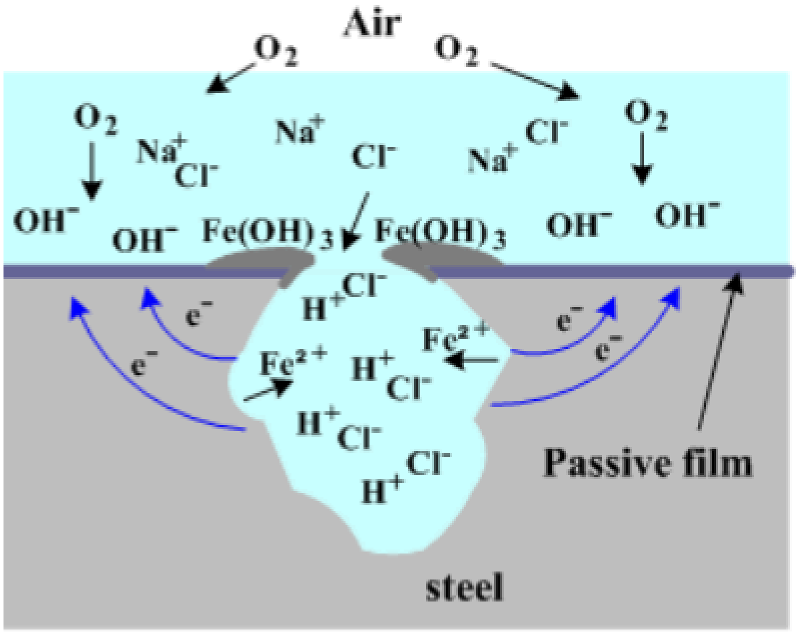
Crevice Corrosion

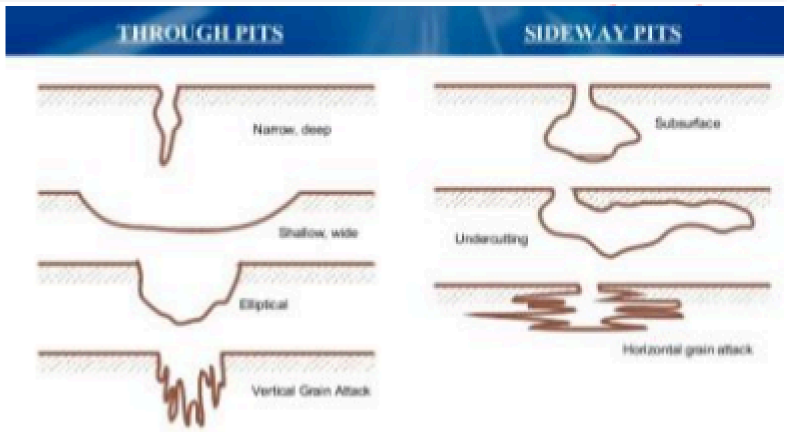
- **Location:** Narrow gaps (crevices) under bolts, gaskets, or deposits.
- **Mechanism:**
  1. Oxygen is depleted inside the crevice.
  2. The crevice becomes strictly Anodic (dissolution of metal).
  3. The area outside remains Cathodic (plenty of O_2).
  4. Positive metal ions accumulate in the crevice, attracting negative ions (Cl^-) and lowering pH (creating acid), which accelerates the attack.



Pitting Corrosion

- **Appearance:** Small, deep holes.
- **Mechanism:** Similar to crevice corrosion but autocatalytic. Often initiated by **Chloride ions** (Cl^-) breaking the passive film.
- **Danger:** Occurs in materials that are otherwise passive (like Stainless Steel). It is insidious and hard to detect.





Synergistic Phenomena

Stress Corrosion Cracking (SCC)

- **Formula:** Tensile Stress + Specific Corrosive Environment + Susceptible Material.
- **Mechanism:** A crack initiates (frequently at a pit). The crack tip is active (anodic), while the walls are passive. The stress keeps opening the tip, exposing fresh metal to corrosion.
- **Result:** Sudden brittle failure in ductile materials.

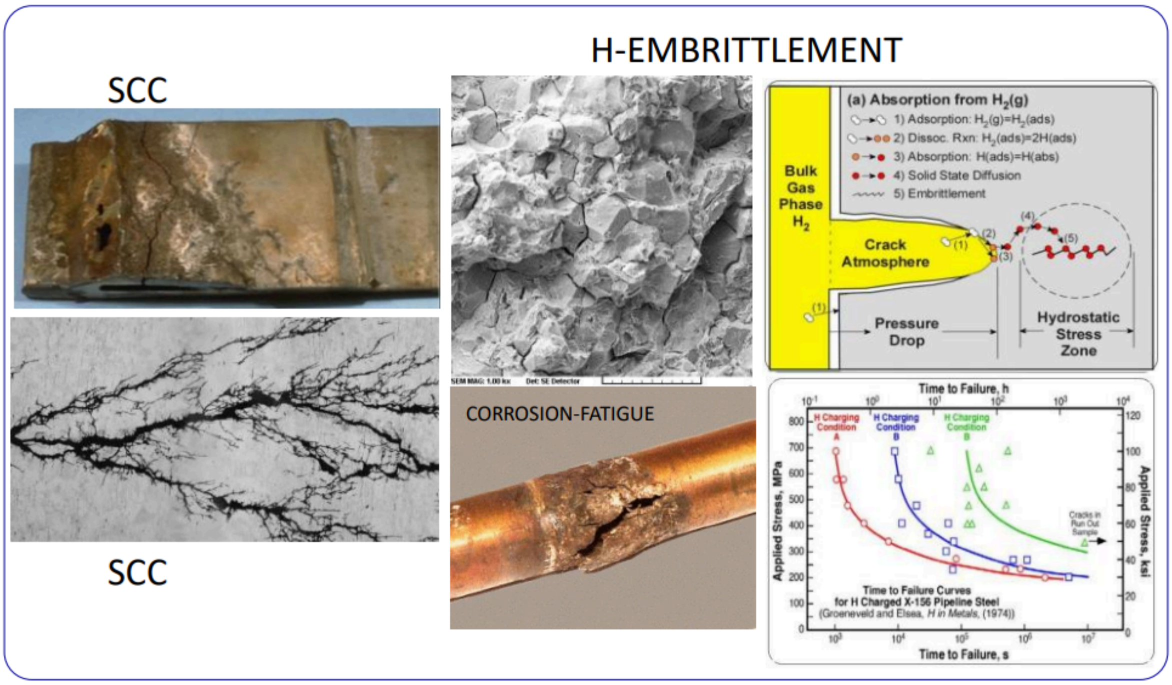
Hydrogen Embrittlement

- **Mechanism:** Atomic Hydrogen (H) diffuses into the metal lattice (interstitial).

- **Sources of H:** Corrosion reactions, welding, electroplating.
- **Effect:** Low ductility fracture. Can be confused with SCC, but strictly due to Hydrogen presence preventing plastic deformation (dislocation movement).

Others

- **Corrosion Fatigue:** Fatigue limit is lowered (or eliminated) by a corrosive environment.
- **Selective Leaching:** One element is removed (e.g., Zinc removed from Brass).
- **Fretting Corrosion:** Corrosion assisted by small-scale vibration/sliding.
- **Erosion Corrosion:** Flowing fluid strips protective films.



The Galvanic Series (Seawater)

Rank	Metals	Role
Noble (Cathodic)	Platinum, Gold, Graphite, Titanium	**Protected** (Will eat other metals)
Passive	Stainless Steel (Passive), Nickel (Passive)	
Active	Steel, Iron, Aluminum Alloys	
Sacrificial (Anodic)	Zinc, Magnesium	**Corrodes** (Used to protect others)

> ⚠ **Design Rule**
>
> Never couple a metal from the top of this list with a small piece of metal from the bottom.

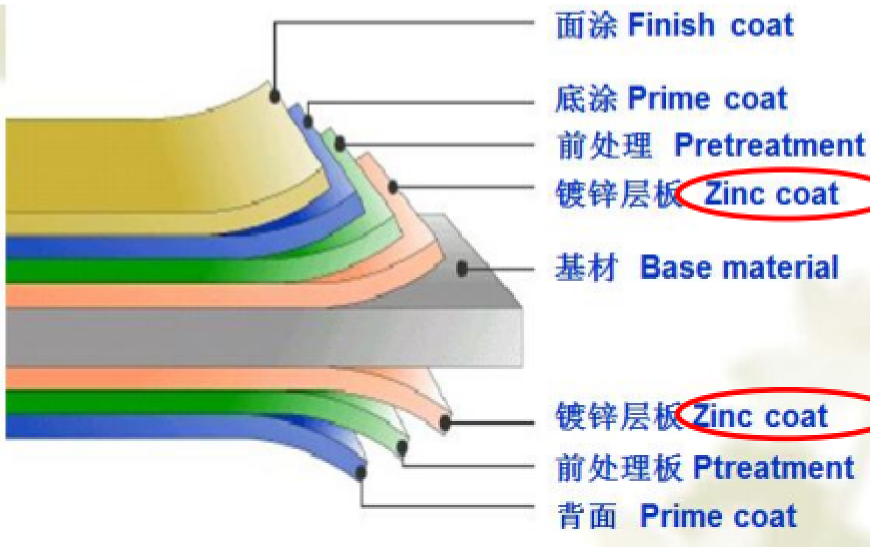
Prevention and Protection

Design Rules

1. **Weld rather than rivet** (avoids crevices).
2. **Drainage:** Design containers to drain completely (avoid standing liquid).
3. **Stress:** Avoid residual tensile stresses in exposed components (prevents SCC).
4. **Galvanic:** Insulate dissimilar metals or keep them far apart in the series.
5. **Heterogeneity:** Avoid varying conditions (heat, stress, aeration) across the surface.

Coatings & Active Protection

- **Sacrificial Anodes:** Connect the steel to Zinc or Magnesium. The Zn/Mg corrodes (anode), forcing the steel to be the cathode (immune).
- **Passivation:** Relying on stable oxide films (e.g., Cr_2O_3 on Stainless Steel).
  - An oxide layer forms on the surface, leading to decreased conductivity and therefore slower corrosion.
  - *Warning:* If the film is damaged and cannot reform (no Oxygen), pitting occurs.
- **Coatings:** Paints, polymers, or metal plating (Cladding, Hot-dipping).



Crystal Microstructures

Crystal Microstructures

Types of Properties

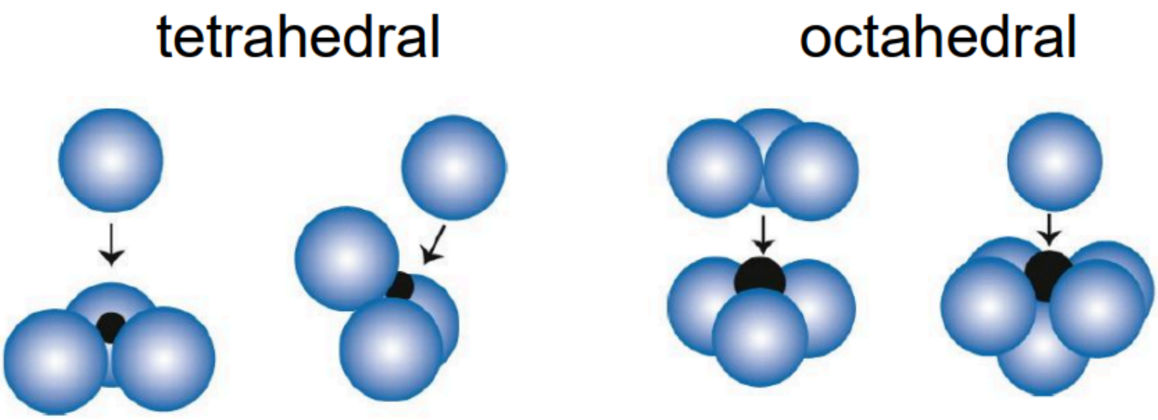
- **Intrinsic Properties:** related to atom bonding (The material itself)
  - Density
  - Thermal conductivity
  - Technology of Metallic Materials/Elasticity
  - Technology of Metallic Materials/Thermal Expansion Coefficient
- **Extrinsic Properties:** Affected by either the addition of impurities or by microstructure as a consequence of materials processing (What we do to the material)
  - Yield strength
  - Hardness
  - Elongation
  - Impact energy (resilience)
  - Toughness and fracture toughness
  - Fatigue resistance
  - Creep resistance
  - Corrosion and oxidation resistance

Electrical resistivity is VERY sensitive to impurities/nanoscopic defects.

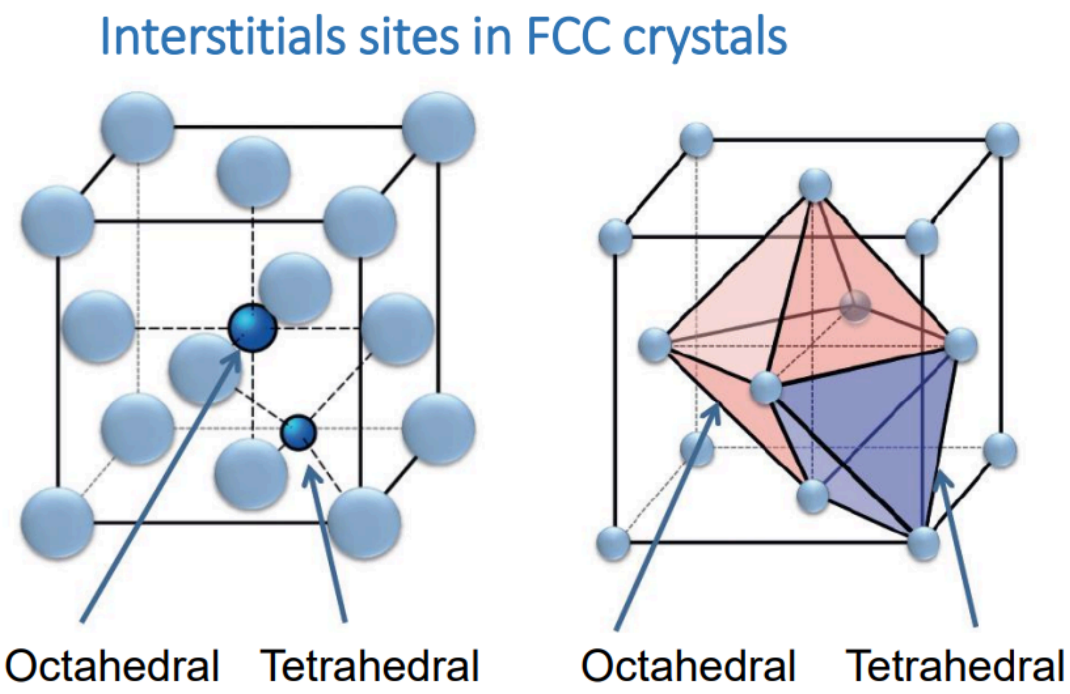
Types of Interstitial Sites

There are two types:

- Tetrahedral
  - There are twice as many interstitial sites as there are atoms in the lattice structure
- Octahedral
  - There are as many interstitial sites as there are atoms in the lattice structure, but those spots are larger than the ones in the tetrahedral structure



> Note
>
> Despite the name "octahedral", the primitive structure has 6 atoms, not 8. (It has 8 faces)



This has applications in metallurgy, such as sin the production of steel. $Fe - \alpha$ (ferrite) is tightly packed with more interstitial sites, but the slots are smaller, meaning that very little carbon can fit $(0.02 - 0.05\%)$. However, above $910^{\circ}C$, the iron structure changes into the FCC $Fe - \gamma$ (austenite), which has fewer larger sites. This actually allows for way more carbon to fit in (up to 2%). By then quenching the material, we can get the structure to readjust to its room temperature BCC formation, while retaining the carbon within it.

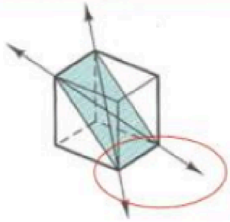
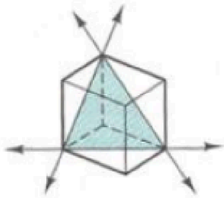
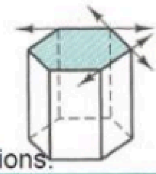
Crystal Anisotropy

Because atomic packing is not the same in all directions (atoms are more tightly packed on specific crystallographic planes), mechanical properties differ depending on the direction of the load. In a single crystal, this is **anisotropy**.

In **polycrystalline materials**, because of the large number of randomly oriented grains, these anisotropic properties usually average out, making the material macroscopically **isotropic**. However, mechanical processing (like rolling) can force grains to align in a preferred orientation. This creates **texture** (or banding), re-introducing macroscopic **anisotropy** where properties differ relative to the rolling direction.

Plastic deformation occurs on **Slip Systems**. A single Slip System is defined as the combination of a specific **Slip Plane** and a **Slip Direction**.

Each structure (FCC, BCC, HCP) has characteristic slip systems. The ductility of the material depends on the number of **independent** slip systems available. According to the **Von Mises Criterion**, a polycrystal requires at least **5 independent slip systems** to deform arbitrarily without cracking. FCC metals (12 systems) satisfy this and are ductile; HCP metals (often <5 systems) do not, and are often brittle unless they deform by Twinning.

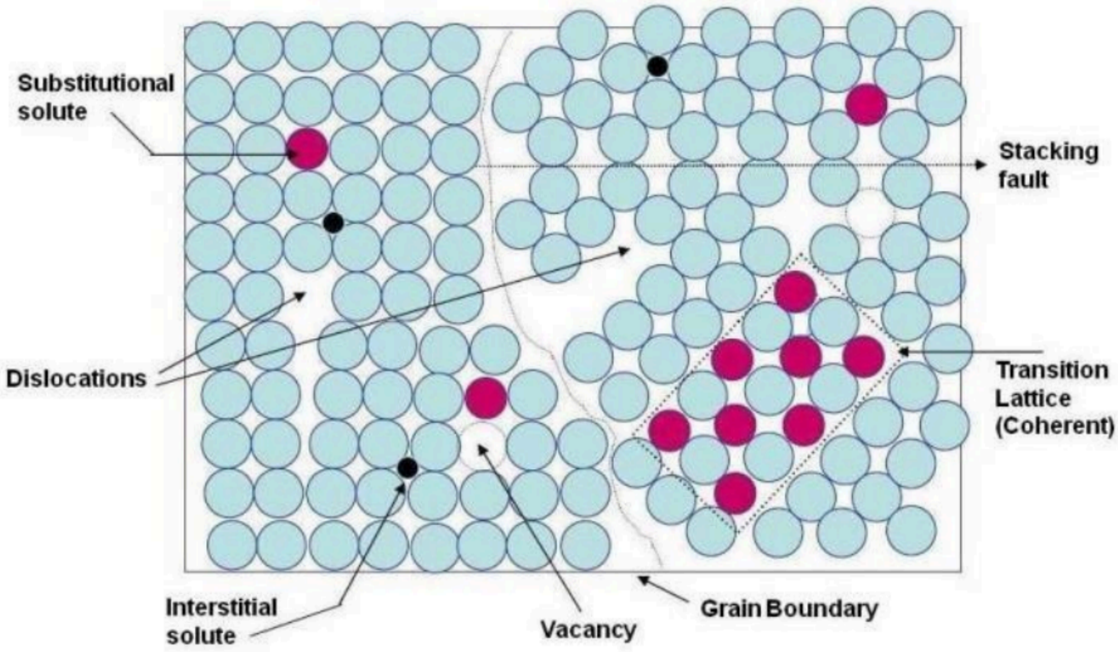
Crystal structure	Slip plane	Slip direction	Number of slip systems	Unit cell geometry	Examples
bcc	{110} {112} {123}	$\langle\bar{1}11\rangle$ // //	$6 \times 2 = 12$ 6 x 2 = 12 6 x 4 = 24 In total: 48		α-Fe, Mo, W
fcc	{111}	$\langle 1\bar{1}0\rangle$	$4 \times 3 = 12$		Al, Cu, γ-Fe, Ni
hcp	(0001)	$\langle 11\bar{2}0\rangle$	$1 \times 3 = 3$		Cd, Mg, α-Ti, Zn

Dislocations can only move on slip planes along slip directions.
The slip planes and directions are the closest packed in a lattice

Defects

Defects

Summary of Lattice Defects



Various Crystal Defects

Defect	Type	Improved Materials Properties	Adversely affected Materials Properties
Point Defect	Vacancy f(T)	- Diffusivity - Color Centers - Ionic Conductivity	- Electron mobility - Carrier Lifetime
	Substitutional	- Conductivity (dopant) - Strength (hardness) - Characteristic T (like T_M)	- Conductivity (impurities) - Ductility - Characteristic T
	Interstitial	- Strength - Characteristic T - Electrical Properties	- Ductility - Characteristic T - Electrical Properties
Line Defect	Dislocation	- Ductility (Malleability) - Strength (at high density)	- Strength - Yield Stress - Optical Properties - Lasing Action
Planar Defect	Grain Boundaries	- Strength - Electrical Properties - Magnetic Properties	- Creep - Electrical Properties - Magnetic Properties

Energetics of 2D Superficial Defects

mJ/m^{-2}	Al	Cu	Pt	Fe
Stacking fault energy	200	75	95	-
TB energy	120	45	195	190
GB energy	625	645	1000	780

Grain boundaries energies are far much larger than those of other defects and thus effective to retain disocations.

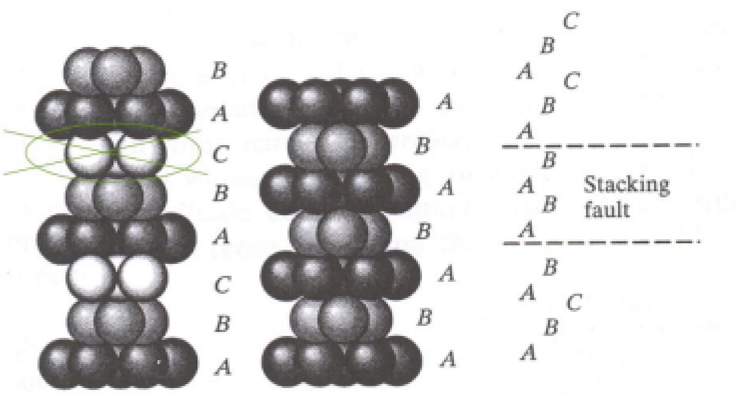
Surface Corrosion

Inside a material, metal atoms are surrounded by other atoms. This makes them low-energy since they are bound everywhere. However, on the surface of the material, atoms are not bound everywhere and are therefore in a thermodynamically unstable state, making them more reactive.

This allows for the surface of metals to be prone to corrosion (reaction with outside elements) on the surface.

$$E_{\text{Free Energy Surface}} > E_{\text{Internal}}$$

Stacking Faults



(a) FCC stacking (b) HCP stacking (c) Stacking fault (HCP stacking) in FCC structure

> In FCC crystals, we can have stacking faults: a layer is missing and therefore resembles an HCP structure for a small segment. This makes the materials with more of these faults to be more resistant to plastic deformation.

We define "Stacking Fault Energy" as the energy per unit area required to create a stacking fault. When this is high (such as in aluminium), it is common to see slipping occur as the material gets deformed.

Metal	$\gamma_{\text{SFE}}\ (mJm^{-2})$
Aluminium	166
Zinc	140
Copper	78
Magnesium	125
Silver	22
91Cu:9Si (Silicon Brass)	5
Gold	45
Zirconium	240
Nickel	128
304 Stainless steel	21
Cobalt (FCC)	15
70Cu:30Zn (Brass)	20

E_{SF} decreases as we add impurities (solute atoms) to an alloy.

Twinning

When stacking fault energy is low, such as in brass, stainless steel (also common in HCP metals such as titanium and magnesium), we tend to get **Mechanical Twinning**: a planar defect where small fractions of the crystal volume which rotate to form a mirror image (a twin) of the original lattice.

> **Twinning**
>
> Mechanical twinning is a plastic deformation mechanism in crystalline materials where a shear stress causes a portion of the lattice to reorient into a mirror image of the surrounding matrix.
> It occurs as a rapid, stress-mediated process often at low temperatures or high strain rates, particularly in HCP metals and low-stacking fault energy FCC alloys, typically forming thin, lens-shaped regions.

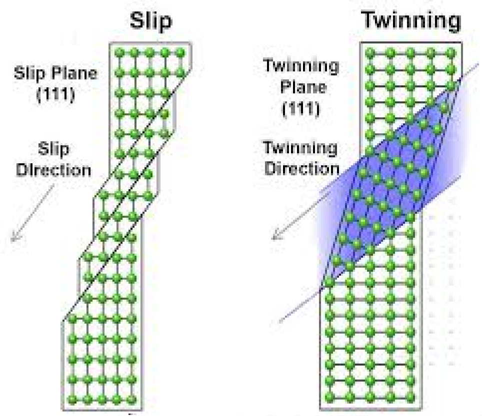
> **Warning**
>
> Twinning involves only small sections of the lattice. These small sections will reverse the direction with respect to the rest of the structure.

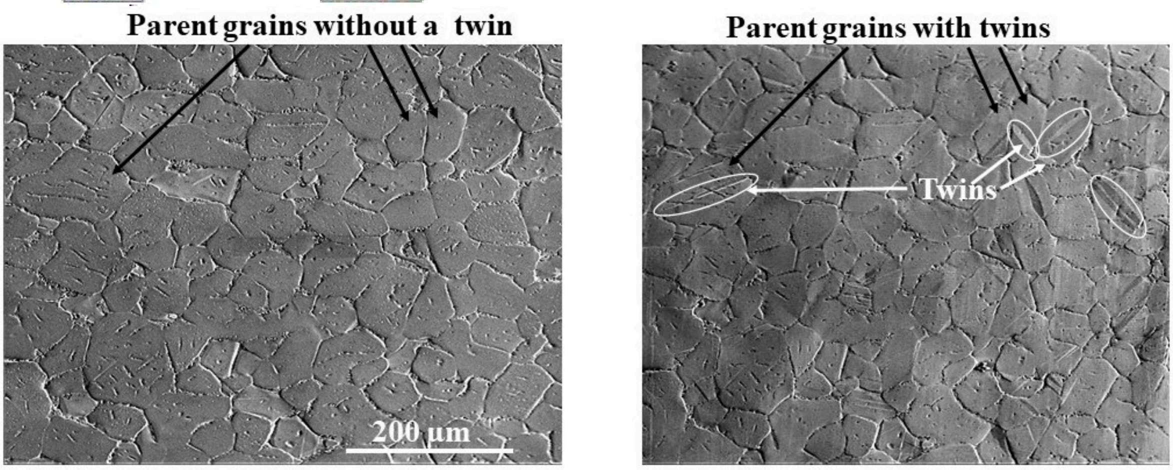
Twinning is promoted by:

- Low temperatures
- High strain rates
  - Explosions, impacts, or ballistic hits (slip is too slow to accommodate rapid deformation)
- Large grain size
  - Small grains resist twinning.
- Low SFE

A use for this

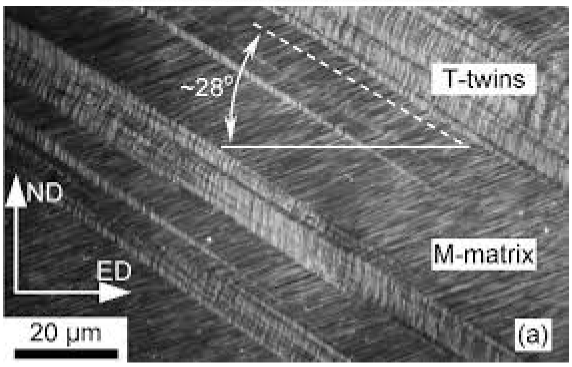
The presence of "twins" in a material which has failed can hint at the reason for its failure. For example, in a plane crash in the 90s, an investigation showed that parts of the steel of the plane's frame had signs of twinning, which told them that the plane was likely hit by an explosive rocket. (Explosion = high $\frac{d\varepsilon}{dt}$)





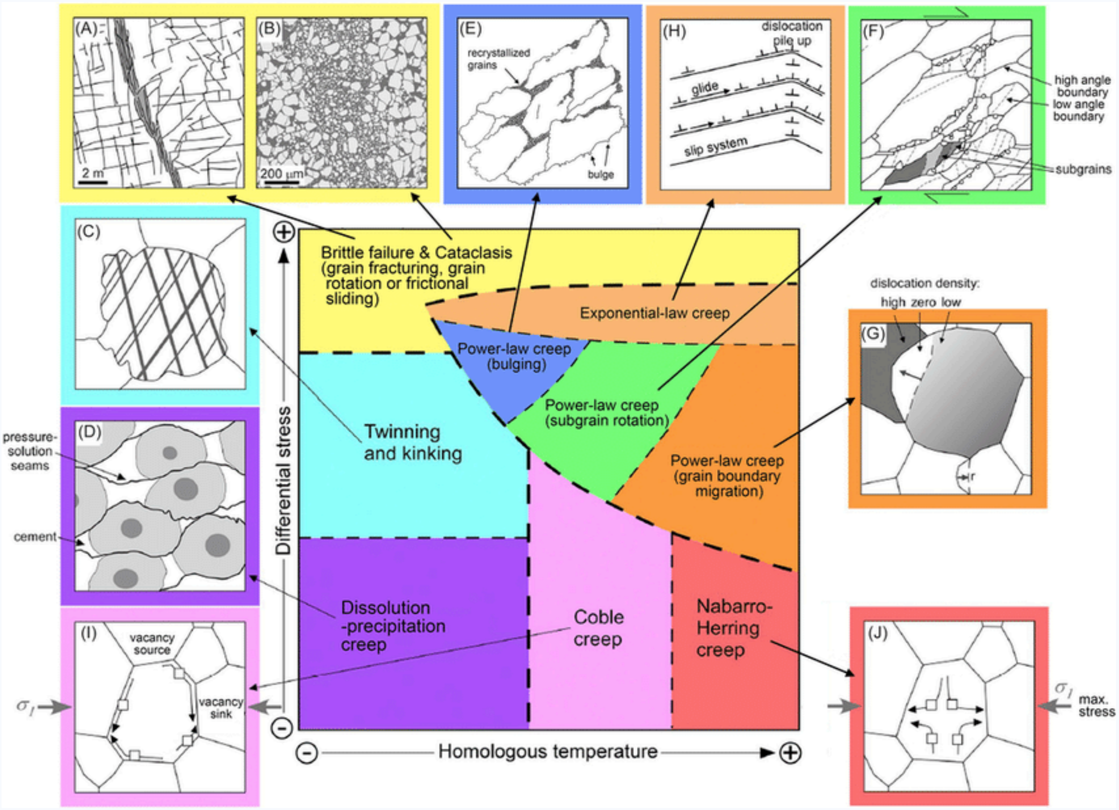
Grains before deformation

After deformation



Deformation Mechanism Map

The following diagram shows how different stress rates and temperatures affect the way the material plastically deforms.



Feature	Slip	Twinning
Volume Involved	Involves all volume of the crystal	Takes part into a small fraction of the crystal volume, the amount of deformation is small
Surface Effect	Slip leaves a series of steps (lines) at the free surface after deformation	Twinning leaves a small but defined twin after deformation
Lattice Orientation	The lattice direction does not change	The lattice direction changes
Atomic Movement	All atoms on one side of the slip plane move equal distances	Atoms move distances proportional to their distance from the twinning plane corresponding to a fraction of the interatomic distance

Grain Boundaries

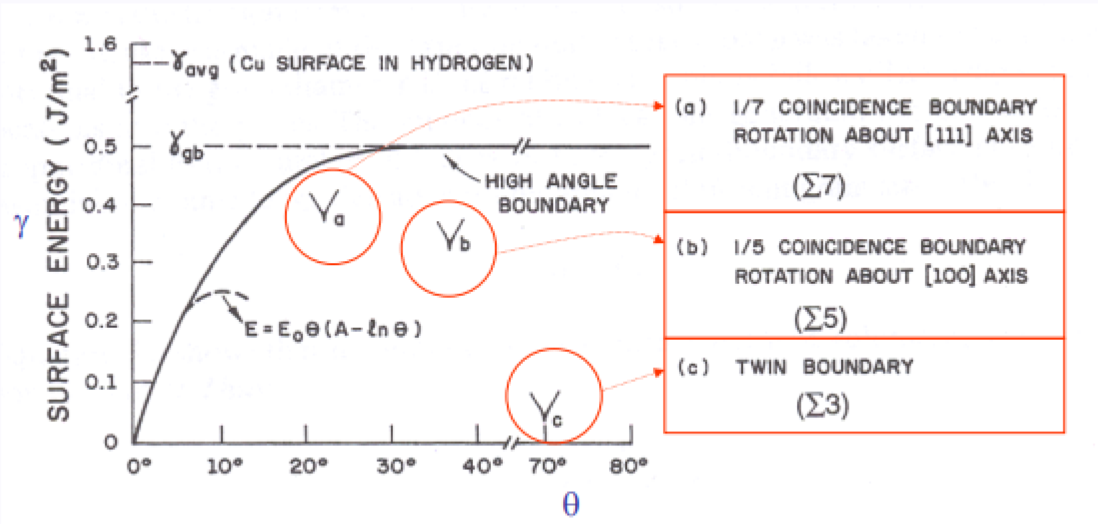
1. We can't always see grain boundaries. We need to use some sort of etching to actually see them.
2. Grain boundaries are high-energy and usually have free interstitial sites.

3. Because of these interstitial sites, impurities tend to clump up on grain boundaries

We have two different types of grain boundaries depending on the difference in orientation between the two grains θ:

- Low Angle Grain Boundaries (*LAGB*)
  - $\theta < 15^\circ$
  - Since the misalignment is not significant, the energy of the GB is relatively low and closer to the energy within the grain
  - The structure is adjusted by inserting an occasional "extra half-plane" of atoms to "bridge the gap"
  - Mathematically, this acts just like a vertical stack of edge dislocations
    - The energy is the sum of energies of those dislocations
    - Higher angle $\implies$ More dislocations needed $\implies$ Higher energy (linear-ish behaviour)
- High Angle Grain Boundaries (*HAGB*)
  - $\theta > 15^\circ$
  - Beyond around 15°, the misalignment is huge
  - In these GBs, grain boundaries have a layer of disordered (quasi-amorphous) structure as the material transitions from one orientation to another
  - At this point, energy is maximized and increasing energy beyond $\sim 15^\circ$ will not increase it much further.
    - Here, energy is constant and at its maximum

An example for Copper



Consequences of grain boundaries:

- They are sources and sinks for dislocations
- They contribute to mechanical strengthening and change the sliding system
- They act as sinks for impurities dissolved in the alloy

- They contribute to the formation of second phases
  - Primary nucleation sites for the growth of second phases
- They are material portions with no crystallinity (amorphous)

Micro-Yielding

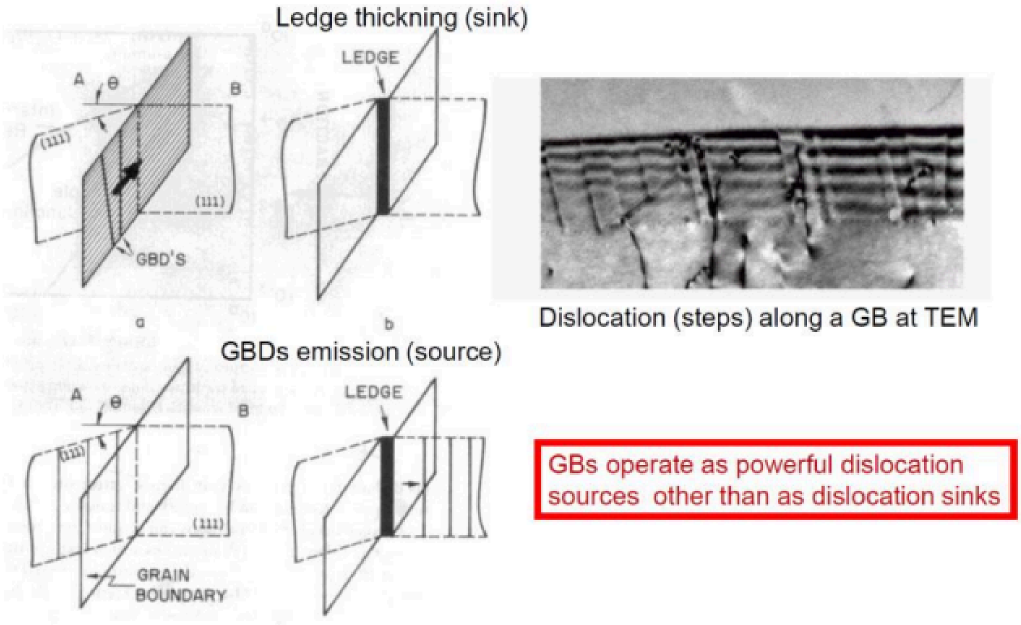
When a polycrystalline material is stretched, local tensile stresses will be stronger around grain boundaries. This means GBs will yield before the overall material has started yielding. This phenomenon is called micro-yielding.

The dislocation forests created via this micro-yielding are responsible for strengthening the overall structure by applying a stress which counters the external one, leading to an overall lower stress.

GB Ledges and Gb's Dislocation Source

When dislocations hit grain boundaries, they tend to get stuck and can't proceed further. This way, the GB acts as a **ledge** or a sink for dislocations.

However, after many dislocations pile up, or if stress is high enough, the energy will be too high and the GB will act as a powerful dislocation source, emitting dislocations. This is somewhat similar to Frank-Read Dislocation Sources, but in this case, the obstacle is a GB.



Grains

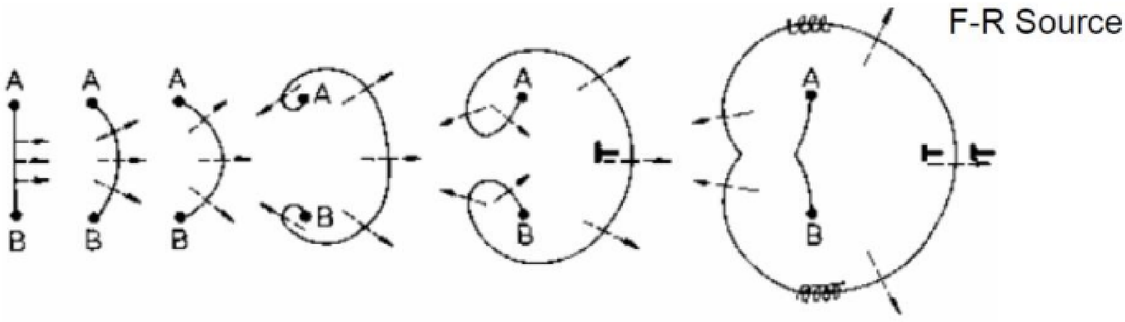
ASTM defines a value that describes grain density.

$$N = 2^{n-1} \implies n = \log_2 N + 1$$

Where:

- N is the number of grains per square inch
- n is the **grain size number**

Frank-Read Dislocation Sources

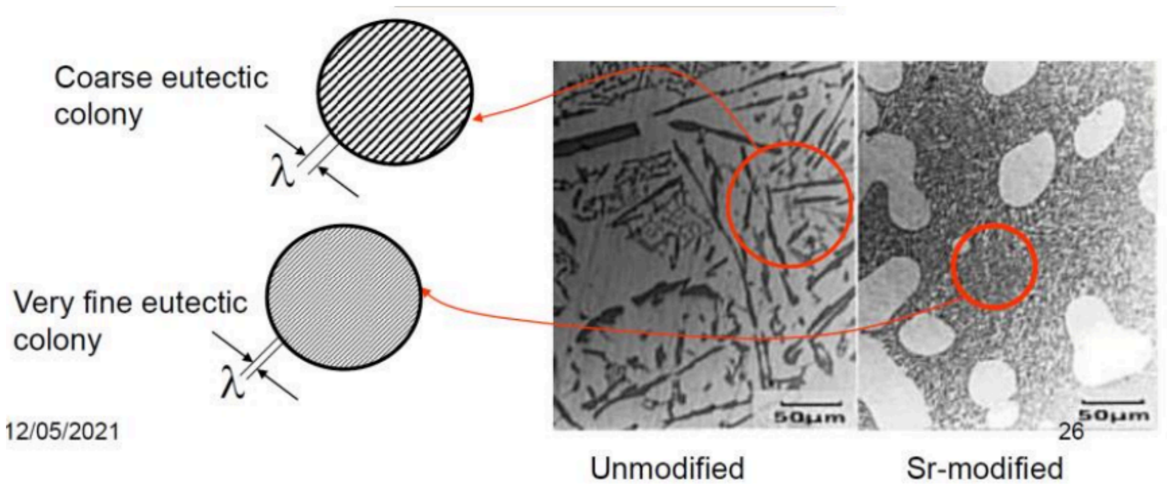


$$\tau = \frac{Gb}{L}$$

- τ: Critical shear stress, or the stress required such that dislocations "replicate" as shown above
- G: Shear Modulus (How stiff is it to shear?)
- b: Burgers Vector (magnitude of the lattice distortion)
- L: The length of the source (distance between the two pinning points shown as A, B above)

Sr-Modified $AlSi$ Casting

Normally, silicon is very brittle, while aluminium is quite soft. A pure $AlSi$ alloy therefore has quite poor mechanical properties. We can therefore add a small amount of Sr or Na into the alloy before casting to create very fine structures, strengthening the material.



> As shown, the addition of a tiny amount of Sr can completely change the structure of the material, turning it from a weak material with large and sharp precipitates, to very fine eutectic colonies.

Elasticity

Elasticity

$$E = \frac{\sigma}{\varepsilon}$$

> Note
>
> Elasticity is not always isotropic. Because of directional slip planes, the elastic modulus E can vary depending on the alignment with the lattice structure.

Some values for E for metals at different lattice orientations (Values in GPa):

Metal	E_{100}	E_{110}	E_{111}
Al	36.7	72.6	76.1
Cu	66.7	130.3	191.1
Fe	125.0	210.5	272.7
W	384.6	384.6	384.6

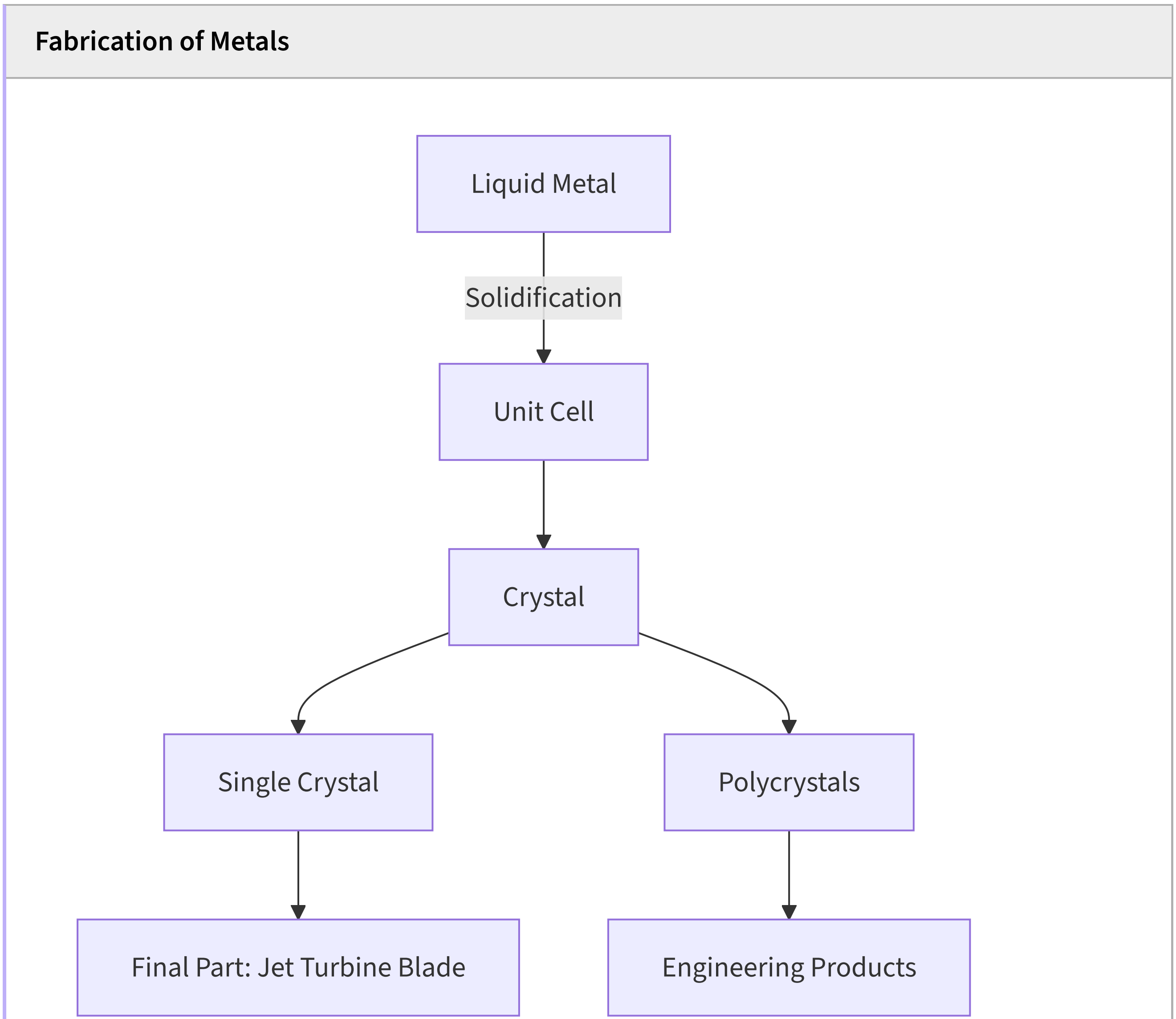
Relation to Condon-Morse Model

The Condon-Morse Model provides us with en explanation as to why certain alloys have a value for E.

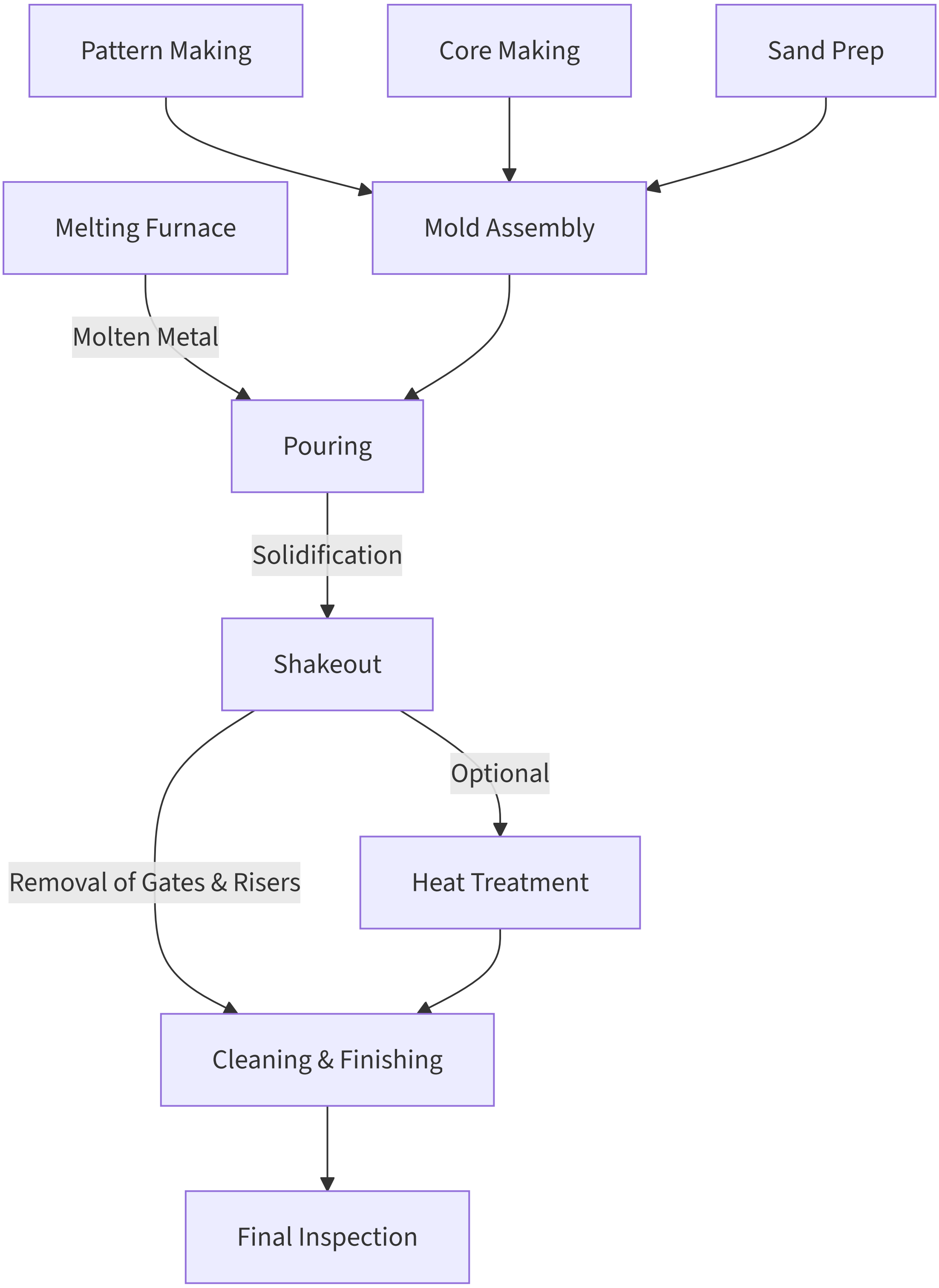
$$E = \frac{1}{r_m} U''(r_m) = \frac{1}{r_m} F'(r_m)$$

Since repulsive forces increase as T increases, the average stable atomic distance r_m also increases, therefore decreasing E. (Note that $U''(r_m) = \frac{d^2U}{dr^2}$ at point $r = r_m$).

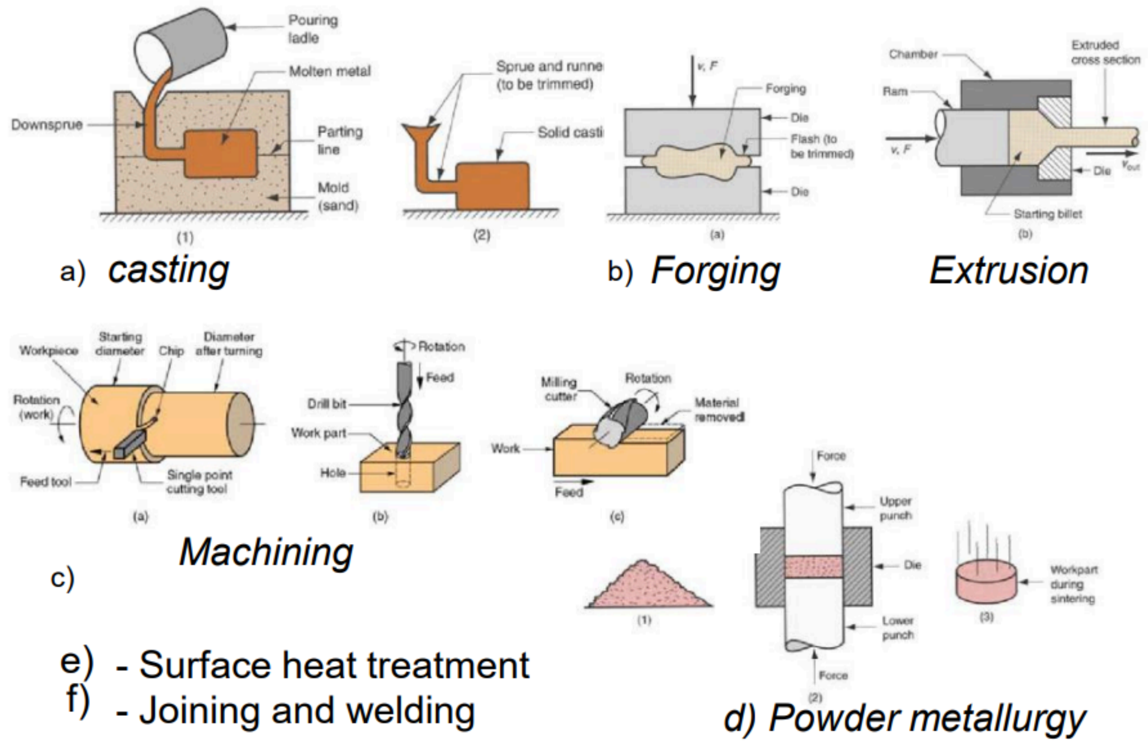
Fabrication of Metals



Sand Casting

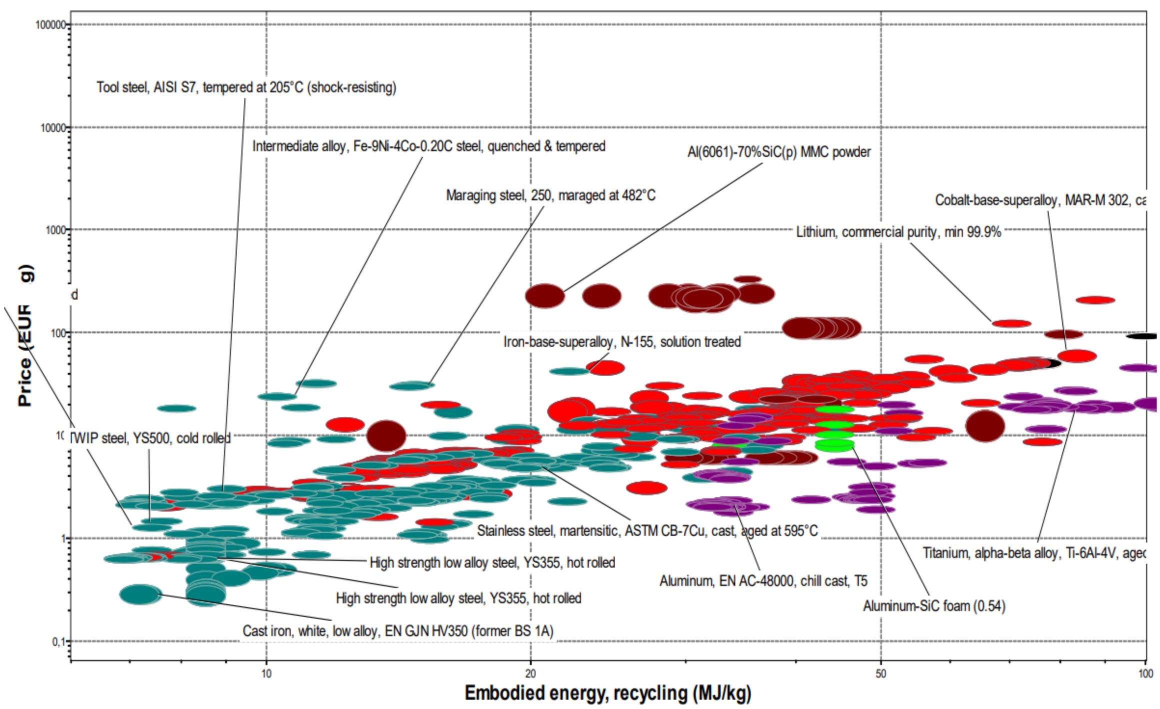


Relevant Shaping Methods



Embodied Energy

> **Definition**
>
> Embodied Energy is the energy required to get the required material in $MJKg^{-1}$ to produce the material in a raw shape.



> The above graph shows the cost of acquiring different materials, both in €/Kg and in embodied energy.

Microstructure Control

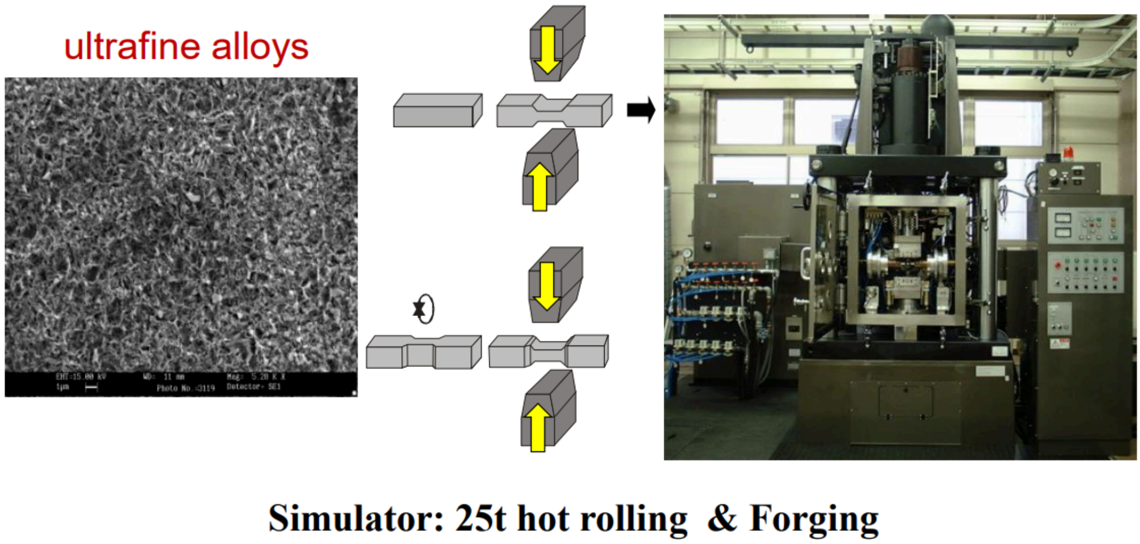
We recall the Hall-Petch relationship that describes yield strength's relationship with grain size:

$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{d}}$$

We can therefore say that a decreased grain size d will increase yield strength σ_y. We should therefore produce the material with grains as small as possible if we need to maximize σ_y.

Smaller grains create a stronger AND tougher material.

Severe Multi-Directional plastic Deformation



> The process of severe multi-directional plastic deformation involves inducing plastic deformation over and over onto a material sample, crushing the existing grains into smaller and smaller sizes.
> The equipment in the photo is usually found in a lab to produce samples for testing. However, the method is also used for production.

nc Metals by Electrodeposition

To ensure that a material has extremely small grains from the start, electrodeposition can be used.

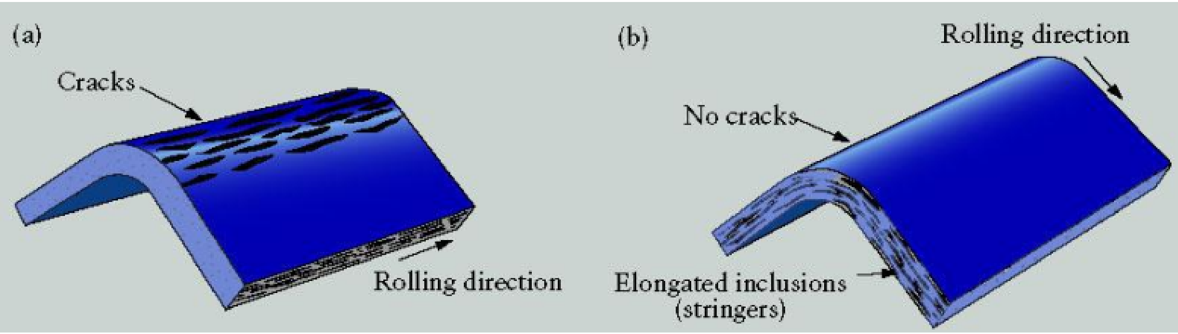
This process involves adding a seed to a solution of the metal ion and using electricity to cause deposition of the ion on the seed (and after the reaction started on the sample) which is then neutralized by the current.

Electrodeposition leads to metals with extremely fine grains, which can have super-plastic behaviour. For example, Cu typically snaps at $\varepsilon \approx 50\%$, but with this process (the form is called nCu), it can reach up to $\varepsilon \approx 5100\%$.

Strengthening by Texture

In order to give strength to a material in a certain direction, texturing can be used. There are several methods to achieve this:

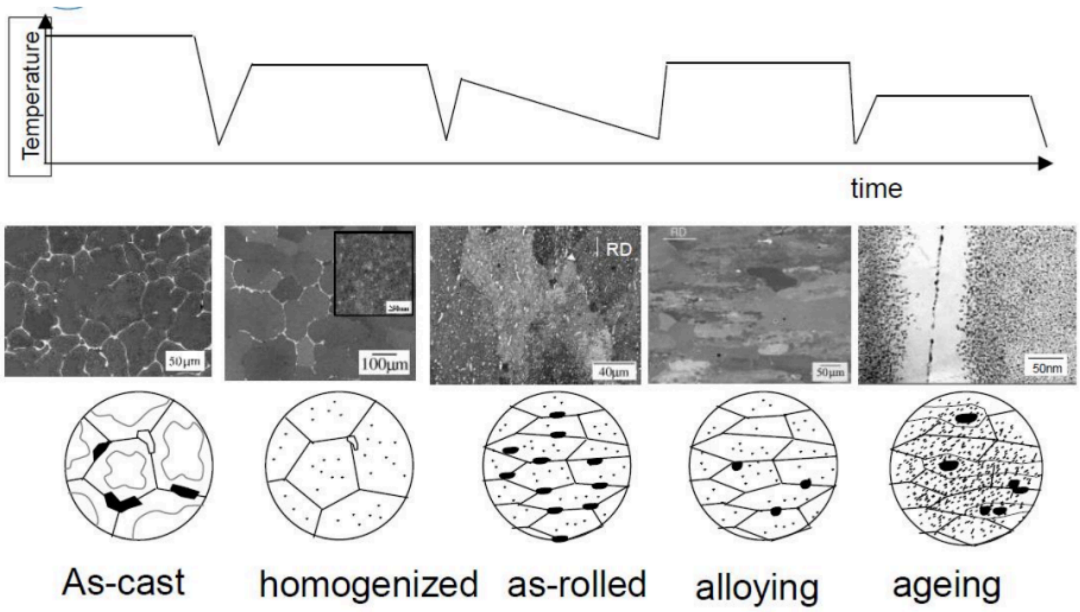
- Rolling: by rolling the metal in a certain direction, grains, and their crystals align with the rolling direction
- Forging: by forging a shape, you allow the texture to follow the shape of the object following how the metal is poured (bottom-up)
- Pressing: By pressing a rod on its sides, it is forced to elongate, aligning the crystals in the direction of the rod.



Production of High Strength 7XXX Series Aluminium (Al, Zn, Mg)

7XXX Series Al is a very strong material often used in structural components in aircrafts (Such as wings on b777)

The process is as follows:



1. We cast, forming a disorganized structure with second phases on grain boundaries
2. We heat it up, allowing second phases to dissolve into the grains, homogenizing the material
3. We roll it to strengthen it in the desired direction (direction of rolling), therefore providing it with a texture.
4. We heat up the material again to remove second phases on grain boundaries
5. We quench and age the material to create controlled second phases that strengthen the material.

index

index

Auto-Generated Monolithic PDF:

Overview of Metals

Overview of Metals

Combined Yield Strength

$$\sigma_y = \sigma_{\mathrm{PN}} + k\sqrt{c} + \frac{k_y}{\sqrt{d}} + \alpha G b \sqrt{\rho}$$

- σ_{PN}: the "starting point" for the material (Peierls-Nabarro Stress)
- $k\sqrt{c}$: Solid Solution
- $\frac{k_y}{\sqrt{d}}$: Grain Boundaries
- $\alpha G b \sqrt{\rho}$: Strain Hardening

An application in the production of 7XXX Al-alloy:

Material	Yield Strength ksi	%elongation
Pure annealed Al	2.5	60
Solid solution Strengthened with 1% Mn	6	45
Highly cold worked pure Al	22	15
Precipitation hardened alloy 7075	80	10

Main strengthening methods of alloys

Alloy	Typical uses	Solution hardening	Precipitation hardening	Work hardening
Pure Al	Kitchen foil			✓✓✓
Pure Cu	Wire			✓✓✓
Cast Al, Mg	Automotive parts	✓✓✓	✓	
Bronze (Cu–Sn), Brass (Cu–Zn)	Marine components	✓✓✓	✓	✓✓
Non-heat-treatable wrought Al	Ships, cans, structures	✓✓✓		✓✓✓
Heat-treatable wrought Al	Aircraft, structures	✓	✓✓✓	✓
Low-carbon steels	Car bodies, structures, ships, cans	✓✓✓		✓✓✓
Low alloy steels	Automotive parts, tools	✓	✓✓✓	✓
Stainless steels	Pressure vessels	✓✓✓	✓	✓✓✓
Cast Ni alloys	Jet engine turbines	✓✓✓	✓✓✓	

Symbols: ✓✓✓ = Routinely used. ✓ = Sometimes used.

Unique Properties of Metals

- many methods of part shaping (wrought, casting, PM, joining, etc.)
- Many methods of strengthening (as well as a large variety of mechanical properties)
- Excellent compromise between high-strength and high-toughness
- Sensitive to cooling/heating rates
- Can combine structural and functional performance
- Can undergo significant plastic deformation

Inconveniences:

- Affected by environmental and on-service degradation and embrittlement
- Very sensitive to strain rate
- Sensitive to transition temperature

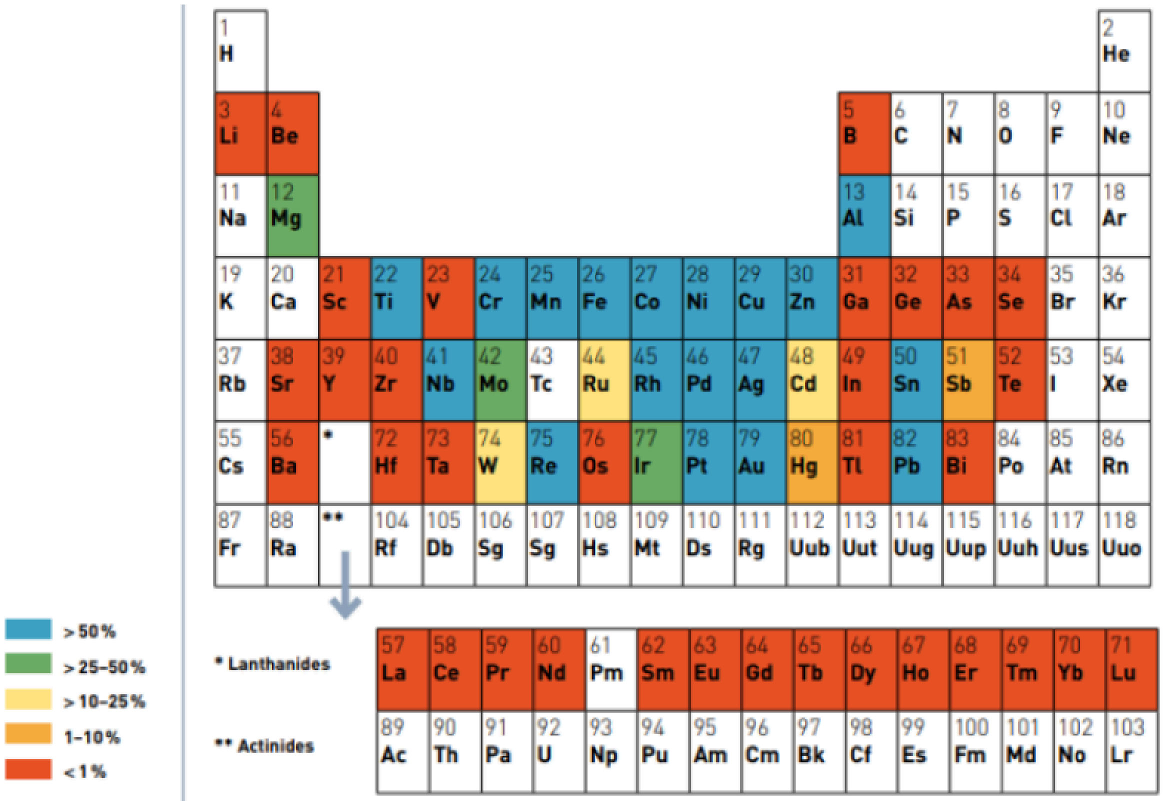
Properties of "The Big 6" Metals

Property	Iron (Fe)	Aluminium (Al)	Copper (Cu)
Available?	**Yes** (Very Abundant)	**Yes** (Most Abundant Metal)	**Yes** (Moderate)
Cheap? (£ / tonne 1997)	**Yes** (~£100 - £150)	**Medium** (~£1,000)	**No** (~£1,500 - £1,800)
M.P. (°C)	**1538**	**660**	**1085**
Density ($kg\ m^{-3}$)	**7870**	**2700**	**8960**
Allotropy	**Yes** (BCC α, FCC γ)	**No** (Always FCC)	**No** (Always FCC)

Property	Iron (Fe)	Aluminium (Al)	Copper (Cu)
Dissolves things?	**Yes** (Carbon, Nitrogen)	**Yes** (Copper, Magnesium, Silicon)	**Yes** (Zinc, Tin, Nickel)
T-Variable solubilty	**Yes** (Crucial for Steel hardening)	**Yes** (Crucial for Age hardening)	**Yes** (Variable)
Compounds	Carbides (Fe_3C), Oxides	Alumina (Al_2O_3), Intermetallics	Oxides (CuO), Sulfides
Stability	**Poor** (Rusts/Oxidizes rapidly)	**Good** (Protective Oxide Layer)	**Good** (Noble / Forms Patina)
Hazardous?	**No** (Essential nutrient)	**No** (Dust can be explosive)	**No** (Salts can be toxic)

Property	Nickel (Ni)	Titanium (Ti)	Magnesium (Mg)
Available?	**Medium** (Sulfide ores)	**High** (Abundant but hard to extract)	**High** (Sea water / Dolomite)
Cheap? (£ / tonne 1997)	**No** (~£4,000)	**Very Expensive** (~£8,000+)	**Medium** (~£1,500)
M.P. (°C)	**1455**	**1668**	**650**
Density ($kg\,m^{-3}$)	**8908** (Heavy)	**4506** (Light-ish)	**1738** (Very Light)
Allotropy	**No** (FCC)	**Yes** (HCP $\alpha \to$ BCC β)	**No** (HCP)
Dissolves things?	**Yes** (Cr, Fe, Co - Superalloys)	**Yes** (Al, V, O)	**Yes** (Al, Zn, Mn)
T-Variable solubility	**Yes** (Precipitation hardening)	**Yes** (Phase transformation)	**Yes** (Age hardening)
Compounds	Intermetallics (γ' Ni_3Al)	Oxides (TiO_2), Carbides	Oxides (MgO), Hydrides
Stability	**Excellent** (High Temp & Corrosion)	**Excellent** (Passivates instantly)	**Poor** (Galvanic corrosion / Flammable)
Hazardous?	**Yes** (Allergen / Carcinogen dust)	**No** (Biocompatible)	**Yes** (Dust/Chips are explosive)

Recycling Rate of Elements



Blank box denotes no data is available

Materials Substitution Table

Material	Consumption	Value	Import content	Energy	Resource life	Security of supply	Ease of use
Steel	1	0	4	2	4	4	4
Aluminium	2	3	3	0	3	3	4
Copper	2	2	3	2	3	2	5
Lead	3	3	3	3	2	3	5
Zinc	3	3	2	1	2	3	4
Tin	4	4	2	3	1	1	-
Nickel	4	4	1	3	4	4	-
Magnesium	4	4	2	0	5	5	3
Mercury	5	5	0	2	1	0	-
Glass	2	2	5	3	5	5	2
Brick	0	2	5	5	5	5	2
Concrete	0	1	4	4	5	5	3
Timber	1	1	2	5	4	3	4
Plastic	2	1	2	1	3	4	4

> Info
>
> The above table shows ratings for several categories for certain materials. The ratings are in the range of 0 (meaning very bad) to 5 (meaning excellent).

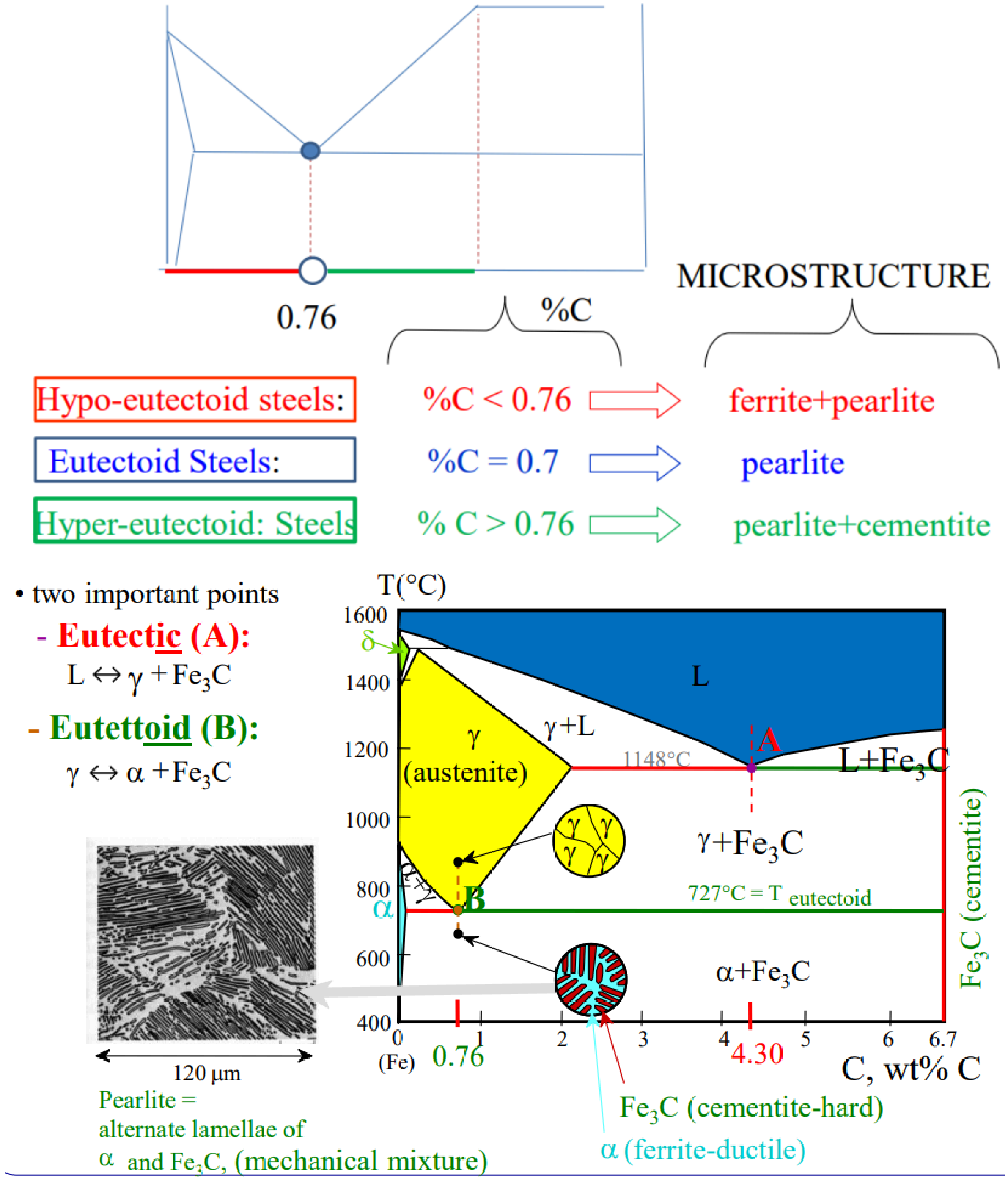
Properties Involved In Selection of Materials

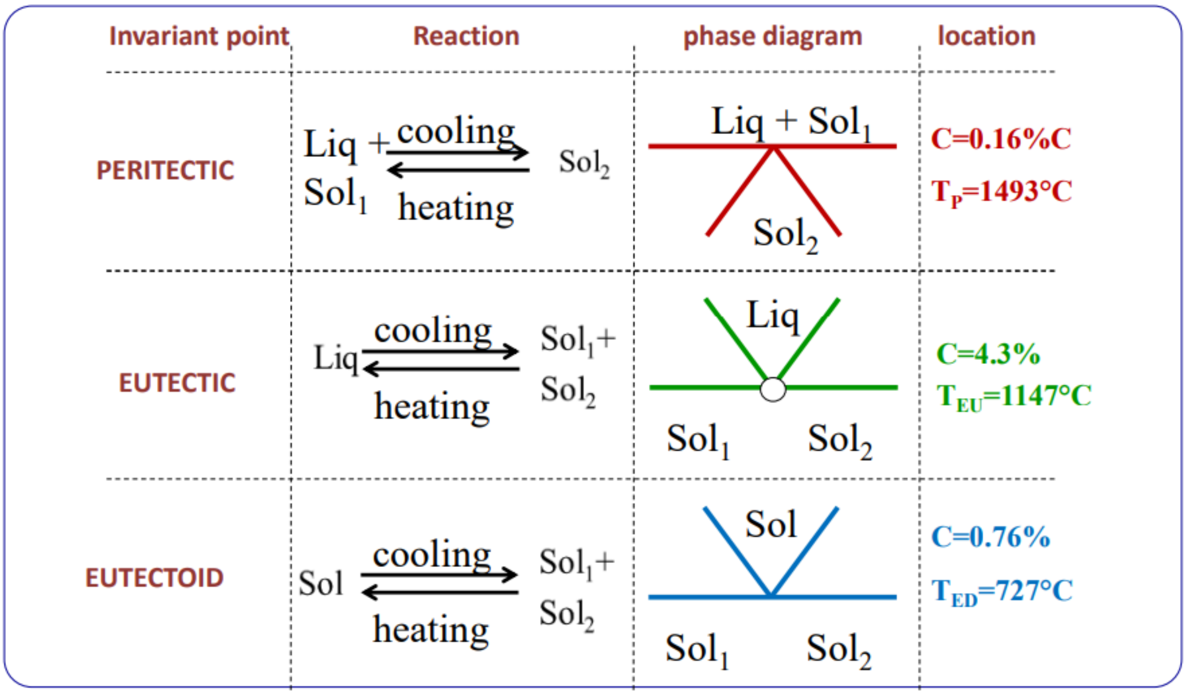
- Chemical composition
- Contamination of contents by corrosion products
- Corrosion characteristics in:
  - Atmosphere
  - Water
  - Soil
  - Chemicals
  - Gases
  - Molten metals
- Creep characteristics @ temperature range
- Crystal structure
- Damping Coefficient
- Density
- Effect of cold working
- Effect of high temperature on corrosion resistance
- Effect on strength after exposure to hydrogen and high temperatures
- Electrical conductivity
- Electrical resistivity
- Fire resistance
- Hardenability
- Maximum temperature not affecting strength
- Melting point
- Corrosion factor
- Susceptibility to corrosion:
  - General
  - Hydrogen damage
  - Pitting
  - Galvanic
  - Corrosion fatigue
  - Fretting
  - Stress corrosion cracking

    - Corrosion/erosion
    - Cavitation damage
    - Intergranular
    - Selective attack
    - High temperature
- Thermal coefficient of expansion
- Thermal conductivity
- Wearing quality:
    - Inherent
    - Via heat treatment
    - Via plating

Overview of Steels

Overview of Steels



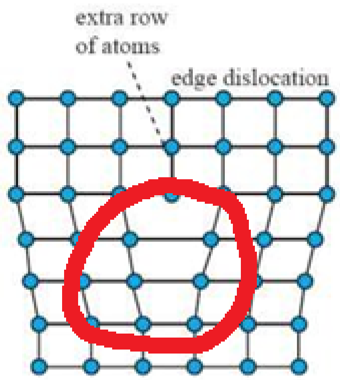


Raw Costs for Stainless Steels

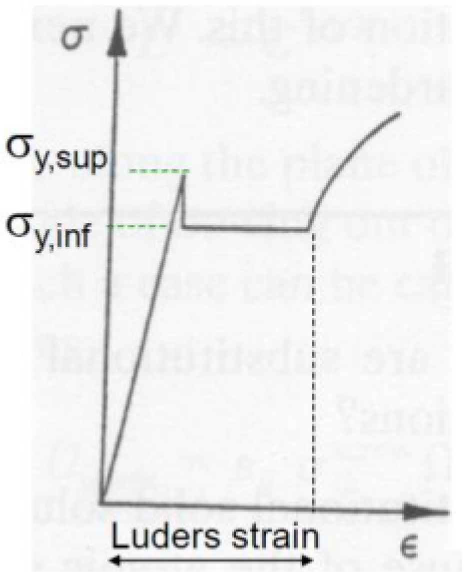
Material	Price in $/tonne
Scrap Iron	149
Chromium (as high-carbon ferro-chromium)	1000
Nickel	6755
Molybdenum (As ferro-molybdenum)	10000
Manganese (As ferro-manganese)	396
Copper	2323
Titanium (As ferro-titanium)	3465
Niobium (As ferro-niobium)	15000

Cottrell Atmospheres

A Cottrell atmosphere is a type of defect that tends to occur most often in steels. It involves an edge dislocation creating space for carbon atoms in the section of the material in tension (Circled in red below).



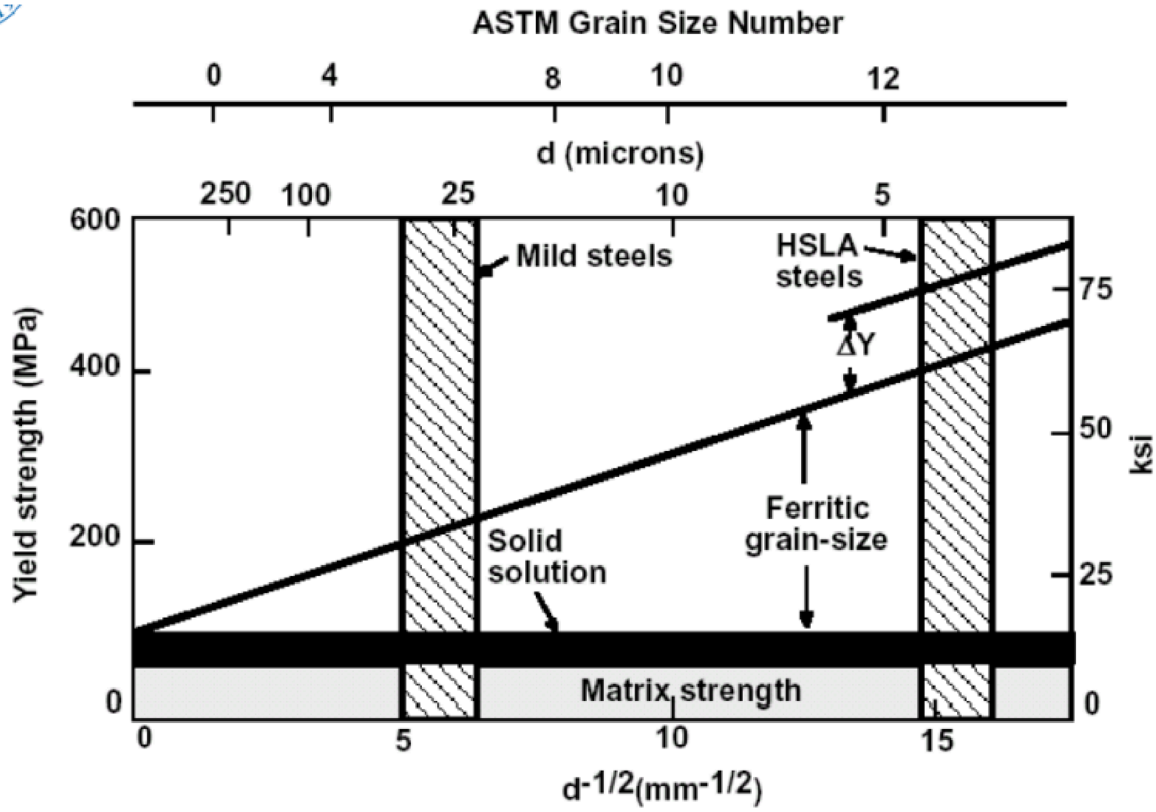
The setup allows for carbon atoms to block dislocation movement. This is why in steel we have an upper and lower yield strength: as long as the carbon in Cottrell Atmospheres is intact and can prevent dislocation movement, the yield strength will be higher, but once these are broken, dislocations can move more easily and therefore σ_y decreases to the lower value.



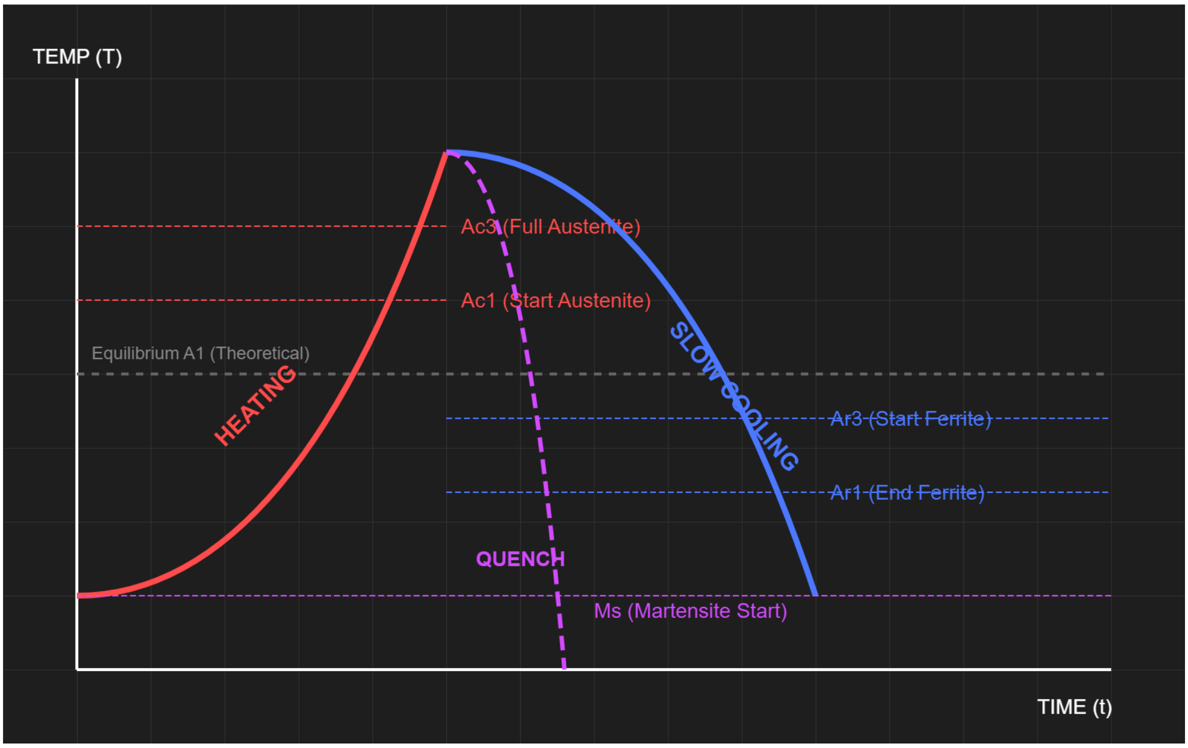
Why "Atmosphere?"

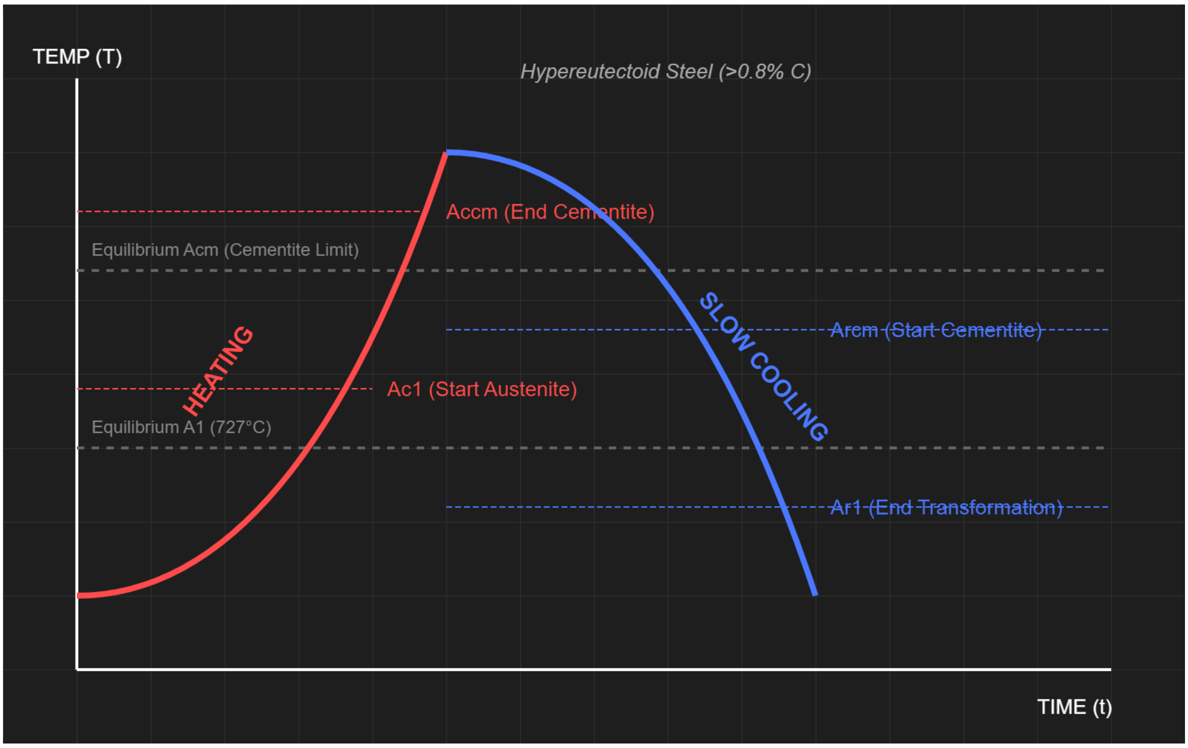
The defect is called an atmosphere because it is not one single carbon ion sitting in the empty spaces, but a dense fog or cloud of atoms hovering around the dislocation line, locking it in place.
Given this, we can say that the Cottrell Atmosphere is a cloud of point defects (the carbon atoms) around a line defect (the dislocation).

High Strength Low Alloy Steels (HSLA)



Non-Equilibrium Phase Diagram



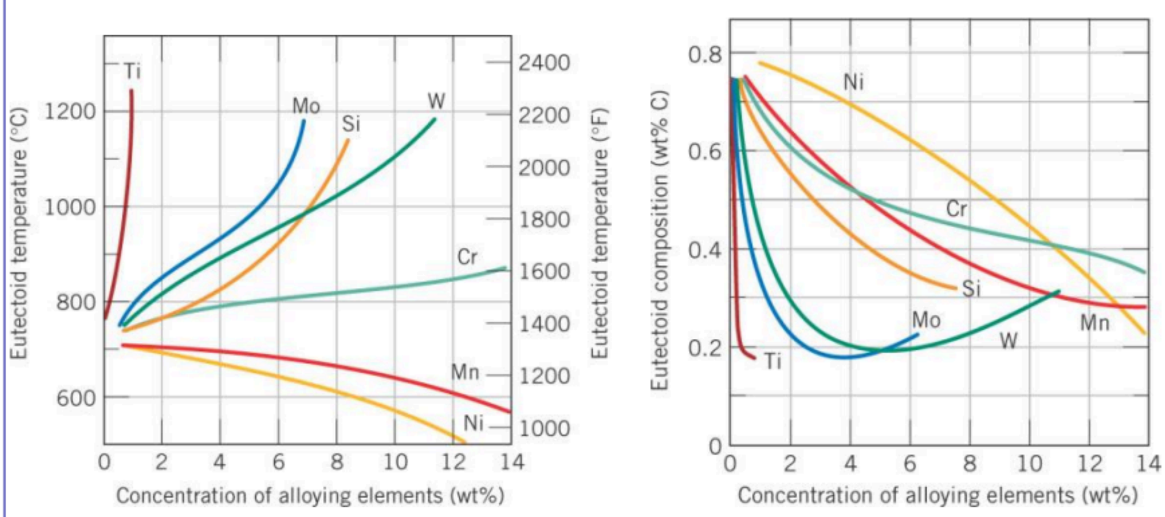


> The above diagrams show a time vs temperature diagram of how different forms of steel are created.
> The first diagram shows hypoeutectoid steel (low carbon), while the second one shows hypereutectoid steel (high carbon)

Austenitizers and Ferritizers

To control at what temperatures steel is stable in a certain form (α, γ, δ) we can add alloying elements to the steel. These are:

- Austenitizers
  - FCC γ phase.
  - Increase temperature range at which austenite is stable.
  - Ni, Mn, Co and weaker ones are C, N, Cu
  - Lower transformation temperatures
    - This is why austenitic stainless steel remains non-magnetic and ductile even at room temperatures and is therefore used in kitchens
- Ferritizers
  - BCC α phase
  - Widen temperature range at which ferrite is stable
  - Cr, Si, Al, Mo, Ti, V, or weaker ones being B, S, Ze, Nb, Ce, Ta
  - Raise transformation temperatures
    - Adding enough of these prevents phase transformation as a whole (especially chromium)

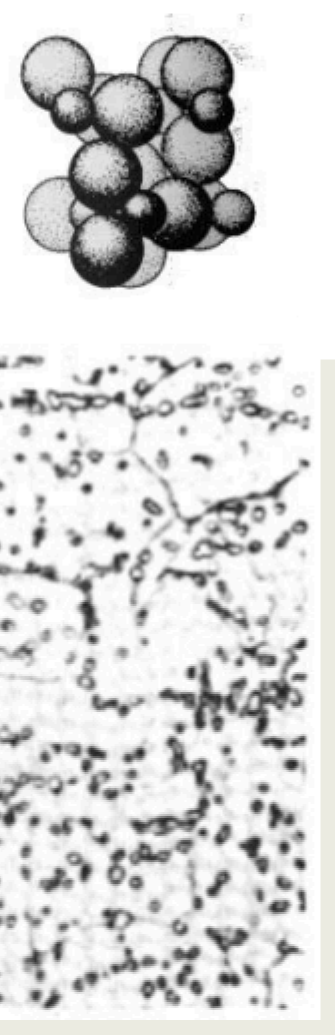


The effect of austenitizers and ferritizers on eutectoid temperature and composition $(wt\%\ C)$

Forms of Steel

Cementite

- Hard and brittle compound
- Fe_3C
- Contains 6.67 $wt\%\ C$
- It is present in all steels when carbon amount is above 0.025% as:
  - Lamellae (pearlite, bainite)
  - Needle (martensite)
  - Spheroids
  - Or as film around austenite GB (in iper-eutectoidic steels)
- It is the reason steels are useful: in the form of impurities in softer forms, it pins the structure in place, allowing it to be harder than it would otherwise be.
- Other alloying elements such as Cr, Mo, Mn can be added, resulting in harder and more stable structures. These can form complex carbides or even pure alloy carbides.



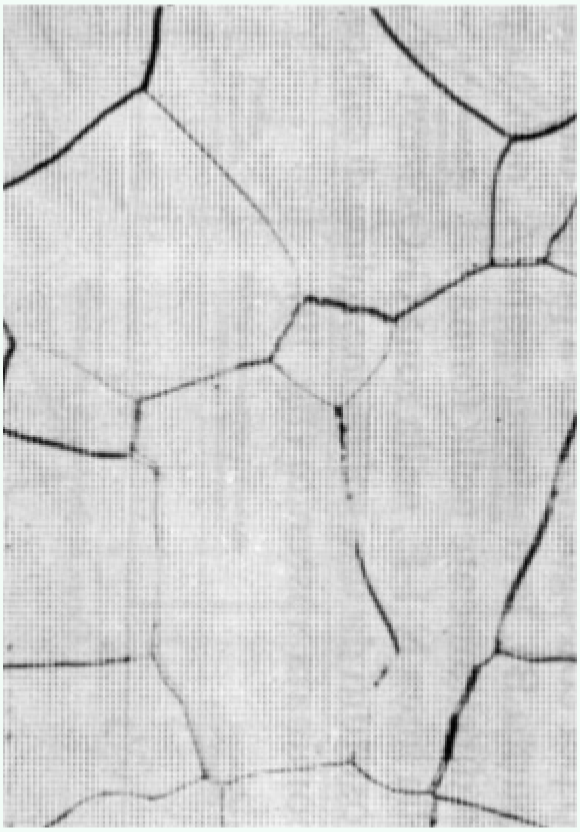
Fine spheroidal carbides in ferritic matrix in hyper-eutectoid steels (500 x)

Graphite

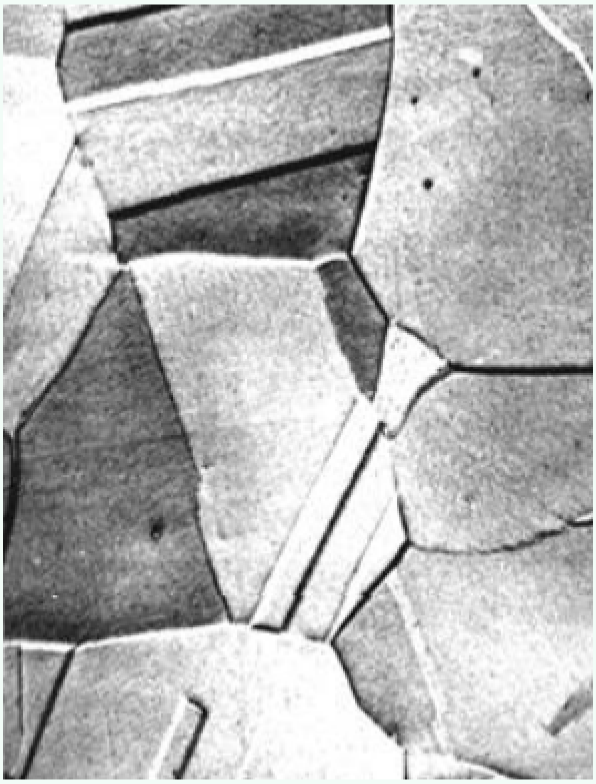
- Less dense than cementite and is NOT a metallic phase
- It is promoted by:
  - Extremely slow cooling
  - High concentration of carbon ($> 2\%$)
  - a small amount of silicon
- It acts as a lubricant in machining operations due to its low internal friction, which increases with temperature
- Can be found in lamellar (small filaments) which provides strong heat dissipation and dampening of vibrations and impacts. It can also take a bulls-eye (spherulitic) form when a strong spheroidizing agent is present (e.g. Mg, Ce), providing great mechanical resistance and ductility.

Ferrite

- BCC structure of almost pure iron
- Very low solubility for carbon ($C \leq_0 .0025\%$)
- Iron atoms can be replaced in the crystal lattice by other alloying elements such as Cr, Mo, Si.

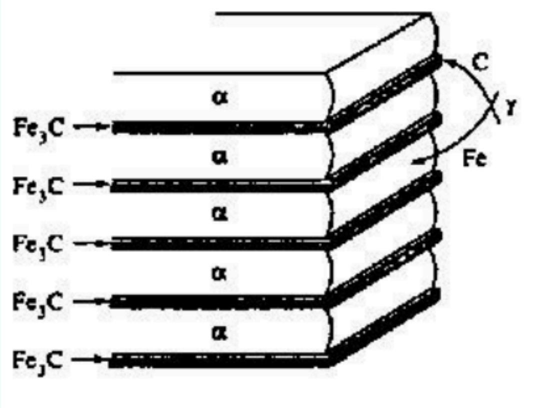


Austenite

- FCC structure of iron
- Increased solubility of any interstitial atoms, such as carbon
- Fe can be replaced by Ni, Mn, which can integrate into the lattice without causing significant distortion.
- 

Pearlite

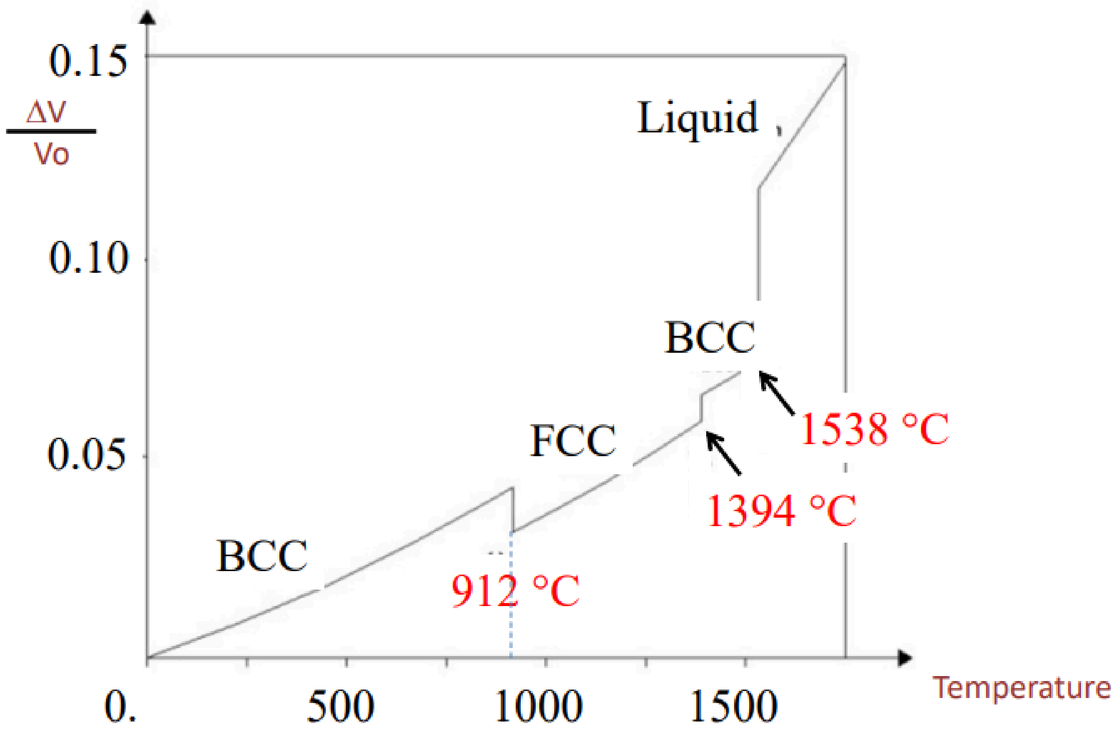
- Eutectoidic steel
- Layers of ferrite (α) and cementite in an alternating form
- Formed when carbon-rich austenite is cooled at eutectoid temperature, and the speed of the cooling affects the width of the layers.
- Is formed from seeds on grain boundaries.



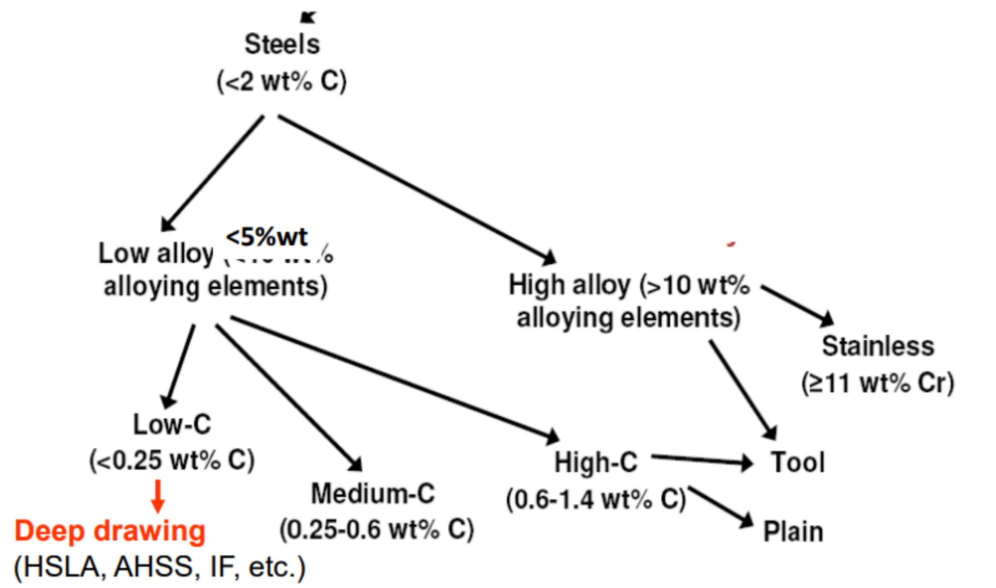
Summary:

	Rm MPa tensile	HRC/ HB	Crystal structure	ELONG %	Resilience	type
austenite	1034	40 -	FCC	10	high	phase
ferrite	280	0 80	BCC	50	high	phase
cementite	35	- 550	orthorombica	0	Very low	phase
graphite			hexagonal		Very low	phase
pearlite	800	20 200	Mechanical mixture	10	high	Microconstituent
eutectic	-	-	Mechanical mixture	-	-	Microconstituent

Thermal expansion for iron:



Classification of Steels



UNI EN 10020

The UNI EN 10020 standard is used to categorize steels into:

- Alloyed: If one of the elements in the table below is over the limit (Plain carbon)
  - General use quality
  - High purity, specific hardenability requirements
- Unalloyed: If all elements below are within the limits.
  - Weldable, magnetic use, useful for rails
  - Useful for tools, high speed components

Element	Limit (%)
Mn	1.65
Cr	0.30
Ni	0.30
W	0.30
V	0.10
Mo	0.06

Example

Stainless steels have over 10.5% Cr and less than 1.2% C

UNI EN 10020 Official Document

Source: https://www.infotech-ved.it/wp-content/uploads/2021/01/CLASSIFICAZIONE-E-DESIGNAZIONE-DEGLI-ACCIAI.pdf

UNI EN 10027-1

UNI EN 10027-1 Official Document

Source:
http://www.emmeengineering.com/didattica/Acciaio/Acciaio_5/Classificazione_acciai_10027.pdf

The standard describes how steels can be named according to their use and properties.

In this standard, steels are named via the following naming convention:
`<Prefix>[Application Symbol]<Sub-category>[Mechanical/Physical Characteristic]<Additional Symbols>`
For example:

```
S235JR

S: Structural Use
235: 235 MPa Yield strength (Min.), from S category
JR: Can take a 27J impact (J) without breaking in a Charpy V-notch test at room temperature (R). Defined by UNI EN 10025 standard.
```

Further reading about UNI EN 10025

Group	Prefix	Application Symbol	Mechanical/Physical Characteristics	Additional Symbols
Group 1 Steels designated by application and mechanical/physical properties	**G** = Cast Steel (if applicable)	**S** = Structural applications	Min. Yield Strength (MPa)	
		P = Pressure purposes	Min. Yield Strength (MPa)	
		L = Line pipe	Min. Yield Strength (MPa)	
		E = Engineering / Machine construction	Min. Yield Strength (MPa)	
		B = Reinforced concrete	Characteristic Yield Strength (MPa)	
		Y = Pre-stressing concrete	Min. Tensile Strength (MPa)	
		R = Rails	Min. Tensile Strength (MPa)	
		H = Cold rolled flat products, high strength for cold forming	Min. Yield Strength (MPa) *OR* Min. Tensile Strength (MPa) (if followed by 'T')	
		D = Flat products	**C** = Cold rolled	Two symbols characterizin

Group	Prefix	Application Symbol	Mechanical/Physical Characteristics	Additional Symbols
		for cold forming	**D** = Hot rolled for immediate cold forming **X** = Rolling condition not specified	the steel (defined by the responsible body)
		T = Tinmill products (Packaging)	Hardness (HR 30 Tm) *OR* Nominal Yield Strength (MPa)	
		M = Magnetic steels	100 × Specific Loss (W/kg) - (hyphen) 100 × Product Thickness (mm)	**A** = Non-oriented grai **D** = Semi-finished (non alloy) **E** = Semi-finished (alloy) **N** = Normal grain oriented **S** = Low loss grain oriented **P** = High permeability grain oriente

S Group

The number in the middle indicates min. Yield strength for the steel.

Usually for group S, the final two characters are one of:

First Character	Meaning of First Character	Second character	Meaning of Second Character
J	>27J	R	20°C (Room temperature)
K	>40J	0	0°C
L	>60J	2	-20°C
		3	-30°C
		$[n]$	$-10n^{\circ}C$

D Group

Deep drawing sheets

- **DX** – not specified
- **DC** – cold rolled
- **DD** – hot rolled- ***UNI-EN-10111:***

old	present	R_{p02} [MPa]	R_m [MPa]	A [%]	C	Mn
Fe P11	DD11	170-340	440	29	<0,12	<0,6
Fe P13	DD13	170-310	400	29	<0,08	<0,4

(11, 13: conventional numbers)

✓The yield stress and ultimate stress are prescribed and can be provided by the producer by various combinations of compositions and thermomechanical treatments

✓The max limits for C, Mn are prescribed for welding purposes

H Group

High strength deep drawing sheets

UNI-EN-10346

group	subgroup Rolling type	property R_m [MPa]	Additional symbols Microstructure
H	C - cold	T(n)nnn	X - dual phase
			F - ferritic-bainitic
	D - hot		T - TRIP
			C - complex phase
			M - martensitic

grade	R_{p02} [MPa]	R_m [MPa]	A [%]	C	Mn
HCT600X	340 - 420	> 600	> 20	< 0.17	< 2.2
HDT950C	720 – 920	> 950	> 9	< 0.25	< 2.2
HDT1200M	900 - 1150	> 1200	> 5	< 0.25	< 2

Naming Based on Chemical Composition

Type	Syntax Rule	Ex
Non-Alloy	$C[C\ wt\% \times 100]$	
Low Alloy	$[C\ wt\% \times 100] + [\text{Elements in ascending order of wt. }\%] + [\text{Code No.}]$	42(
High Alloy (One element with >5%)	$X + [C \times_1 00] + [\text{Elements}] + [\text{Real }\%]$	X100
Rapid Steels (High Speed Steels - HS)	$\text{HS }[\%\text{W}]\text{-}[\%\text{Mo}]\text{-}[\%\text{V}]\text{-}[\%\text{Co}]$	HS

Code numbers are based on the following table:

Elements	Factor (Divide by)
Cr, Ni, Mn, Si, W, Co	4
Al, Mo, Ti, V, Cu	10
P, S, N	100
B	1000

Examples

Tempering Steels

Grade	S (%)	C (%)	Mn (%)	Cr (%)	Mo (%)	P (%)
C45E	< 0.035	0.42 - 0.5	0.5 - 0.8	-	-	< 0.035
C45R	0.02 - 0.08	0.42 - 0.5	0.5 - 0.8	-	-	< 0.035
42CrMo4	< 0.035	0.38 - 0.45	0.6 - 0.9	0.9 - 1.2	0.15 - 0.3	< 0.035
42CrMoS4	0.02 - 0.08	0.38 - 0.45	0.6 - 0.9	0.9 - 1.2	0.15 - 0.3	< 0.035

Carburizing Steels

Grade	S (%)	C (%)	Mn (%)	Cr (%)	Ni (%)	Mo (%)
C10E	< 0.035	0.07 - 0.13	0.3 - 0.6	-	-	-
C10R	0.02 - 0.04	0.07 - 0.13	0.3 - 0.6	-	-	-
20NiCrMo2-2	< 0.035	0.17 - 0.23	0.65 - 0.95	0.35 - 0.7	0.4 - 0.7	0.15 - 0.25
20NiCrMoS2-2	0.02 - 0.04	0.17 - 0.23	0.65 - 0.95	0.35 - 0.7	0.4 - 0.7	0.15 - 0.25

Tool Steel

Grade	C (%)	Mn (%)	Cr (%)	Mo (%)	V (%)	Si (%)
X100CrMoV5	0.95 - 1.05	0.2 - 0.6	4.8 - 5.5	0.9 - 1.2	0.15 - 0.35	0.1 - 0.4
X38CrMoV5-3	0.35 - 0.4	0.3 - 0.5	2.7 - 3.2	2.7 - 3.2	0.4 - 0.6	0.3 - 0.5

AISI/SAE Equivalents

Series	Type / Main Alloy	Description
10XX	Plain Carbon	Plain carbon steels
11XX	Free machining S	Low carbon, added Sulfur

Series	Type / Main Alloy	Description
12XX	Free machining S, P	Added Sulfur and Phosphorus
13XX	Mn	Manganese steels
2XXX	Nickel (Ni)	Increases UTS without reducing toughness.
3XXX	Ni-Cr	Highly tough and ductile.
40XX	Mo	Molybdenum steels
41XX	Cr-Mo	Strong carbide former, prevents temper embrittlement.
43XX	Ni-Cr-Mo	High strength alloy.
51XX	Cr	Strong ferrite strengthener; increases wear resistance.
86XX+	Ni, Cr, Mo, V, Si	Complex alloys for high specific strength.

Hardenability

Definition

How deep hardness goes into the core.

- *High Hardenability:* The center of a thick bar gets just as hard as the surface.
- *Low Hardenability:* The surface is hard, but the core remains soft.

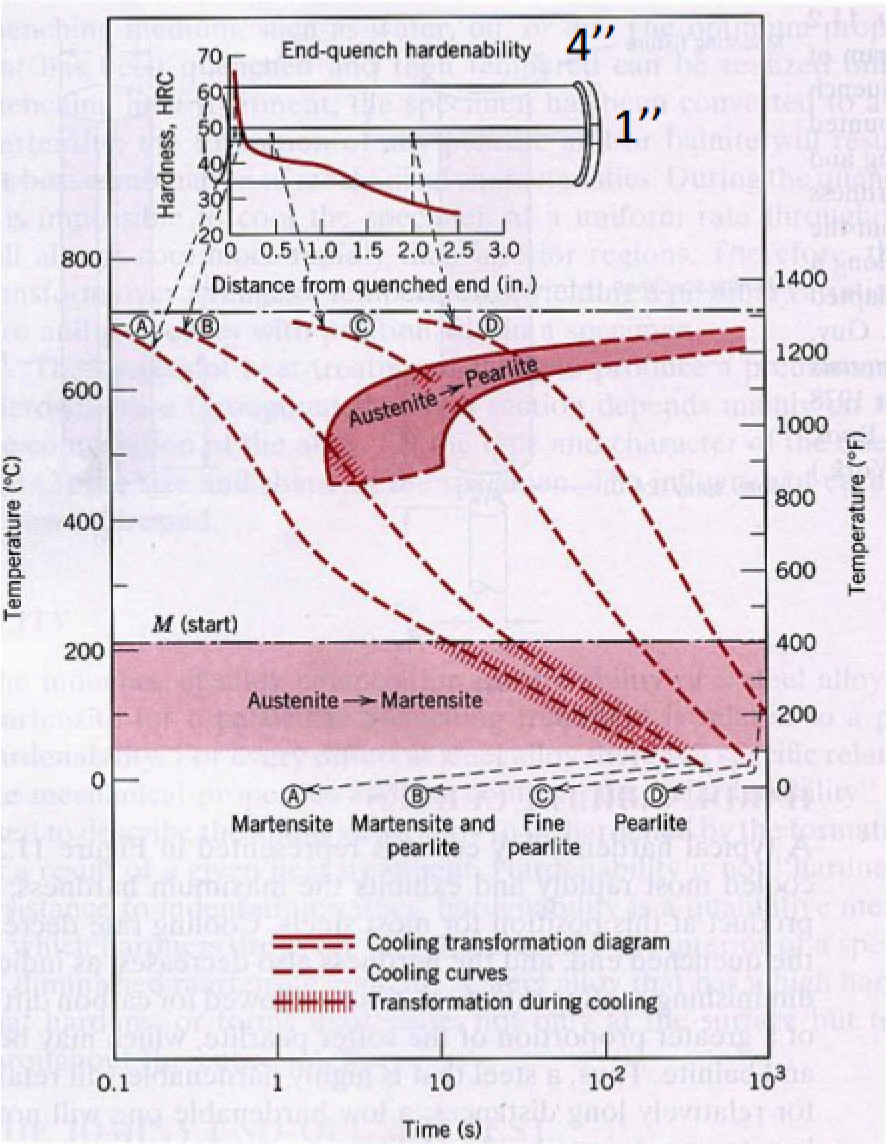
The unit technically is m or cm, but it is not often used in its pure form.

Hardenability shifts the TTT curve to the right.

The Standard Test (Jominy End Quench):

1. Heat a steel bar to Austenite.
2. Spray water on **one end only**.
3. Measure hardness along the bar.
    > - The "hardened depth" is where the structure drops to **50% Martensite**.

Adding Mo, Mn, Cr increases hardenability, allowing larger parts to be hardened all the way through.



Stainless Steels

What Makes Steel "Stainless"?

For a steel to be considered "stainless," it must contain **at least 11.5% Chromium**.

Why? Because at this concentration, Chromium reacts with Oxygen to form a continuous, invisible, and self-healing passive film (Cr_2O_3) on the surface. If you scratch it, it reforms immediately (provided there is oxygen).

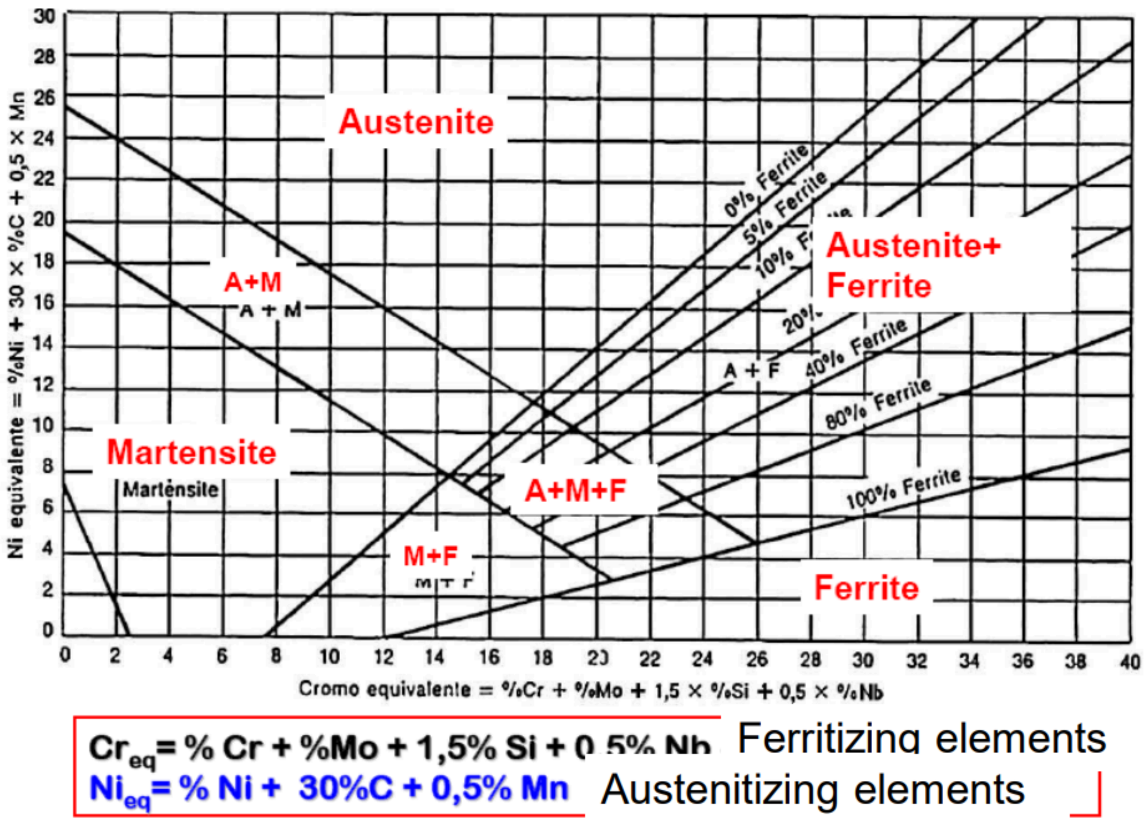
- **The Enemy:** Reducing environments (lack of oxygen) or chlorides (Cl^-) which break the film.
- **The Fix:** Alloying elements like Nickel (Ni) and Molybdenum (Mo).

The Schaeffler Diagram

This is the map we use to predict the structure of a stainless steel (especially after welding). It plots **Chromium Equivalent** against **Nickel Equivalent**.

- **X-Axis (Cr_{eq}):** $\%Cr + \%Mo + 1.5\%Si + 0.5\%Nb$
- **Y-Axis (Ni_{eq}):** $\%Ni + 30\%C + 0.5\%Mn$

By calculating these two values, you can see if your steel will be Martensitic, Ferritic, Austenitic, or a mix (Duplex).



The Families of Stainless Steel

Ferritic SS

- **Composition:** High Cr (12-30%), Low C, No Ni.
- **Properties:** Magnetic. Good corrosion resistance (better than Martensitic SS).
- **Weakness:** Brittle at low temps (DBTT). Grain growth during welding reduces toughness.
- **Use:** Exhaust systems, cheaper chemical equipment.
- Series 400
    - E.g. AISI 430

Martensitic SS

- **Composition:** Medium Cr (12-17%), High C (>0.1%).
- **Properties:** Can be quenched and tempered! High hardness and strength. Magnetic.
- **Weakness:** Lowest corrosion resistance of the bunch. Hard to weld (cracking risk).
- **Use:** Knife blades, surgical tools, shafts.
- Series 400
  - E.g. AISI 410, 420

3. Austenitic SS

- **Composition:** Cr (16-26%) + Ni (6-22%).
- **Properties:** Non-magnetic. Excellent corrosion resistance. High toughness (no DBTT — good for cryogenics). Highly ductile.
- **Series 300.** Examples:
  - **AISI 304:** The standard “18/8” stainless. Kitchen sinks, food industry.
  - **AISI 316:** Adds **Molybdenum (2-3%)**. This drastically improves resistance to chlorides (saltwater) and pitting.
- **Weakness:** Expensive (Ni price). Susceptible to SCC (Stress Corrosion Cracking).

4. Duplex SS (e.g., 2205)

- **Structure:** A roughly 50/50 mix of Ferrite and Austenite.
- **Properties:** Best of both worlds. Higher strength than Austenitic, better SCC resistance.
- **Use:** Heat exchangers, desalination plants.
- E.g. AISI 2205

Pitting Resistance (PREN)

How do we know if a steel will survive in seawater? We calculate the **Pitting Resistance Equivalent Number**.

$$PREN = \%Cr + 3.3 \cdot (\%Mo + 0.5\%W) + 16 \cdot \%N$$

- **Rule of Thumb:**
  - **PREN > 40:** "Superduplex" or "Superaustenitic" (Safe for severe seawater use).
  - Nitrogen (N) is extremely potent here (multiplier of 16!).

Sensitization

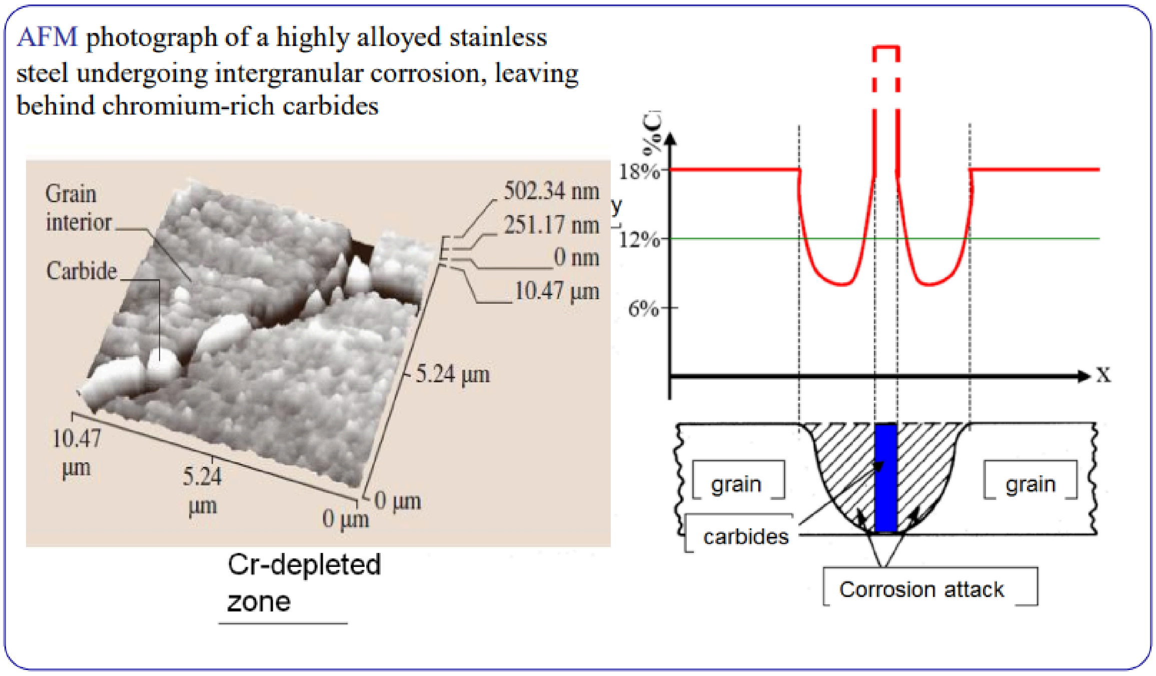
This is the most common failure mode for Austenitic steels (like 304) after welding.

The Mechanism:

1. Heat the steel to **500-800°C** (e.g., in the Heat Affected Zone of a weld).
2. Carbon loves Chromium. They react to form **Chromium Carbides** ($Cr_{23}C_6$) at the grain boundaries.
3. These carbides suck the Chromium out of the surrounding metal.
4. The local Chromium level drops below 11.5% (the “Depleted Zone”).
5. **Result:** The grain boundaries are no longer stainless. They corrode rapidly (Intergranular Corrosion).

The Solutions:

1. **Low Carbon Grades:** Use "L" grades (e.g., **304L, 316L**) where $C < 0.03\%$. Less carbon = less carbides.
2. **Stabilization:** Add elements that love Carbon even more than Chromium does, like **Titanium (Ti)** or **Niobium (Nb)**.
   - *Example:* AISI 321 (Ti stabilized) or AISI 347 (Nb stabilized).



Plastic Deformation

Plastic Deformation

Schmid's Law

Any normal stress can be resolved into a shear stress component τ_{RSS} (resolved shear stress) and a normal stress component σ with respect to a slip plane.

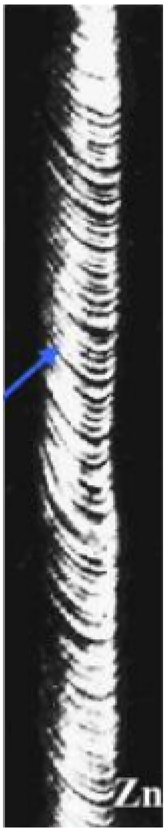
When the F_τ exceeds a threshold value, called **Critical Resolved Shear Stress** τ_{CRSS}, the plane starts slipping.

Schmid's law

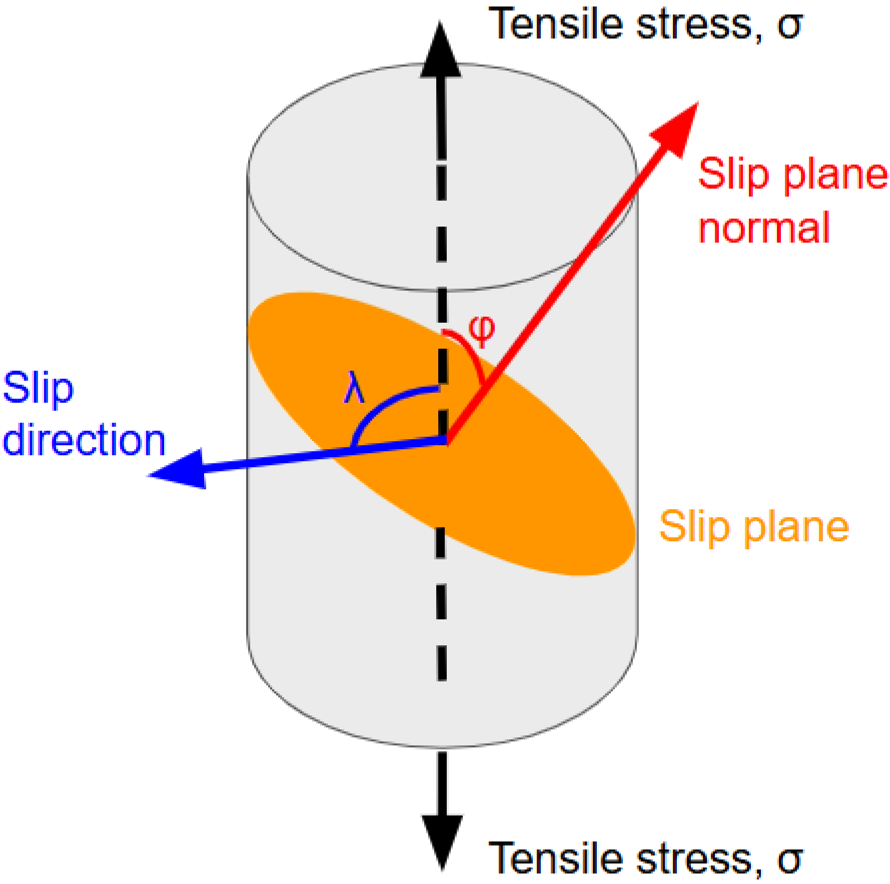
For a dislocation to move over its slip systems, a shear stress acting over the slip plane and along the slip direction must be applied; this is typically determined by an applied normal force to the sample such that as it happens in a tensile test.

τ_{CRSS} is a material property which is closely related to yield stress σ_y.

When planes start to slip, slip lines start forming and eventually, numerous aggregate dislocations form slip bands. The bands and lines follow the primary slip system, which is the direction with the lowest τ_{CRSS}, as shown below.



We define the following angles λ, φ and stress σ:



$$\sigma = \frac{F}{A}$$
$$\tau = \frac{F}{A}\cos\varphi\cos\lambda$$
$$\implies \tau_{\text{RSS}} = \sigma\cos\varphi\cos\lambda$$
$$m = \cos\varphi\cos\lambda = \text{Schmid Factor}$$

Note that m_{max} is 0.5 (When $\lambda = \varphi = 45^\circ$) and the minimum is 0 (When $\lambda = 0^\circ, \varphi = 90^\circ$ or $\varphi = 0, \lambda = 90^\circ$).

When τ_{RSS} is minimized we prevent slip from occurring. The material will therefore snap before it manages to slip.

Using the Schmid Factor, we can get:

$$\sigma_y = \frac{\tau_{\text{CRSS}}}{m}$$

Note

Consider that not all crystal structures have a favourable slip plane and direction, and some will have several slip planes. For example FCC will almost always has at least one system with a favourable Schmid Factor.

If we consider HCP structures (`Hexagonal Close-Packed`, such as Ti, Mg), the Schmid's Law often gives 0 for the coefficient. This is because HCP has very few slip planes. This means that when plastically deforming, they will usually show twinning.

✓ **What happens as we pull?**

Over time, as the material undergoes slip, the slip direction rotates TOWARDS the tensile axis, therefore making it harder to deform the material further, until we have $\cos\varphi = 0$ leading to no more slipping.

Taylor Factor

For polycrystalline materials, since the Schmid Factor is different for all grains, we cannot use a single value for it. If two neighbour grains tried to shapeshift in different ways, a crack would form between them. This means that plastic deformation in polycrystalline materials is **inhomogeneous**.

For real polycrystalline materials we therefore use the Taylor Factor M. Polycrystalline materials are harder to deform since grains "fight each other" while deforming. This is given by:

$$\sigma_y = M \cdot \tau_{\text{CRSS}}$$

A higher value for $\bar{m}$ will mean a greater M, but the correlation is not as simple, since M takes into consideration both $\bar{m}$ and forces on grain boundaries. But we can gather the approximation:

$$\begin{aligned} \sigma_y &\approx 2\,\tau_{\text{CRSS, single crystal}} \\ \sigma_y &\approx 3\,\tau_{\text{CRSS, polycrystal}} \\ \implies M &\approx \frac{3}{2} \cdot \frac{1}{m_{max}} \\ M &\approx \overline{\left(\frac{1}{m}\right)} \end{aligned}$$

(Remember that $\bar{x}$ means the mean value for x)

HOWEVER, this does not always hold. But we can infer that the yield strength for the same metal can increase by 50% just by having grains rather than being a single crystal.

ⓘ **Info**

In FCC metals (e.g. Al, Cu), with random texture, $M = 3.06$

Von Mises Criterion

In a polycrystal, every grain is surrounded by neighbours, therefore if one changes shape, the neighbours must also change shape, otherwise a crack forms and the material fails.
In order for this to happen, the **Von Mises Criterion** states that there must be at least 5

degrees of freedom in order for the shape of the sample to change shape arbitrarily in 3D space (stretch, compress, shear etc.).

Mathematically, there are 6 components to shape change in the strain tensor. Since volume is constant, $\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = 0$ so we have 5 independent components, meaning that at least 5 slip planes MUST exist for all components of the strain tensor to be independently manipulated.

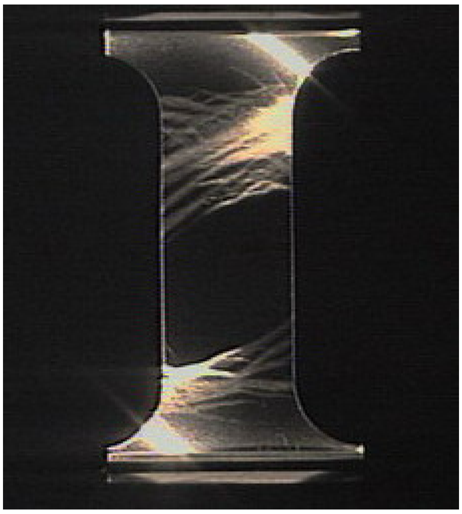
At higher temperatures, more slip planes can be created, meaning that a material that is brittle at room temperature can become ductile at higher temperatures (such as high-carbon steel).

Why do we care?

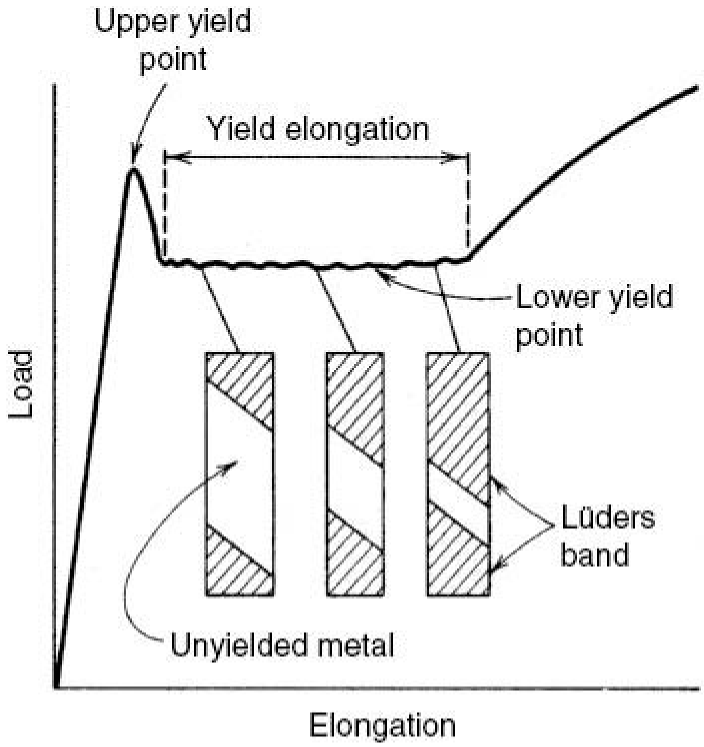
The Von Mises Criterion tells us if a crystal structure is brittle or ductile. If it cannot be freely manipulated, then it will fracture if we try, meaning that the material is brittle.
FCC $(Al, Cu, \text{Austenite})$: Has 12 slip systems, meaning that we can deform it and it is therefore ductile.
HCP (Mg, Zn): Has only 3 slip planes, meaning that the criterion is not met and the structures are brittle.

Lüders Bands

Yielding does not happen everywhere in the metal at the same time: it happens in Lüders Bands (bands where there is higher local stress concentration), and the yielding then propagates across the material.



Since these bands all happen at different stresses, the stress-strain graph for materials which show such behaviour will have a long **yield elongation** at $\sigma = \sigma_{y,\text{ lower}}$ in the form of a jagged line (stress is not perfectly constant).



The ugly marks

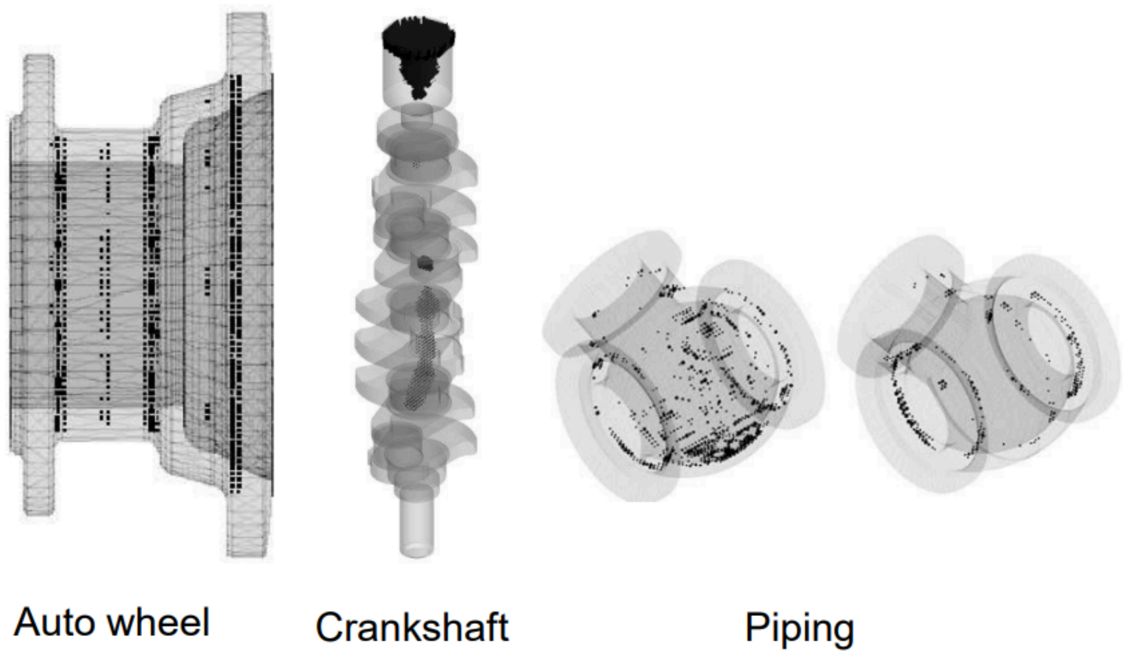
To get rid of Lüders Bands, since they can be ugly to look at, we can polish the surface using a treatment method called **skin passing**.

The reason Lüders Bands happen in steel is because of Cottrell Atmospheres. Each atmosphere "snaps" with a different moment, leading to the yield elongation and the **phenomenon of plastic instability**.

QA

QA

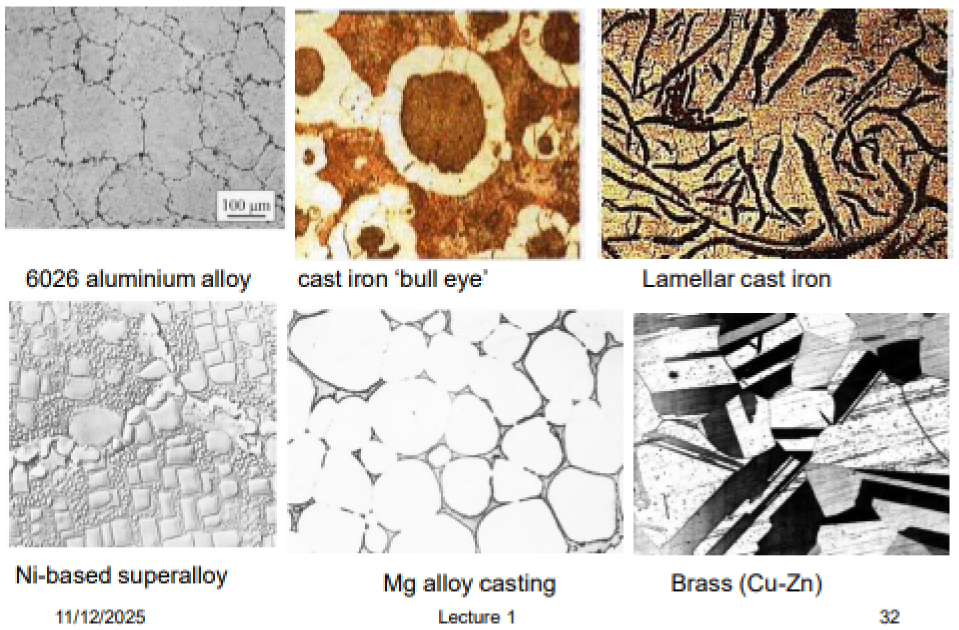
Soundness of Castings by X-Ray



> Casting CAN leave air gaps if not done properly.
> A non-destructive method of checking the internal structure of a metal product is to use x-rays
> The image above shows the result of such x-ray scan. It allows manufacturers to inspect internal macro-pores and air bubbles, which could affect the mechanical properties of the object.

Detecting Material Microstructures

31



Etching

There are two types of etching:

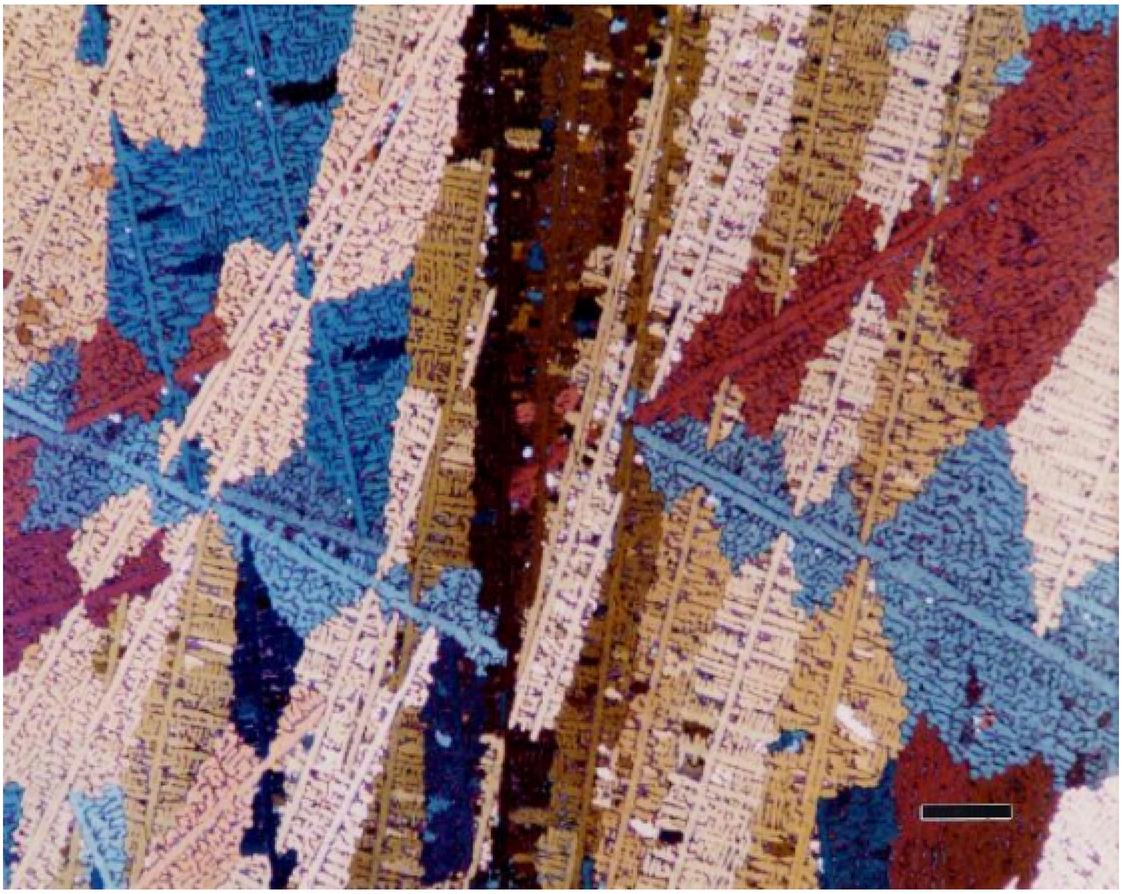
- Chemical etching
- Thermal etching
  Both methods are used to inspect grain boundaries, making them more evident under a microscope's light.

Chemical etching works by attacking the weakest parts of a material: grain boundaries. By attacking GBs first, they become more evident since they get deeper and wider.

Thermal etching works by causing thermal expansion, however, to achieve a lower energy state, grain boundaries get dug deeper into the surface, leading to a similar result as with chemical etching. This method has an issue: it is destructive. By heating it (often close to melting point), the internal structure can change, and the mechanical properties of the material tend to worsen.

Inspection by Polarized Light

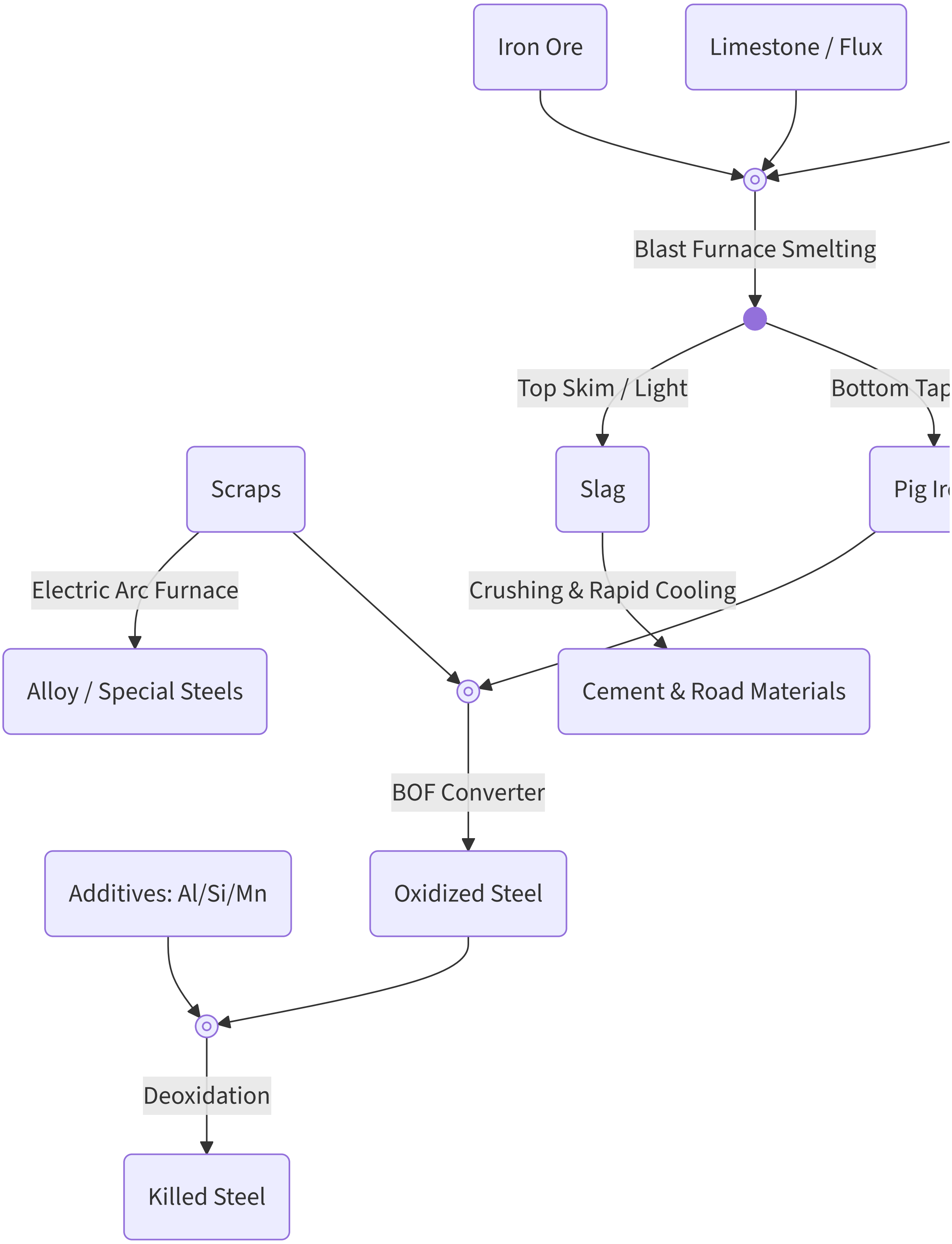
Some metals (such as cadmium) will reflect polarized light differently depending on the angle of polarization and the orientation of the crystals.



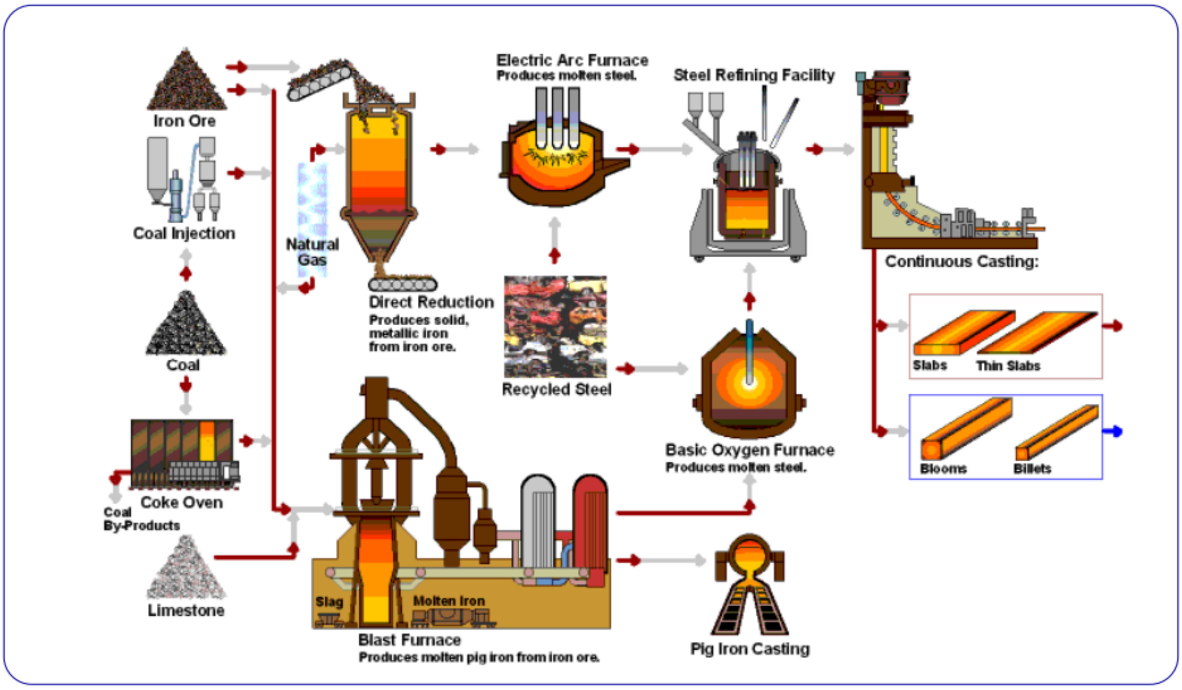
In the image above, we can see the dentrites (tree-like structures) which form different colours. This tells us that the metal is shaped via casting (dentrites form when metals are cooled after casting).

Steel Production

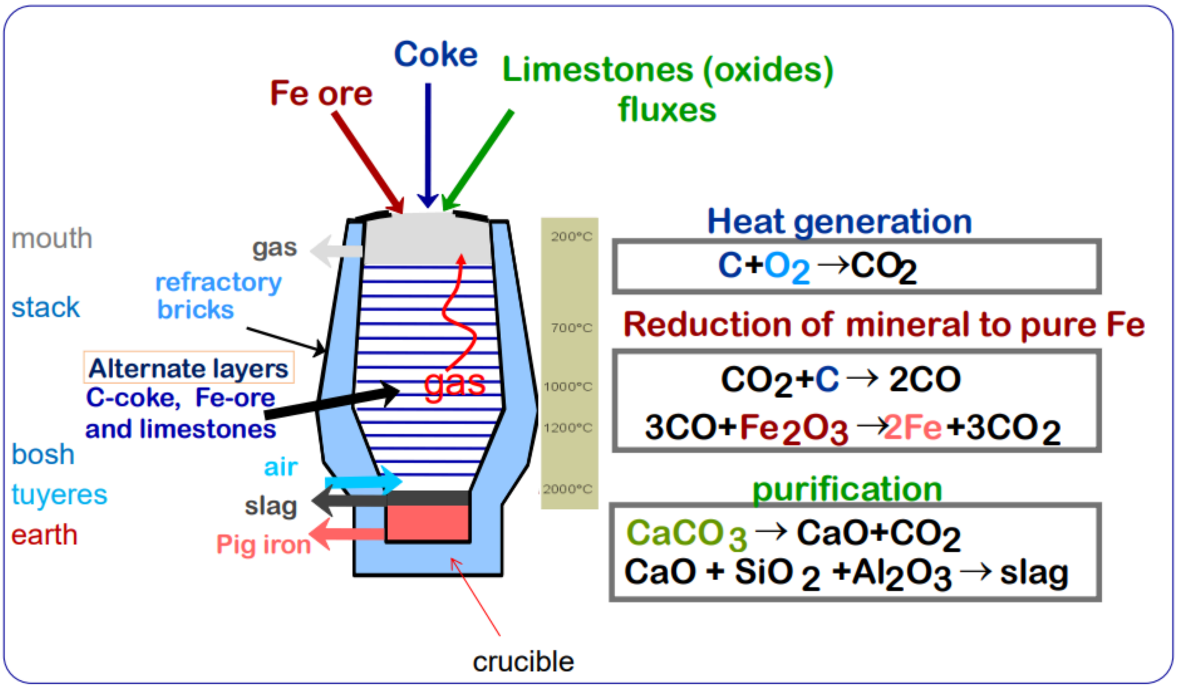
Steel Production



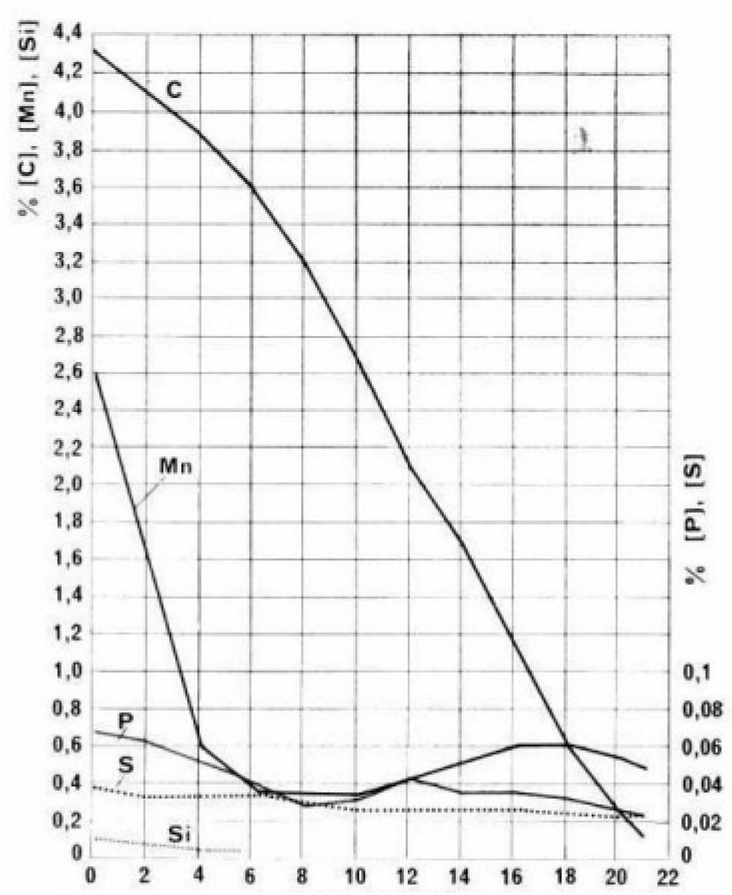
[BOF](#) = **Basic Oxygen Furnace** — a structure that heats up carbon-rich pig iron (4-5%) with the presence of a lot of oxygen, allowing carbon to burn off.



Inside a Blast Furnace



Basic Oxygen Furnace (BOF)



> A graph showing how concentration of impurities changes over time (x-axis, in minutes) when inside a BOF. Note that if the steel is "overcooked," it will oxidize and therefore become useless.

Impurities

Harmful Impurity Limits

For high purity steels, the following are thresholds for "harmful" impurities:

- $S < 0.03\%$
- $P < 0.02\%$
- $Cu < 0.3\%$
- $Sn < 0.06\%$
- $Ni < 0.3\%$
- $Cr < 0.3\%$

S, P impurities are detrimental for ALL steel grades except for rephosphorize and resolphurized steels, where the impurities are intentionally added.

- S contributes to FeS segregation at GBs and therefore causing embrittlement
- P causes embrittlement due to FE_3P segregation

Si, Mn are always present because they contribute to melt purification.

Resolphurized steels are sometimes used to allow for brittle chips to be easily removed during machining. However, sulphur contents remain low ($S < 0.06\text{-}0.35\%$).

Oxygen Removal

After the steel is processed in the DOF, the steel will be filled with excess oxygen within its structure. This MUST be removed since oxidized iron Fe_2O_3 will lead to huge embrittlement, even as low as 100 ppm of oxygen or nitrogen can be detrimental.

There are three ways of fixing this:

- Argon degassing
  - Argon is blown into the steel bringing O, S with it. If Ar is left in the steel it will not cause damage since it is inert.
- Vacuum degassing
  - The steel is placed in a vacuum chamber, allowing pressure to force the gases out of the steel structure. This can be very expensive.
- Additives
  - By adding reactive additives in the structure (such as Al, Si, Mn), the oxygen will react and can be separated along with slag or stay within the structure as solid precipitates.
  - $2Al + 3O \to Al_2O_3$
  - $Mn + S \to MnS$
  - $Mn + S + 4O \to MnSO_4$
  - Al is the best for oxygen removal. Silicon is less strong, and manganese is the weakest, but is good for sulphur impurities.

> Note
>
> At this point in steel processing, it is all in the form of liquid pig iron.

Stainless Steel Production

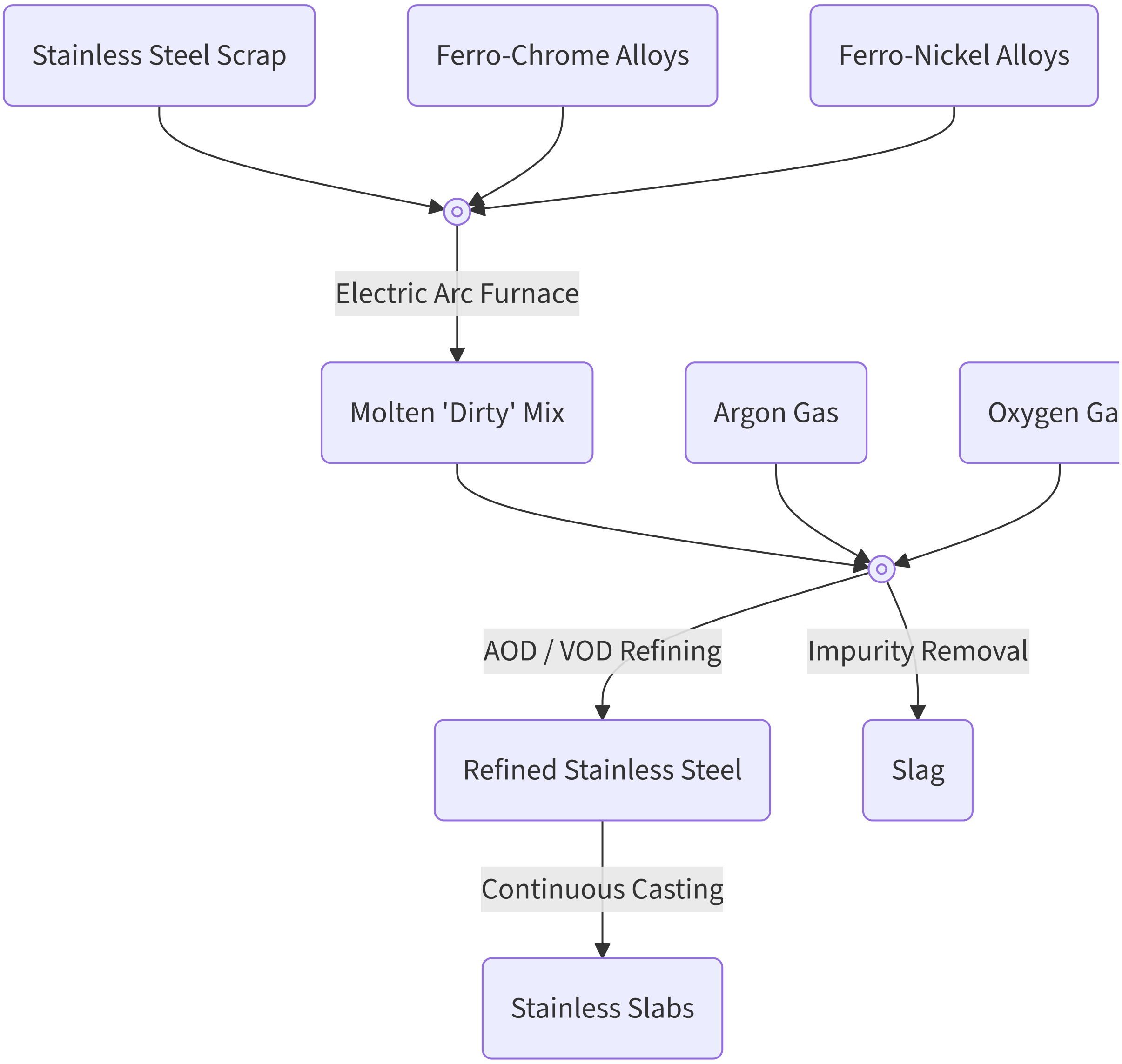
Cr is very reactive with oxygen, meaning that if we produce stainless steel, we cannot use regular decarbonization methods that use oxygen, or Cr would be the first one to burn off. Since to remove carbon we create a gas (CO), the reaction will speed up with a lower CO partial pressure, so the solution is to decrease it (since solid reactions are not affected by pressure).

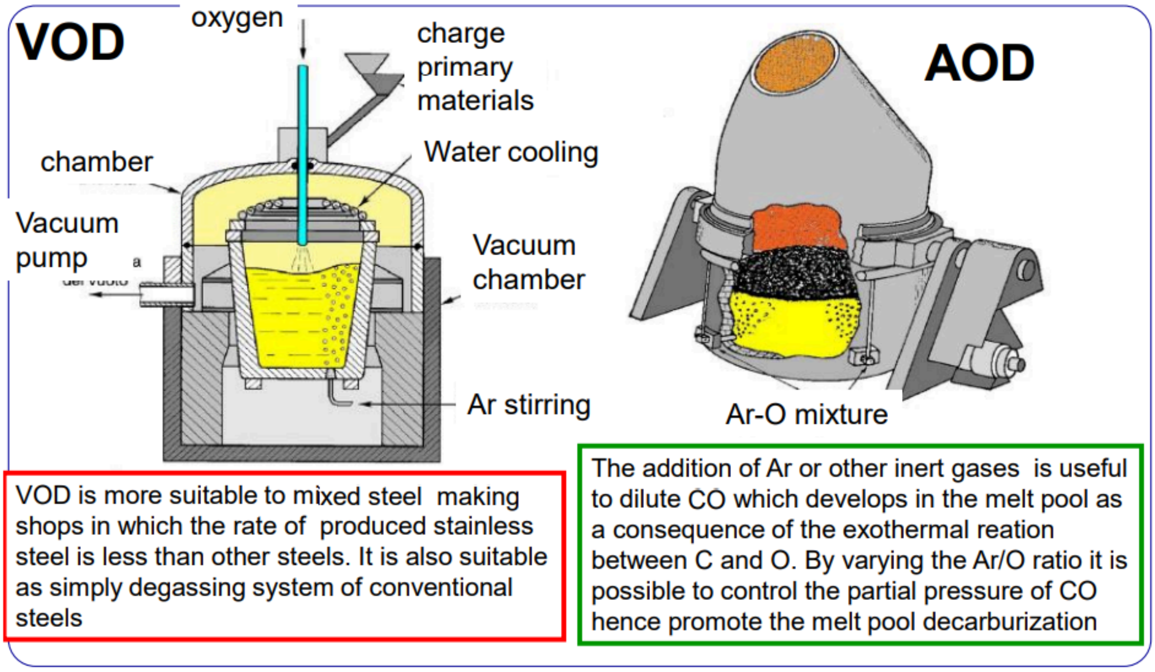
The solution is to use alternative methods:

- **VOD (Vacuum Oxygen Decarburization)**

- Decarbonization occurs under a vacuum with low oxygen pressure
- This is slow, but can reach very low concentrations of C

- **AOD (Argon Oxygen Decarburization)**
  - Rather than creating a vacuum, air is replaced with argon, meaning that CO PARTIAL pressure decreases, leading to higher reactivity of $C + O$
  - This uses huge amounts of argon



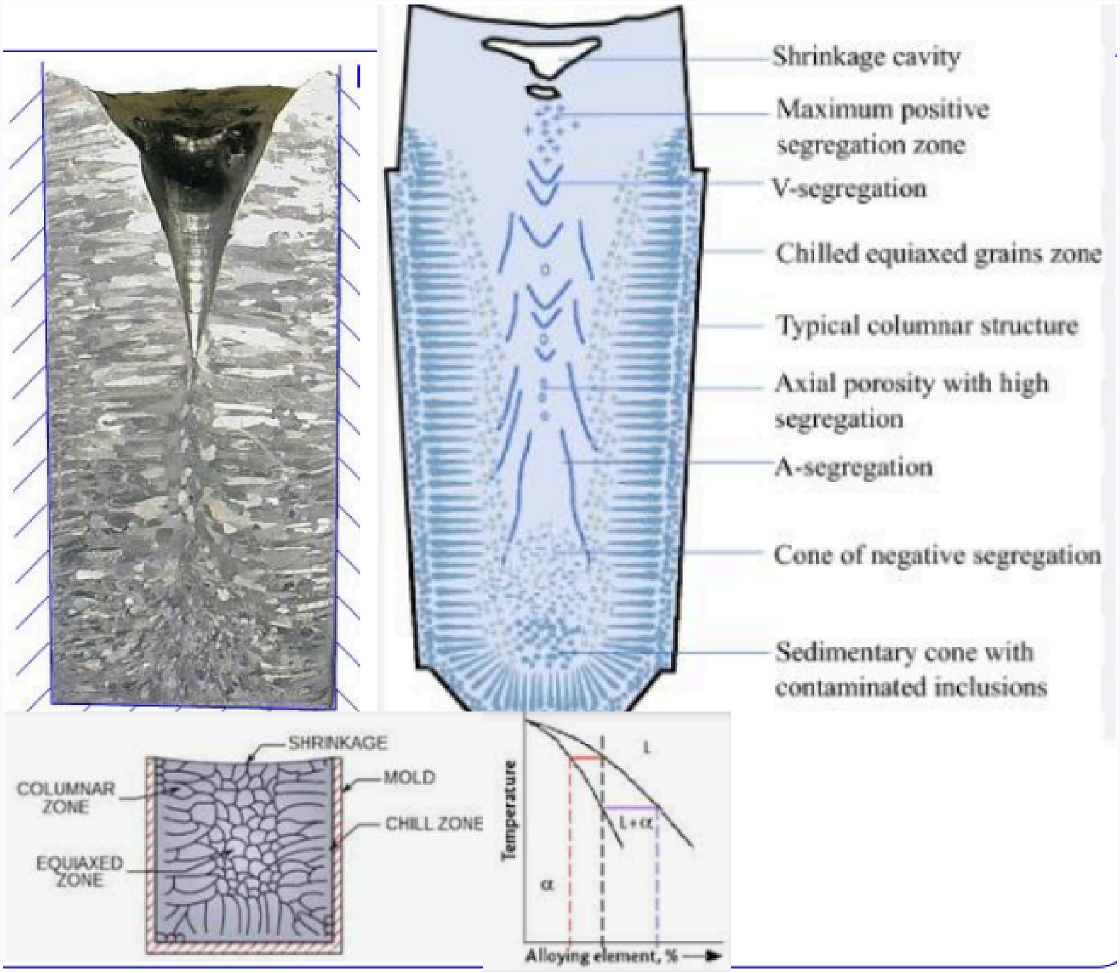


Macrosegregation in Ingots

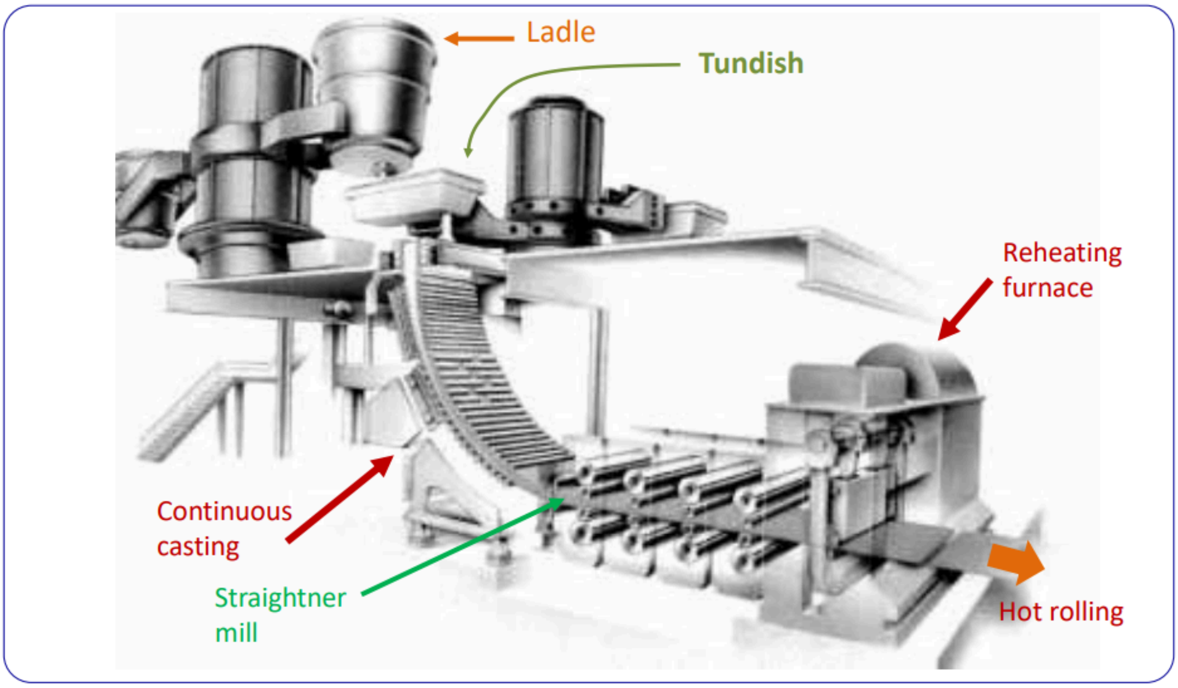
When pouring steel into ingot casts, macro-defects appear in the form of **macrosegregation**.

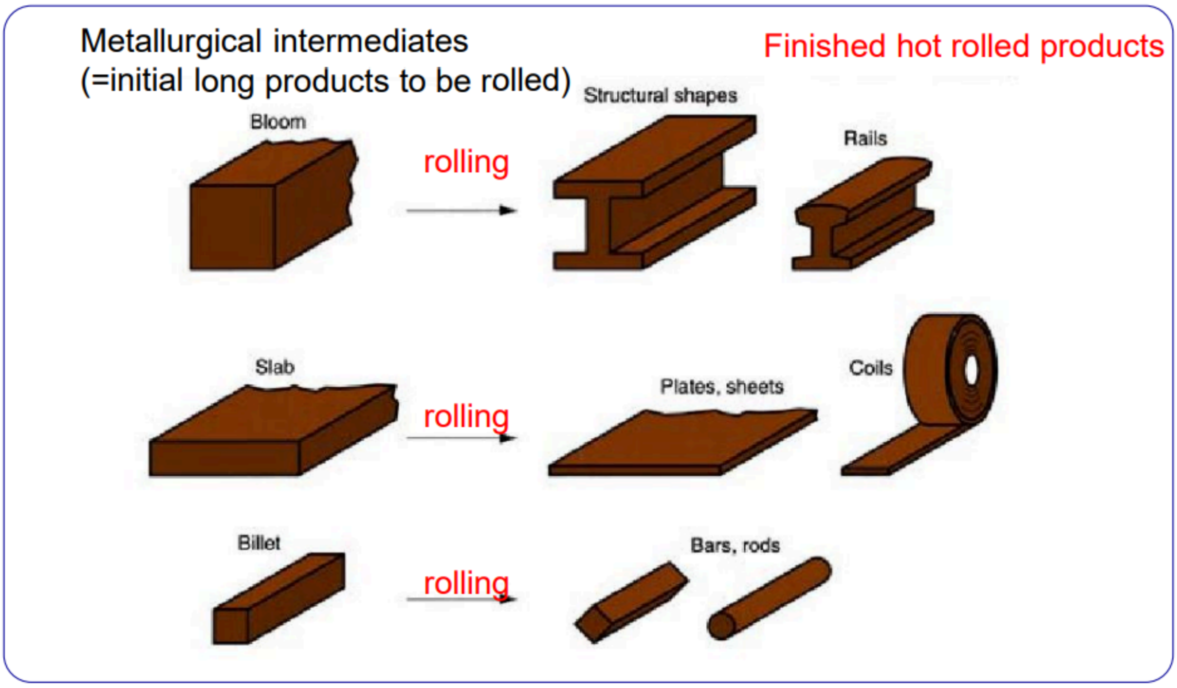
Definition

When an ingot is poured into a cast, the outside solidifies earlier, leading to the inner part contracting later. This creates a cone-shaped hole starting from the top of the mould. The result is a loss of about 20% of the steel, which goes back into the processing line (energy, time, and labour are wasted).

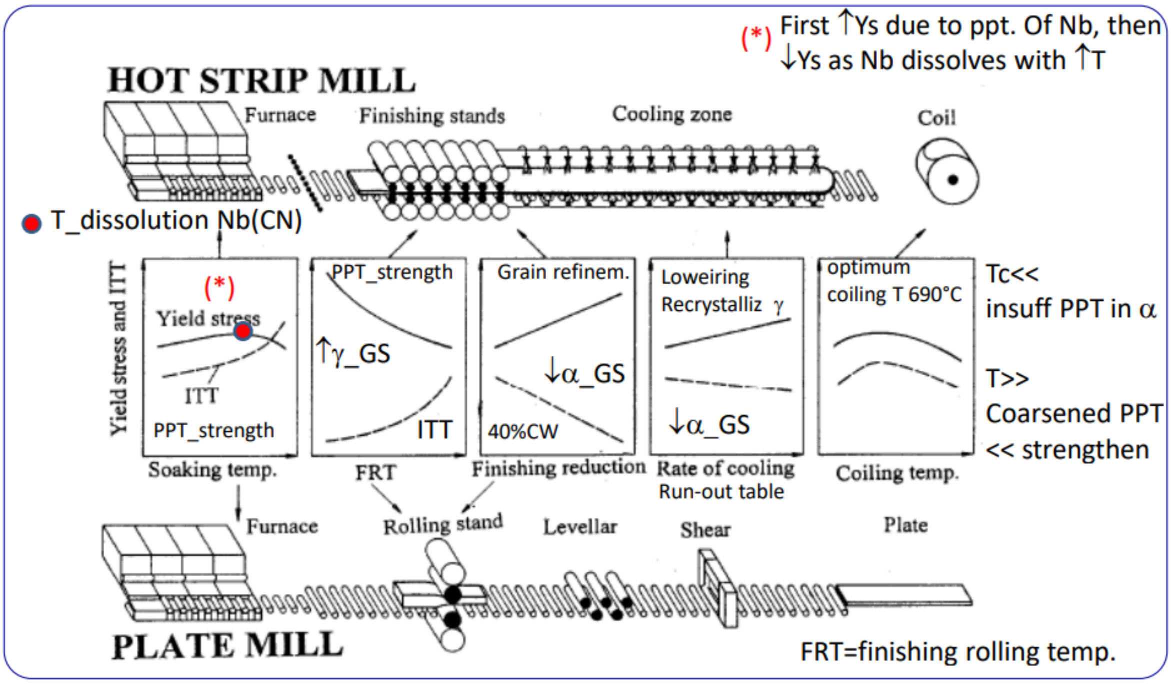


The solution to this is continuous casting:





TMCP of HSLA Steels



Effect of hot rolling parameters on mechanical properties during/after hot rolling (strips, plates)

- **TMCP (Thermo-Mechanical Control Process):** Carefully controlling temperature and deformation of hot rolling to adjust properties of the product.
- **HSLA (High-Strength Low-Alloy):** A strong form of steel that has few alloying elements in it. It is formed by manipulating physical composition rather than the chemical one.

$Nb(NC)$ (in very small amounts, $< 0.05\%$) is added to strengthen the steel by bonding with C, N to form small, hard precipitates.

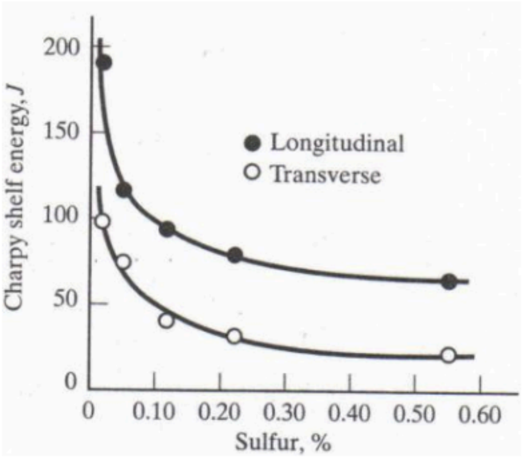
The process in the diagram can be summarized as follows:

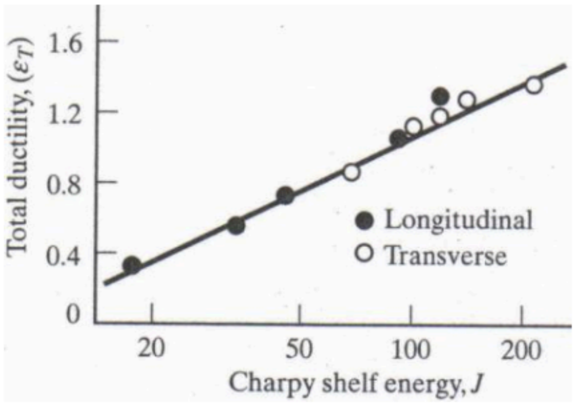
1. Soaking: re-heating of the steel to allow for the niobium carbonitride to dissolve in the steel
2. Rolling: Austenite γ grains get flattened, but cannot re-crystallize since the Nb particles pin the GBs. This produces stressed steel with many defects.
3. When cooled down, the stress shatters the brittle ferrite α grains into many ultra-fine grains, leading to great strength and toughness.

Inclusions

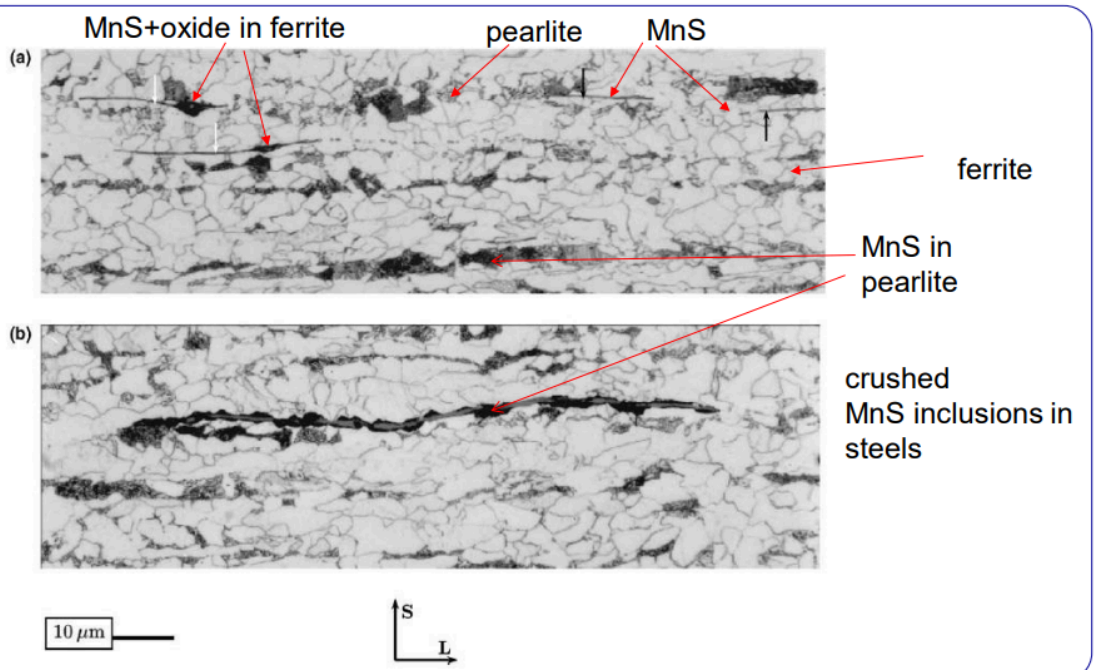
Definition

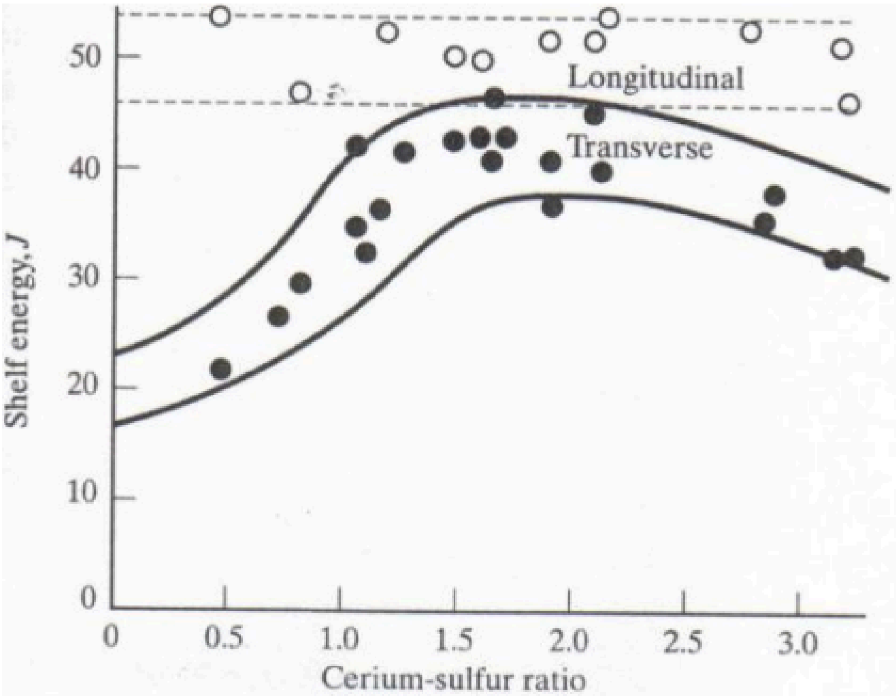
Inclusions are types of Defects that appear during casting of steels. When deoxidizing steel, solids such as Al_2O_3, MnS are formed. Usually, these float to the surface with slag, but some can remain in the steel and form solid precipitates which cause embrittlement.





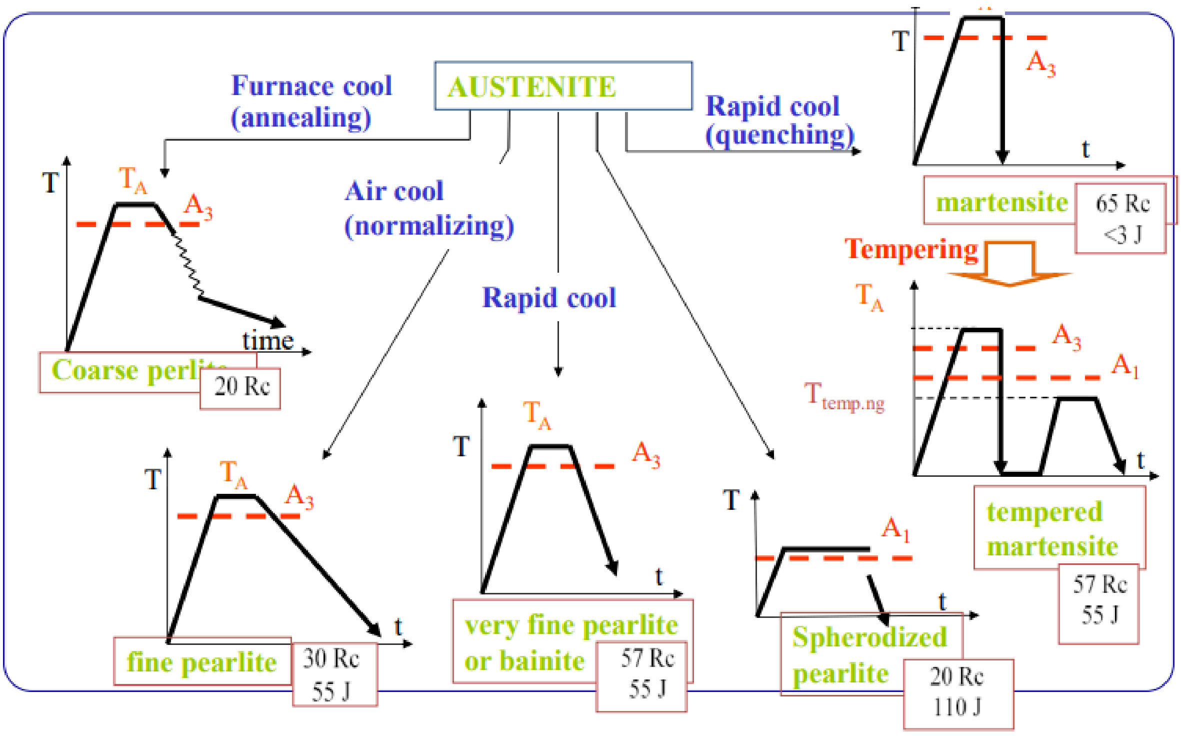
Non metallic inclusion effects on the upper energy shelf of an impact energy test curve (CVN) as well as on overall ductility.





Influence of rare earth elements (Cerium) on impact test of samples taken along a transversal direction due to globular inclusions.

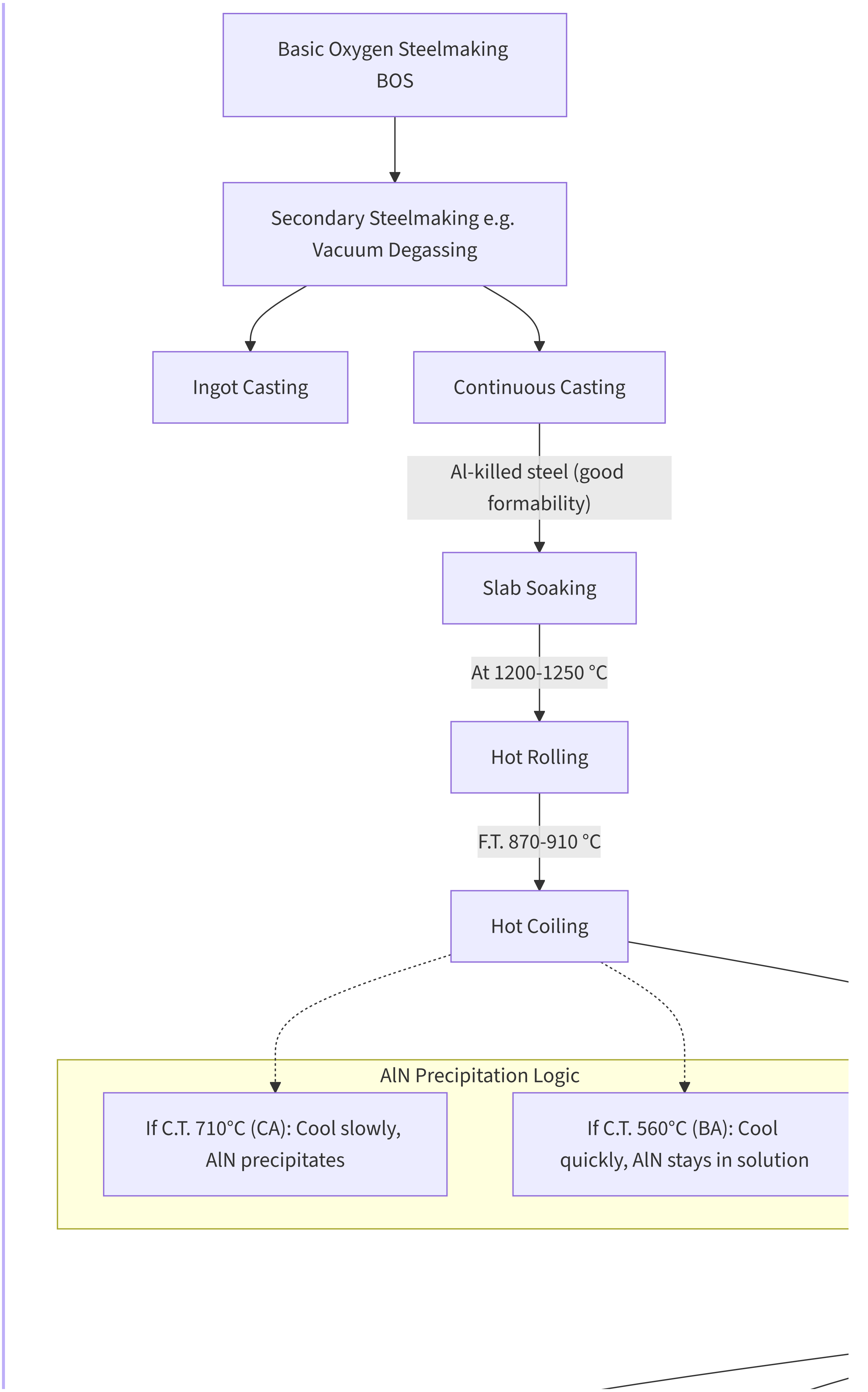
Cooling Rates for Different Forms of Steel

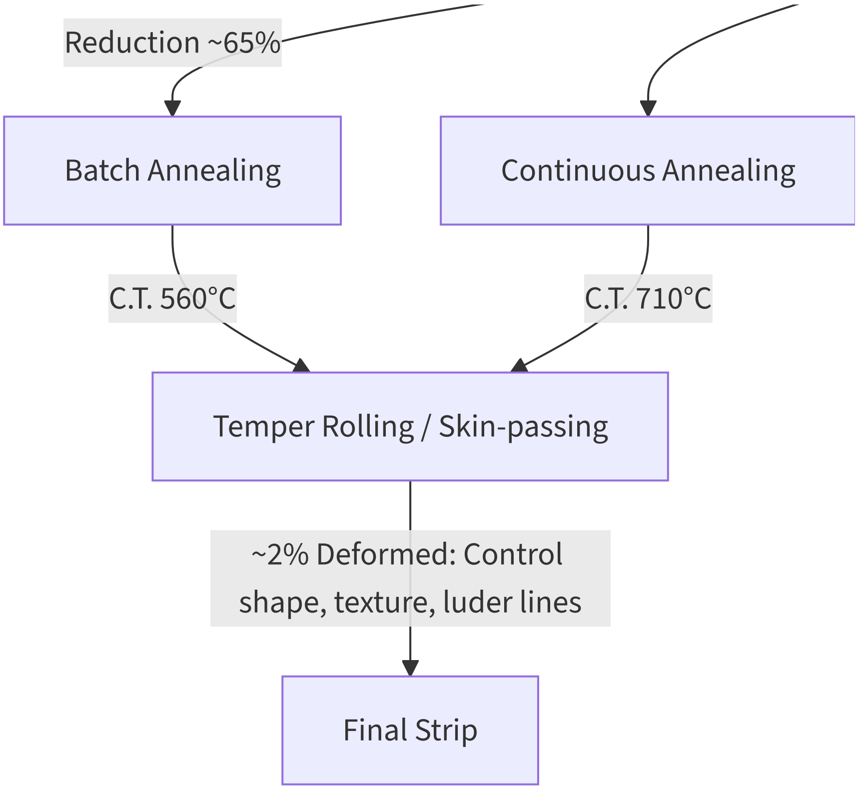


bainite is defined in here.

Strengthening of Steels

Strengthening of Steels


Basic Oxygen Steelmaking BOS
Secondary Steelmaking e.g. Vacuum Degassing
Ingot Casting
Continuous Casting
Al-killed steel (good formability)
Slab Soaking
At 1200-1250 °C
Hot Rolling
F.T. 870-910 °C
Hot Coiling
AlN Precipitation Logic
If C.T. 710°C (CA): Cool slowly, AlN precipitates
If C.T. 560°C (BA): Cool quickly, AlN stays in solution

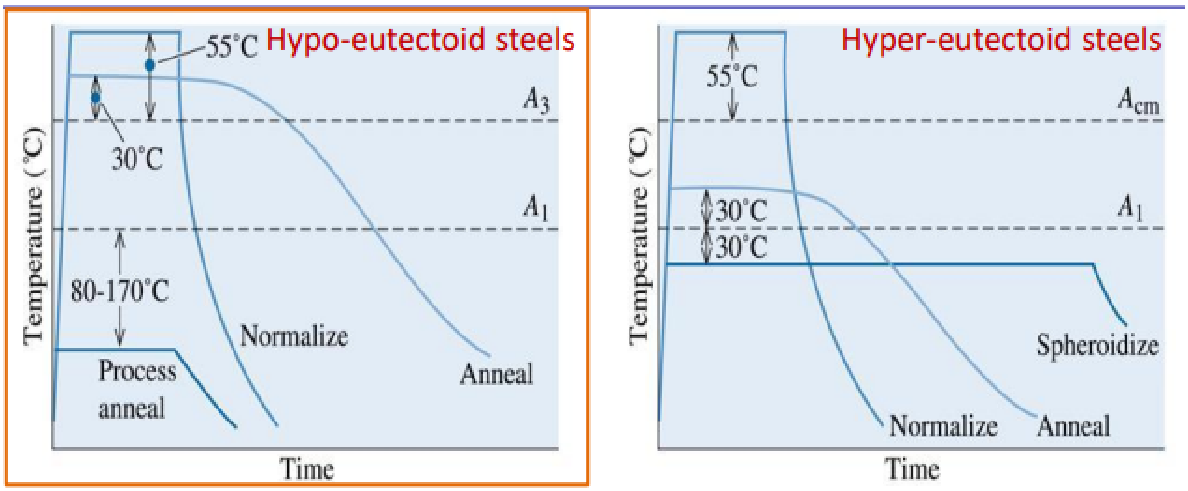


Heat Treatment of Steels

Conventional heat treatments for Hypo- and Hyper-eutectoid steels. The goal is to modify microstructure (Grain size, phase distribution) to alter mechanical properties.

Reminder from [Overview of Steels > Non-Equilibrium Phase Diagram]

- A_1: Eutectoid temperature (~727°C). Boundary between Austenite and Pearlite.
- A_3: Upper critical temperature for **Hypo**-eutectoid steels (Austenite limit).
- A_{cm}: Upper critical temperature for **Hyper**-eutectoid steels (Cementite solubility limit).



Hypo-Eutectoid Steels ($C < 0.77\%$)

Normalizing

- **Process:** Heat to $A_3 + 55°\text{C}$ (Austenitization) $\rightarrow$ **Air Cool**.
- **Result:** Moderate grain refinement.
- **Properties:** Harder and stronger than annealed; good mechanical properties at low cost.
- **Microstructure:** Fine Pearlite + Ferrite.

Full Annealing

- **Process:** Heat to $A_3 + 30°\text{C} \rightarrow$ **Furnace Cool** (Very slow).
- **Result:** Maximum chemical homogenization and softening.
- **Properties:** Maximum ductility, lowest hardness.
- **Microstructure:** Coarse Pearlite + Ferrite.

Process Annealing

- **Process:** Heat to $80 - 170°\text{C}$ **below** A_1.
- **Result:** Recrystallization of ferrite without phase transformation.
- **Use Case:** Restoring ductility after cold working (strain hardening recovery).

Hyper-Eutectoid Steels ($C > 0.77\%$)

Normalizing

- **Process:** Heat above $A_{cm} \rightarrow$ Air Cool.
- **Goal:** Break up the brittle Cementite network at grain boundaries.

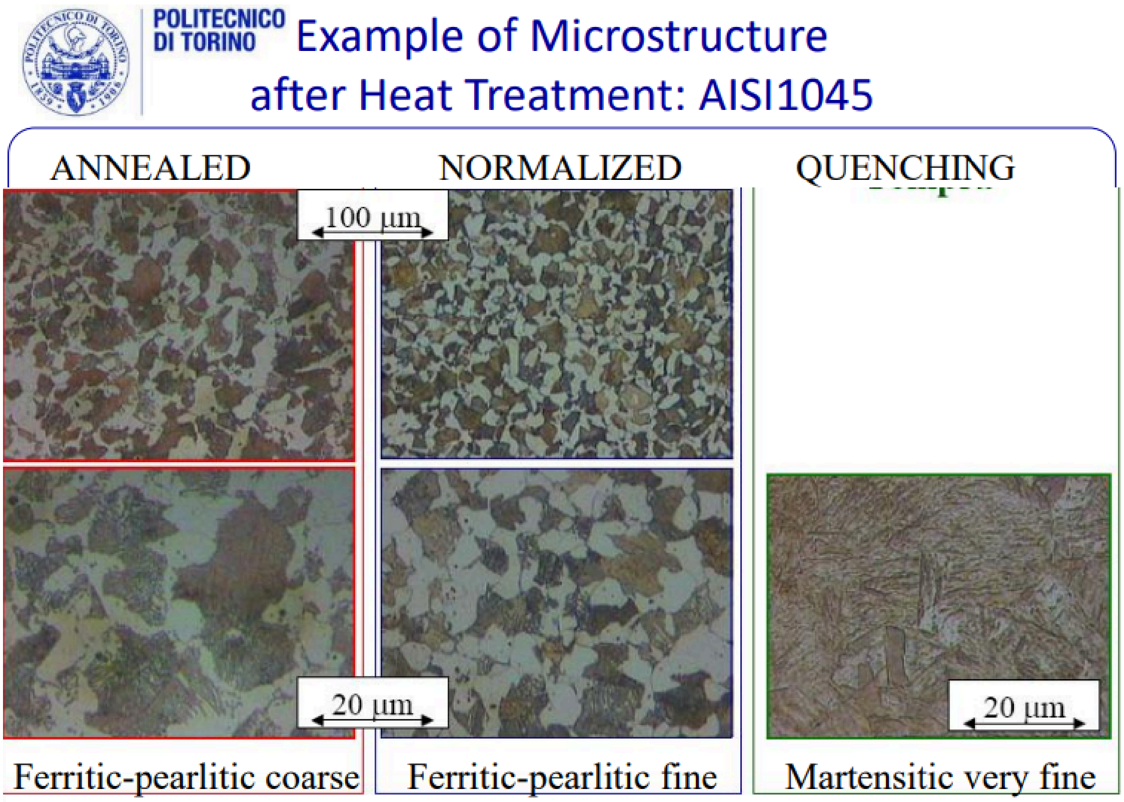
Spheroidizing

- **Process:** Pendulum heating (oscillating) around A_1.
- **Result:** Spheroidization of Pearlite and Cementite.
- **Properties:** The **softest, toughest** possible condition for high-carbon steel.
- **Use Case:** Essential for machinability of high-carbon steels.

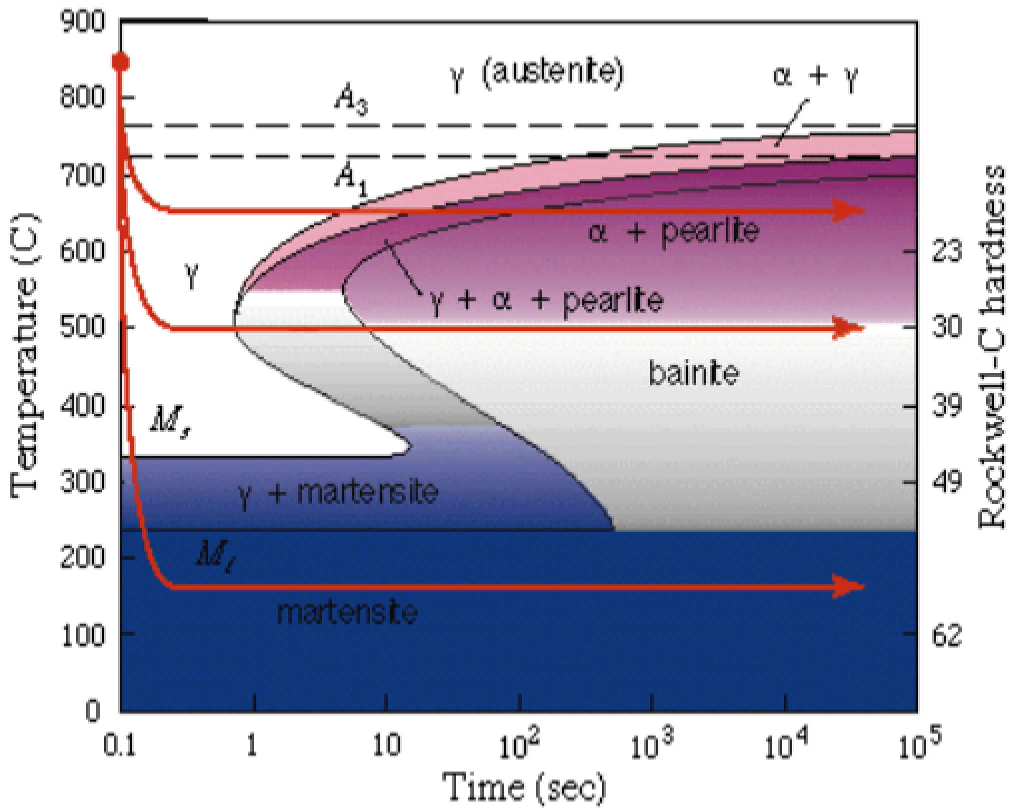
Overview of Heat Treatments

- **Austenitization:** Holding at T to dissolve C into γ-Fe (max solubility/homogeneity).

- **Annealing:** Diffusion-driven. Max softening. Equilibrium microstructure.
- **Normalizing:** Air-cooled. Slightly non-equilibrium. Moderate refinement.



Isothermal H.T. On a TTT/CCT Diagram



Bainite

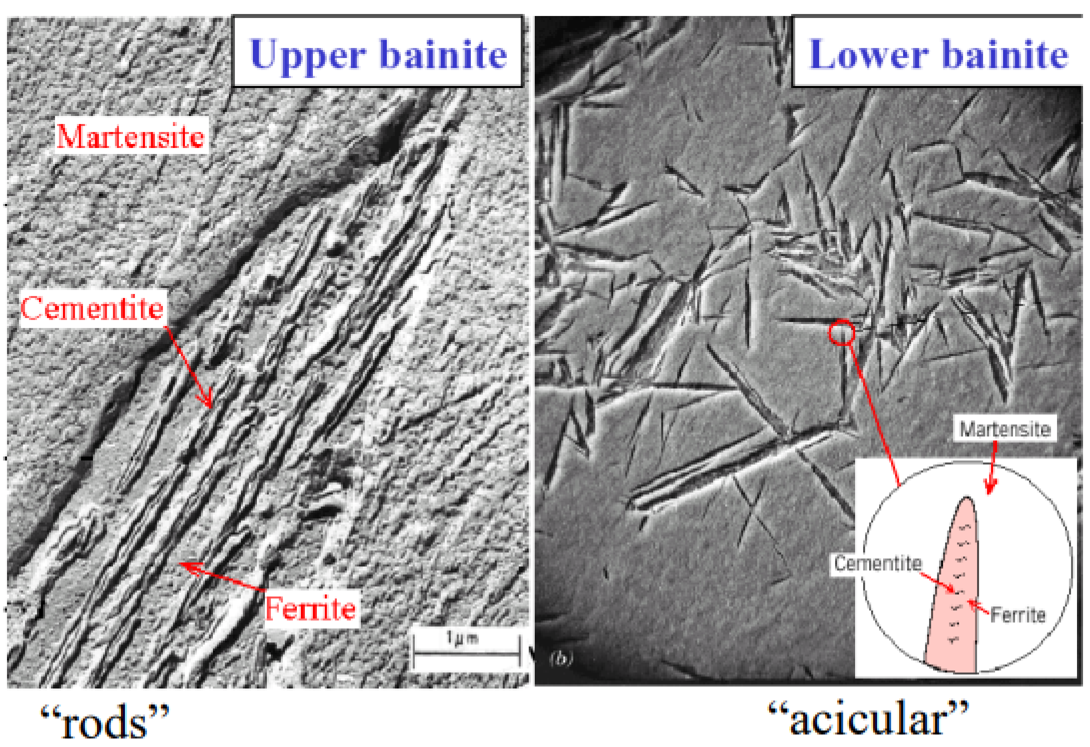
A microstructure of Ferrite and Cementite that forms between the temperature ranges of Pearlite and Martensite (roughly 250°C – 550°C). While martensite is BCT, bainite is BCC.

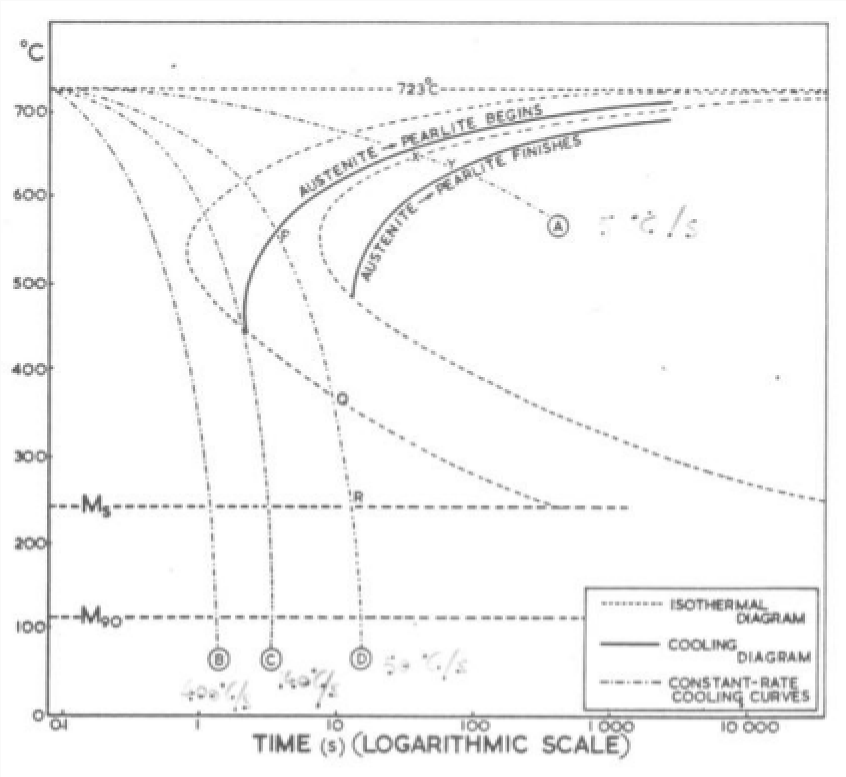
Formation: Created via **Austempering** (isothermal holding). You cool the steel fast enough to miss the Pearlite nose, but hold it above the Martensite start (M_s) line until it fully transforms.

The Two Types:

- **Upper Bainite (400°C – 550°C):** Forms at higher temps. Looks "feathery." The carbides precipitate *between* the ferrite plates. It's tough, but lower bainite is usually better.
- **Lower Bainite (250°C – 400°C):** Forms at lower temps. Looks like needles (acicular). The carbides precipitate *inside* the ferrite needles. High strength and high toughness.

Why it matters:
It offers a unique balance. You get hardness similar to tempered martensite but with better ductility and toughness. Plus, since you don't do a violent quench to room temperature, you avoid the internal stresses and cracking risks associated with Martensite.



> Note
>
> TTT (Time-temperature-Transformation) diagrams show transformations in isotermal environments. In the real world, this is impossible, since materials cannot change temperature instantly.
> CCT (Continuous Cooling Transformation) diagrams show the real world since things cool down gradually. Typically, reactions are slower than in an ideal world, so in a CCT diagram reactions are shifter bottom-right with respect to a TTT diagram. (reactions are slower and happen at lower temperatures).
>
> 
>

Quenching

Quench Severity Coefficient aka. H-Value

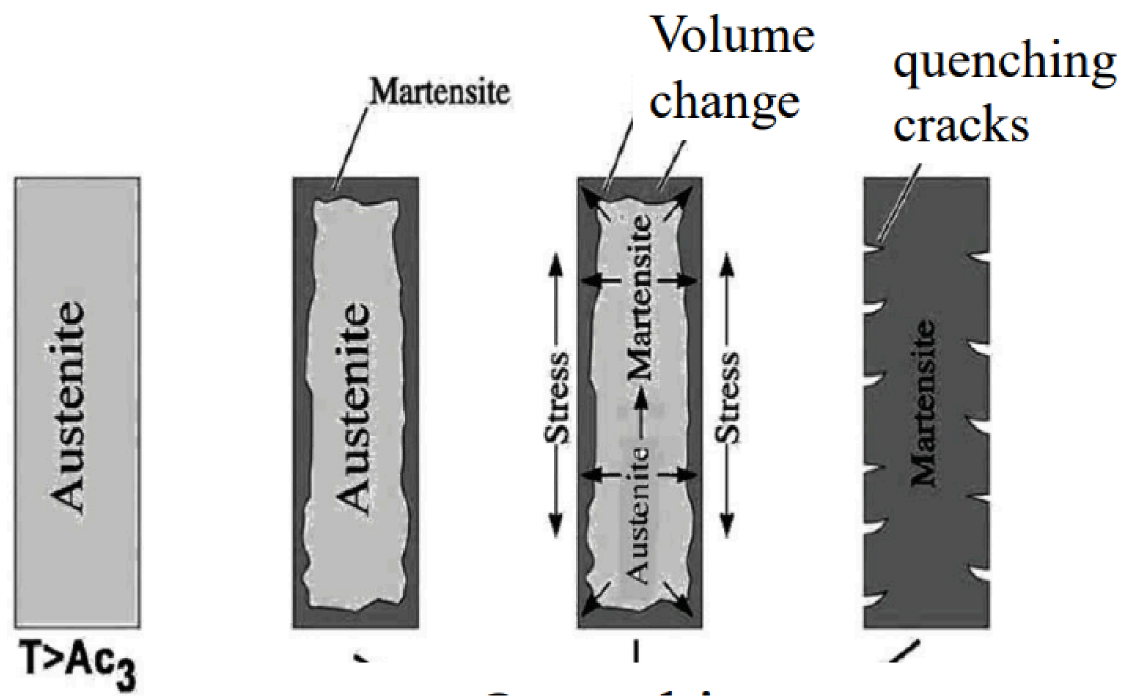
> Definition
>
> Describes how aggressively a medium (the liquid the metal is quenched in) cools down the material, with 1 being the baseline and the value for still water.

$$Q = HA\Delta T$$

Quench Medium	Agitation?	H Coefficient	Cooling Rate (°C/s)*
Oil	No	0.25	18
Oil	Yes	1.0	45

Quench Medium	Agitation?	H Coefficient	Cooling Rate (°C/s)*
Water (H_2O)	No	1.0	45
Water (H_2O)	Yes	4.0	190
Brine	No	2.0	90
Brine	Yes	5.0	230

**Cooling rate measured at the centre of a 1-inch bar.*



> In a thick part, the surface cools much faster than the core. The surface transforms to Martensite (and expands) first, creating a hard shell. When the core later tries to expand, it is trapped, leading to high residual stresses and **quench cracking**. Quenching cracks are very common in larger pieces.

✓ Marquenching: the solution to quenching cracks

An interrupted quenching method designed to minimize distortion.

1. **Quench:** Rapidly cool to a temperature just above the Martensite Start (M_s) point.
2. **Hold:** Keep it there until the temperature equalizes (Surface Temp $\approx$ Core Temp).
3. **Finish:** Air cool through the Martensite transformation range.

Benefit:
Since the temperature is uniform, the transformation happens simultaneously across the entire cross-section. This drastically reduces residual stress and cracking.

Residual Austenite (γ_{res})

Definition

Austenite that fails to transform into Martensite during quenching because the quench didn't get cold enough (specifically, the temperature didn't drop below M_f, the Martensite Finish temp).

Causes:

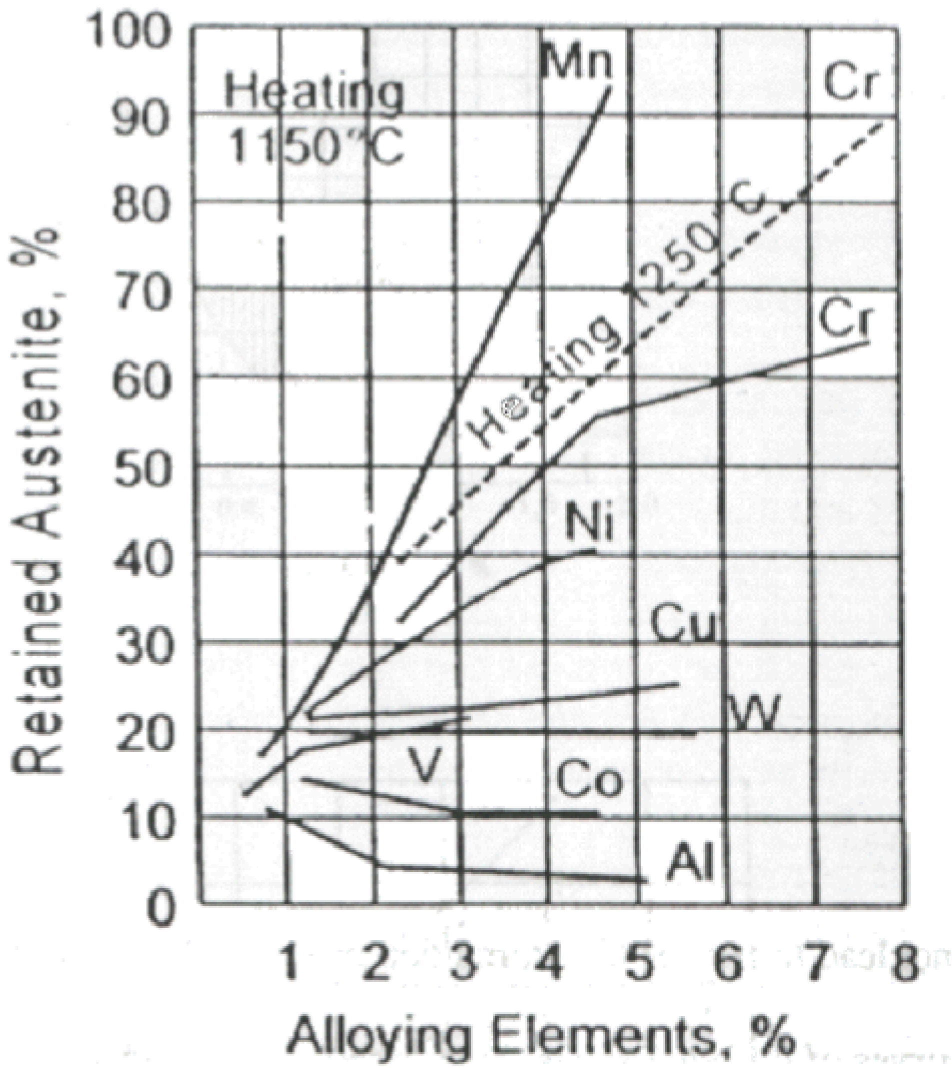
- **High Carbon/Alloy Content:** These elements push the M_f temperature way down (often below 0°C).
- **Stepped Quenching:** Isothermal holding stabilizes the Austenite.

Consequences:

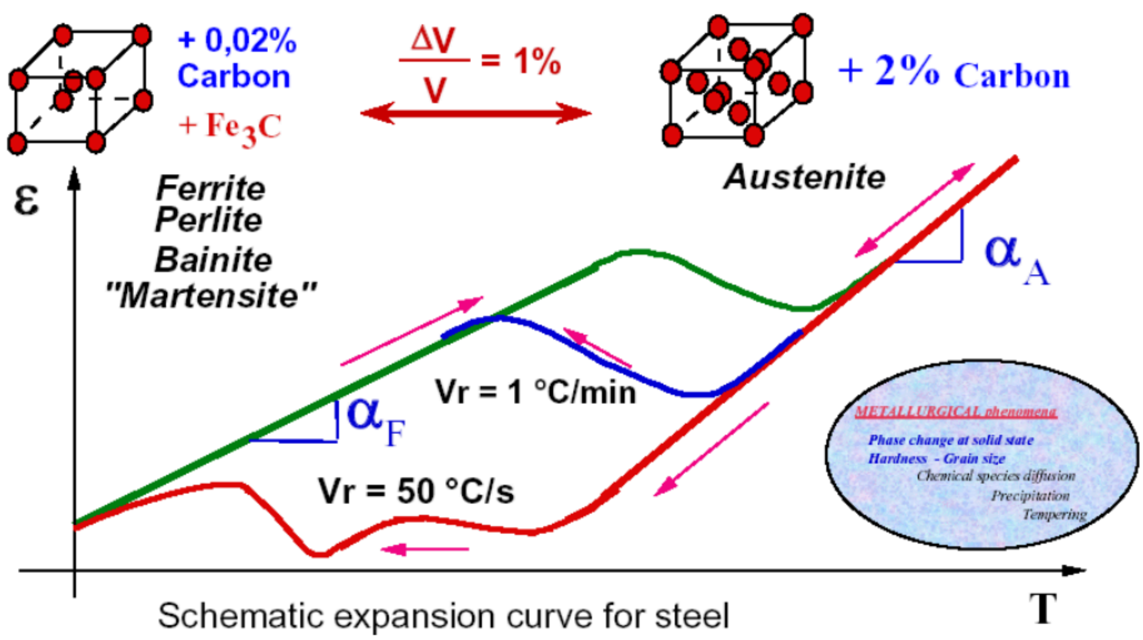
1. $\downarrow$ **Hardness & Fatigue Strength:** Soft spots in the hard martensite matrix.
2. **Dimensional Instability:** The residual γ will eventually transform later in service. This transformation causes Volumetric Expansion & Distortion.
3. **Internal Stresses:** The delayed expansion creates new internal stress.

Solutions:

- **Cryogenic Treatment:** Continue quenching into sub-zero temperatures (Liquid Nitrogen at -150°C or Dry Ice at -80°C) to force the cross of the M_f line.
- **Multiple Tempering:** Execute two or more Tempering cycles to decompose the retained austenite into stable phases.



Volumetric Expansion & Distortion



- **Thermal Contraction:** As temperature drops, the metal *wants* to shrink.

- **Phase Transformation:** As Austenite turns into Martensite (or Ferrite), the crystal lattice wants to expand.
- **Austenite (FCC):** Ideally packed atoms. High density.
- **Martensite/Ferrite (BCC/BCT):** Loosely packed atoms. Low density.
- **The Result:** When the phase flips, the volume suddenly increases by roughly **1%**.

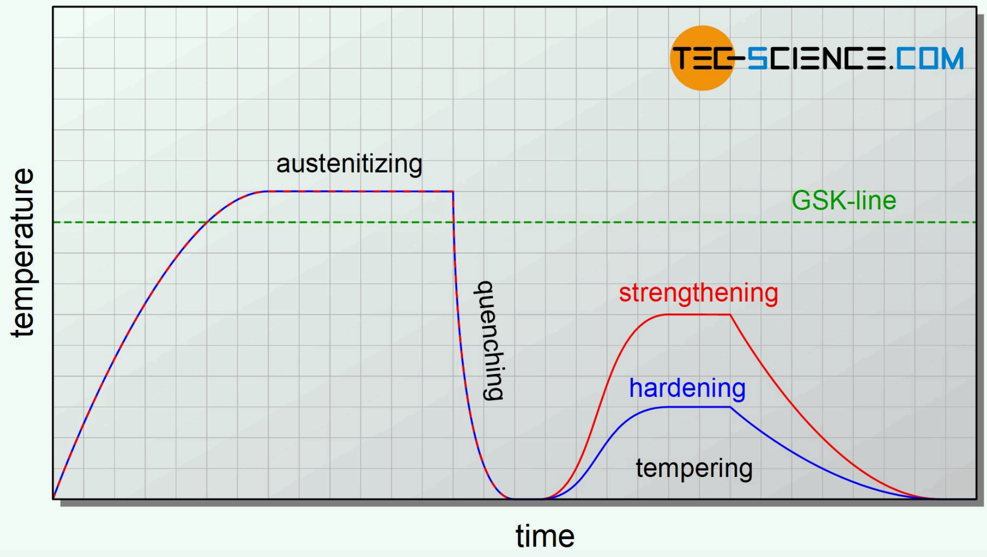
This phenomenon can cause huge internal stresses, which can lead to quenching cracks or overwhelming deformations of the object.

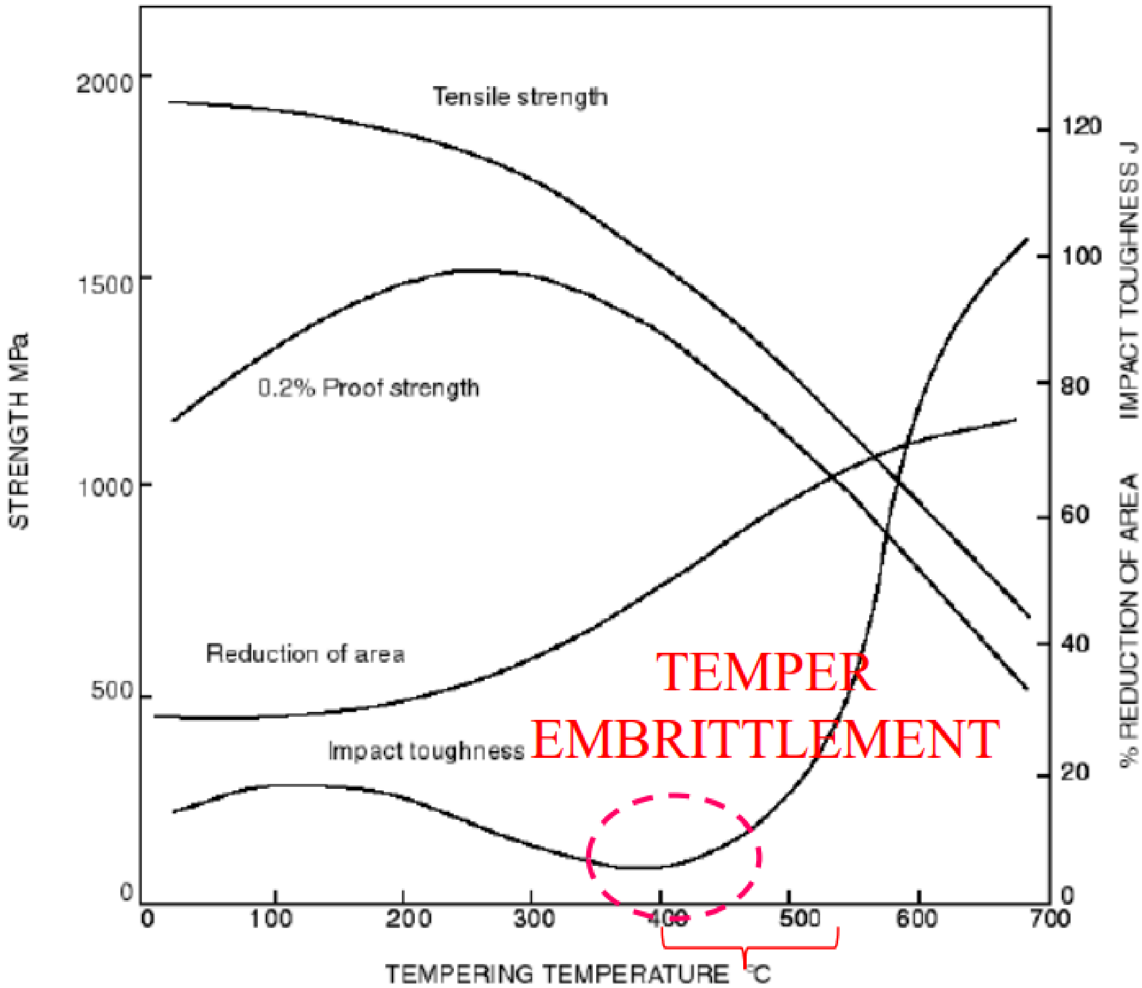
Tempering

Definition

Tempering is a heat treatment process, mainly for metals like steel, that involves reheating a hardened material to a specific temperature below its critical point and then cooling it slowly to reduce brittleness, increase toughness, and relieve internal stress, creating a better balance of strength and ductility for practical use.

Graph




Tensile strength
0.2% Proof strength
Reduction of area
Impact toughness
TEMPER
EMBRITTLEMENT
STRENGTH MPa
2000
1500
1000
500
0
IMPACT TOUGHNESS J
% REDUCTION OF AREA
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
TEMPERING TEMPERATURE °C

Temper Embrittlement (Krupp's Illness)

Normally, tempering increases toughness (K). However, if you hold the steel in the **400°C – 550°C** range (or cool slowly through it), the toughness drops dramatically.

You ruin the steel if you do any of these:

- Temper it specifically inside the **400-550°C** range.
- Temper it *above* this range (>600°C) but then **cool it slowly** through the danger zone.
- Hold it in this range for too long during service.

The Result:

- **Fracture Mode:** Intergranular (the metal cracks along the grain boundaries because impurities segregate there).
- **Reversibility:** It is **reversible**. You can fix it by reheating above 600°C and quenching.

Who is Vulnerable?

- **Safe:** Plain Carbon Steels (with $Mn < 0.7\%$) are immune.
- **At Risk:** Low alloy steels with high Mn or Cr.
- **High Risk:** Steels with coarse grains (more segregation).

How to fix it

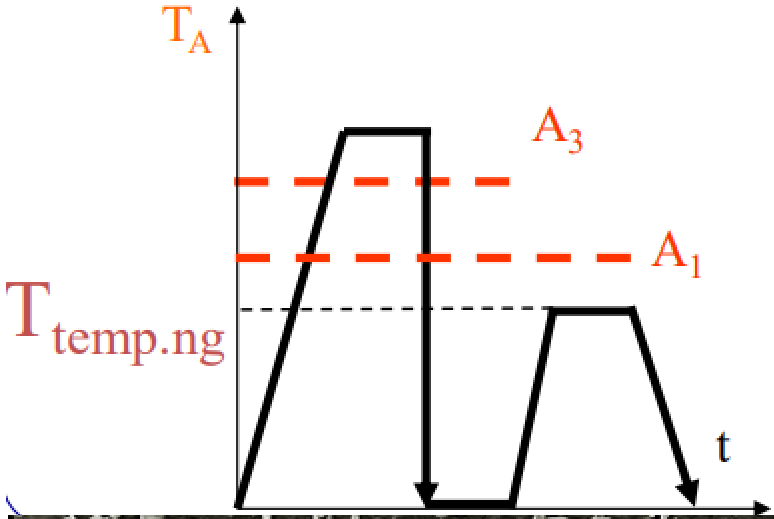
1. **The Alloying Fix:** Add Mo **(>0.2%)** or W **(0.4%)**. This is why Chrome-Moly steel is great: the Molybdenum blocks the impurities from moving to the boundaries.
2. **The Process Fix:** If you temper at high temps (>600°C), quench the part afterwards. Do *not* furnace cool it. You must "jump over" the 550-400°C gap quickly.

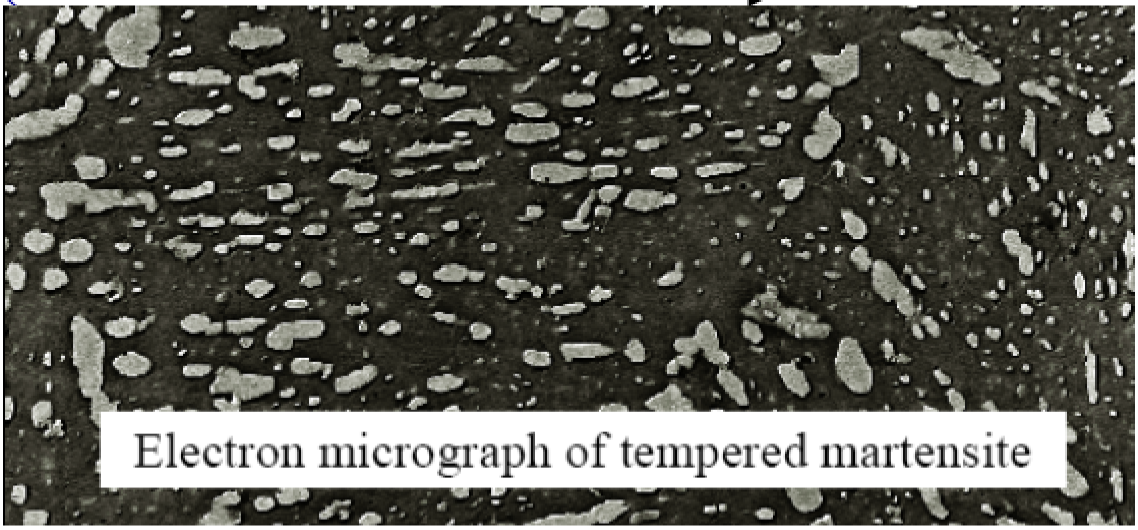
Why it Happens

- Impurities precipitate on grain boundaries at that temperature range
- Cr, Mn combine with impurities, separating from the main alloy.
- Mo, W are more stable in their carbide forms and therefore do not react with impurities.

Tempered Martensite

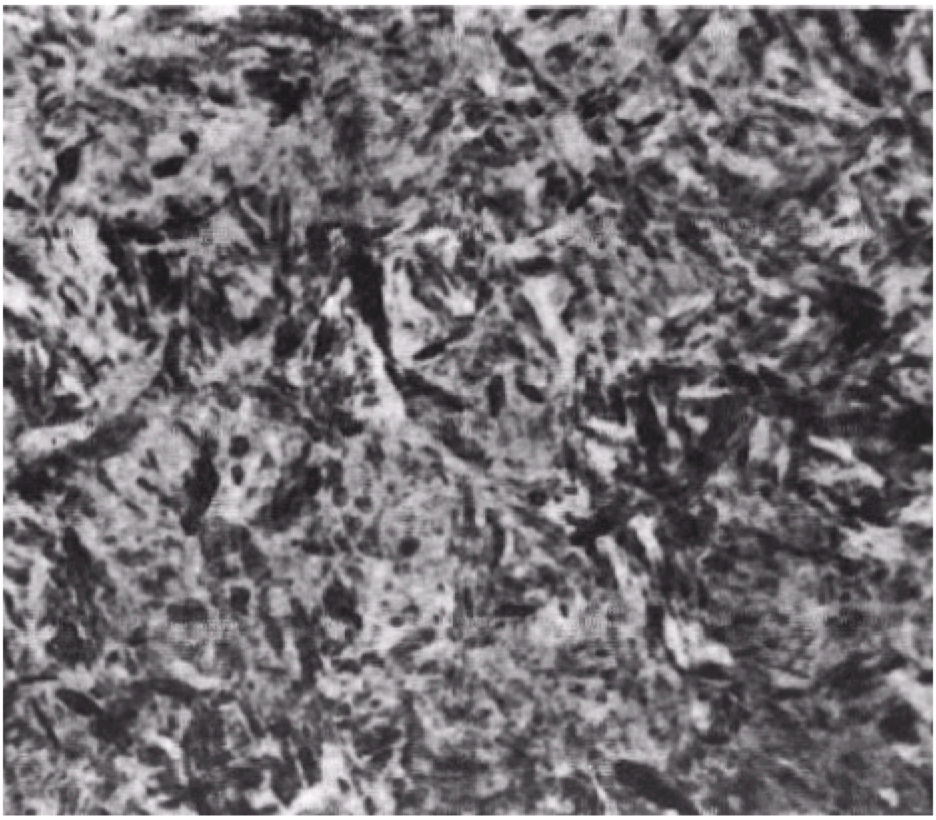
Martensite is extremely hard and brittle. After tempering, the cementite phase turns into spheroidal shapes. The tempering is done at 250-650 °C. This reduces internal stresses and increases toughness.





Electron micrograph of tempered martensite

Tempered Carbon Steels



Element	Primary Roles	Advantages	Disadvantages	Notes
C	Hardener.	↑ Yield Strength, ↑ Hardness (HRC), ↑ Hardenability	↓ Toughness (CVN)	Combines with $Cr, Ti, Ta, W,$ to form carbid
Mn	Hardenability Agent & Austenitizer.	Massive ↑ Hardenability (H), Strong Austenitizer (after Ni)	↓ Ductility, ↓ Weldability (as concentration rises)	Role depends c
Al	Deoxidizer & Grain Refiner.	Powerful deoxidizer in the melt, refines grain size	Detrimental if > 0.1%	Used in "killed' steels.
Si	Deoxidizer & Elasticity Booster.	↑ Elastic Limit, Deoxidizer (less than Mn)	Detrimental to surface finish if excessive	Less effective tl Mn for HRC.
Cu	Corrosion Shield.	↑ Corrosion Resistance (Rcorr) (if 0.2% - 0.5%)	↓↓ Surface finish in hot-worked steels if excessive	Keep < 0.5%.
Ni	Ferrite Strengthener & Toughener.	↑ Tensile Strength (UTS) *while maintaining* high Toughness and Ductility. Strong Austenitizer	*None*	Stays in solid solution; best a rounder.
Mo	Best for high temperature.	↑ Creep Resistance at high T, ↑↑ Hardenability (H)	*None*	Overcomes ten embrittlement.
B	Increases hardenability.	↑↑↑ Hardenability (H)	*None*	-
Cr, Ti, Ta, W, Nb, V	Grain Refiners & Hardeners.	↑↑ Hardness (HRC) without	*None*	Strong carbide formers and gr refiners.

Element	Primary Roles	Advantages	Disadvantages	Notes
		depressing toughness, ↑ Wear Resistance, ↑ High T Resistance		

Surface Treatment of Steels

Surface Treatment of Steels

Hardening by Carburizing

The primary goal here is to achieve a surface that is hard and wear-resistant while maintaining a tough, ductile core to absorb shock.

The Mechanism
This process exploits specific metallurgical factors:

- Martensite hardness increases as the carbon percentage increases.
- Martensite forms from austenite upon quenching.
- Carbon is highly soluble in austenite.
- The diffusion/absorption rate increases significantly with temperature.

Process Parameters

- **Temperature (T_c):** $870 - 950°C$.
- **Time:** $10 - 20$ hours.
- **Applicable Materials:** Plain carbon steels ($< 0.2\%C$) and low carbon low alloy steels.

Applications
Used for components requiring durability under load, such as gears, shafts, bearings, and piston rods.

Outcome

- A carbon concentration profile develops along the thickness, achieving maximum Vickers Hardness (HV) on the surface.
- The austenite transforms into martensite via oil quenching.

Hardening by Nitriding

Unlike carburizing, this process aims for an *extremely* hard surface while retaining a tough core.

The Mechanism

- Nitrogen forms very hard compounds (nitrides) with Iron.
- Nitrogen solubility in ferrite is very low.

- At ferrite stability temperatures, diffusion is slow, and the formation of nitrides inhibits further Nitrogen diffusion.

Process Parameters

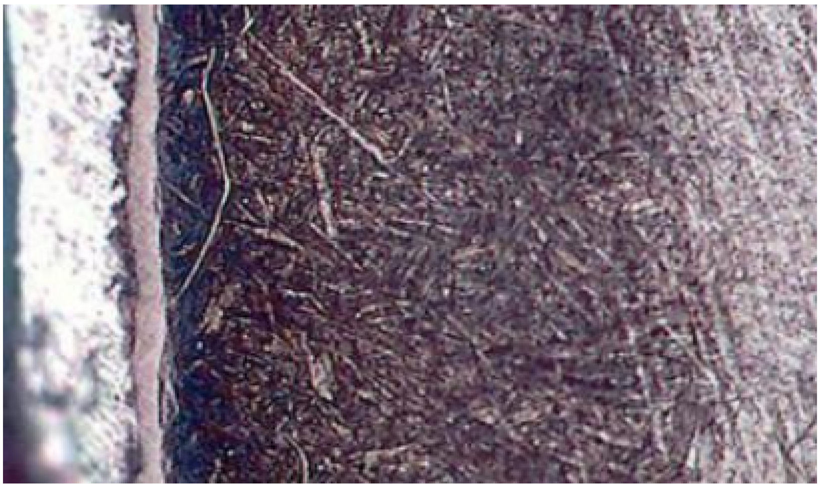
- **Temperature (T_N):** $500 - 600^{\circ}C$.
- **Time:** Approx. 70 hours (can range 40-100h).
- **Chemical Reaction:** Ammonia dissociates: $2NH_3 \Rightarrow 2N + 3H_2$. Atomic Nitrogen then dissolves into the steel.

Applicable Materials

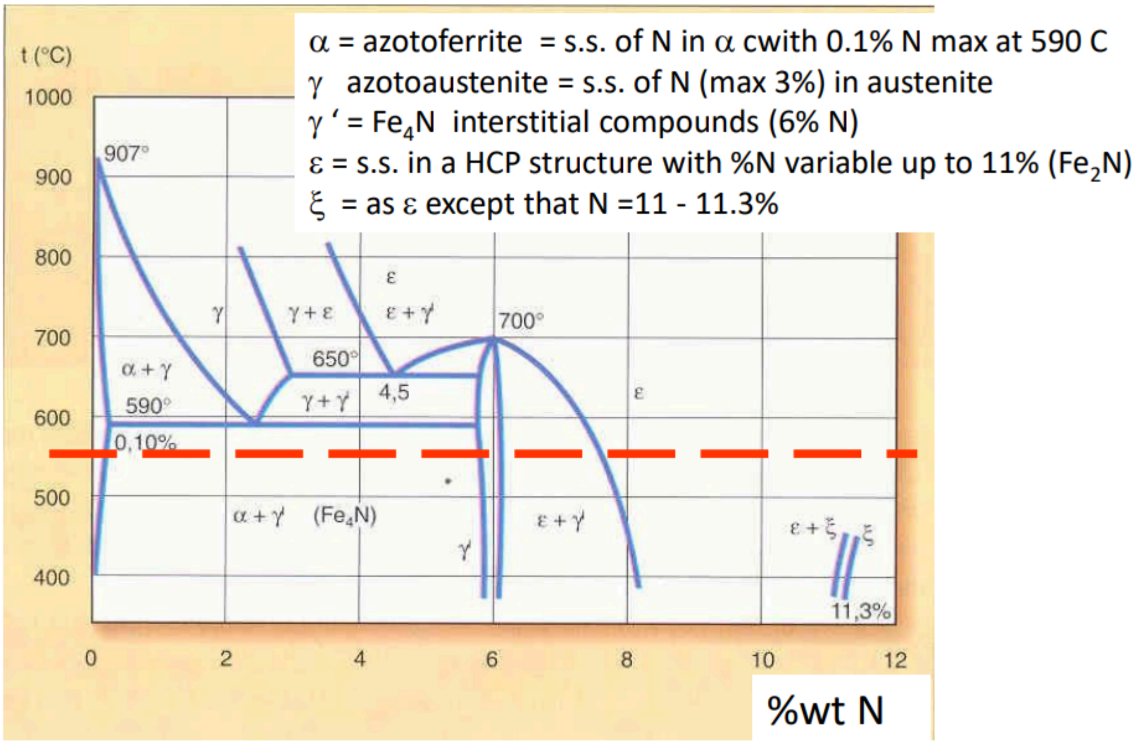
- Nitriding steels: Plain medium carbon steel ($0.4 - 0.6\%C$) and medium carbon low alloy steels (tempered/semi-finished).
- Common alloying elements: Al, Cr, V, Mo.

Structure of the Nitrided Layer

- **Outer Layer:** $(Fe, Al, Cr)_2N$.
- **Inner Layer:** $(Fe, Al, Cr)_4N$.
- **Depth:** A thin layer, typically $0.2 - 0.3$ mm.
- **Hardness:** Very high superficial hardness (~ 1100 HV).



The Fe-N Metastable Phase Diagram



Nitriding Steel Compositions

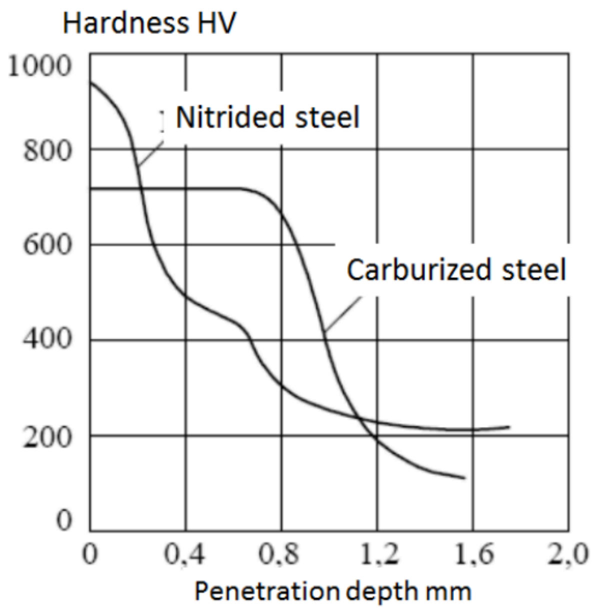
Specific alloys are required for optimal nitriding results.

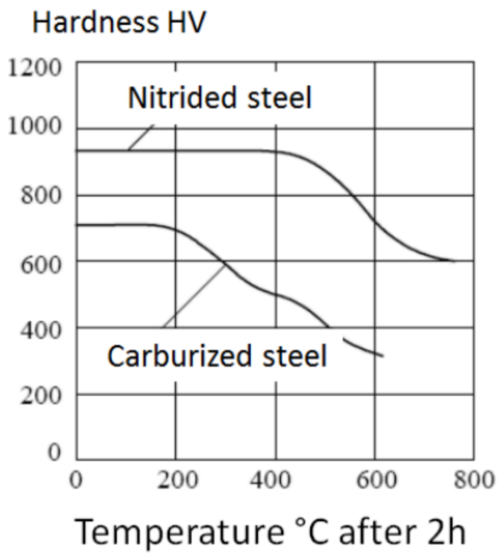
Steel Type	%C	%Si	%Mn	%Cr	%Mo	%Al	Hardness after Nitriding
30 Cr Mo 10	0.30	0.35	0.60	2.50	0.40	-	650 HV
38 Cr Al Mo 7	0.38	0.30	0.60	1.70	0.25	1.0	1050 HV
42 Cr Al Mo 7	0.42	0.35	0.55	1.70	0.35	0.40	900 HV

Comparison: Nitriding Steels vs. Carburizing

Performance Comparison

- **Nitrided Steel:** Achieves higher surface hardness (up to 1000-1200 HV) but the depth of penetration is shallow (< 0.6 mm).
- **Carburized Steel:** Lower peak surface hardness (~ 800 HV) but maintains hardness to a greater depth (> 1.0 mm).





Harris' Formula for Penetration Depth
To calculate the depth of the treatment:

$$\text{Depth}(mm) = 660 \cdot \sqrt{t} \cdot e^{-\frac{8287}{T}}$$

Where T is temperature in **Kelvin** and t is time in **hours**.

Post-Treatment Processing

Process Step	Carburized Parts	Nitrided Parts
Pre-treatment	Normalizing + work hardening annealing	Normalizing + Work hardening annealing
Machining	Roughing (medium thickness)	Roughing (medium thickness)
Main Process	Carburizing	Tempering
Hardening	Quenching + tempering at $150^{\circ}C$	Finish Nitriding
Finishing	Finish by grinding	Finish by grinding

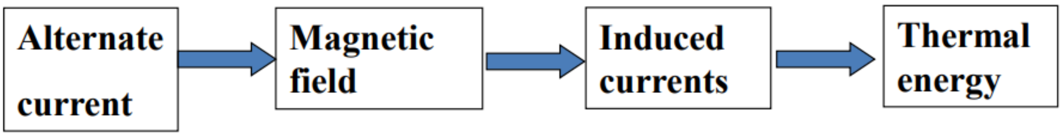
Induction Hardening

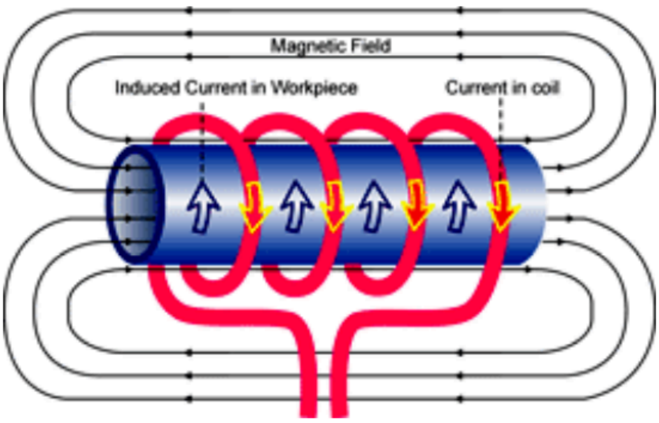
Definition

The process uses alternating current to generate a magnetic field, which creates induced currents in the workpiece. This results in localized thermal energy.

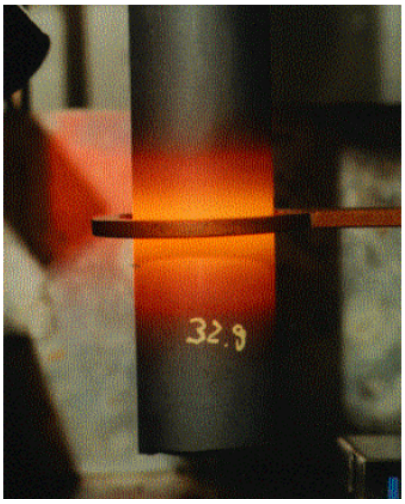
Current Penetration Depth (δ)
The depth of heating is controlled by the frequency:

$$\delta \cong \sqrt{\frac{\rho}{\pi \mu f}}$$





Current supply

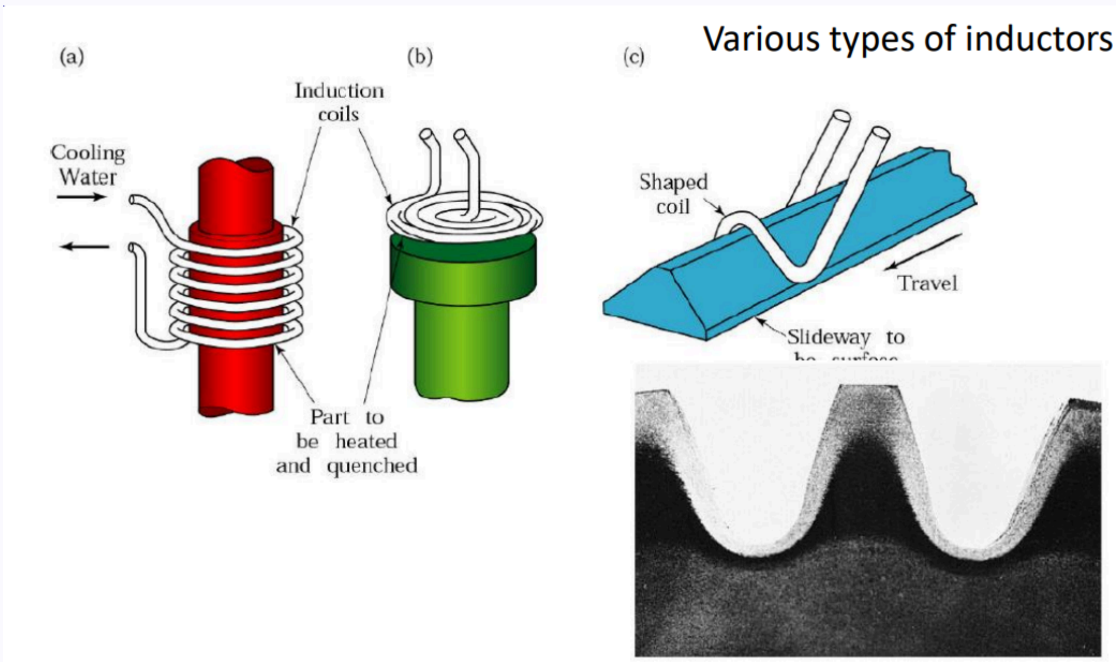


Inductor Types

Various shapes exists for different geometries:

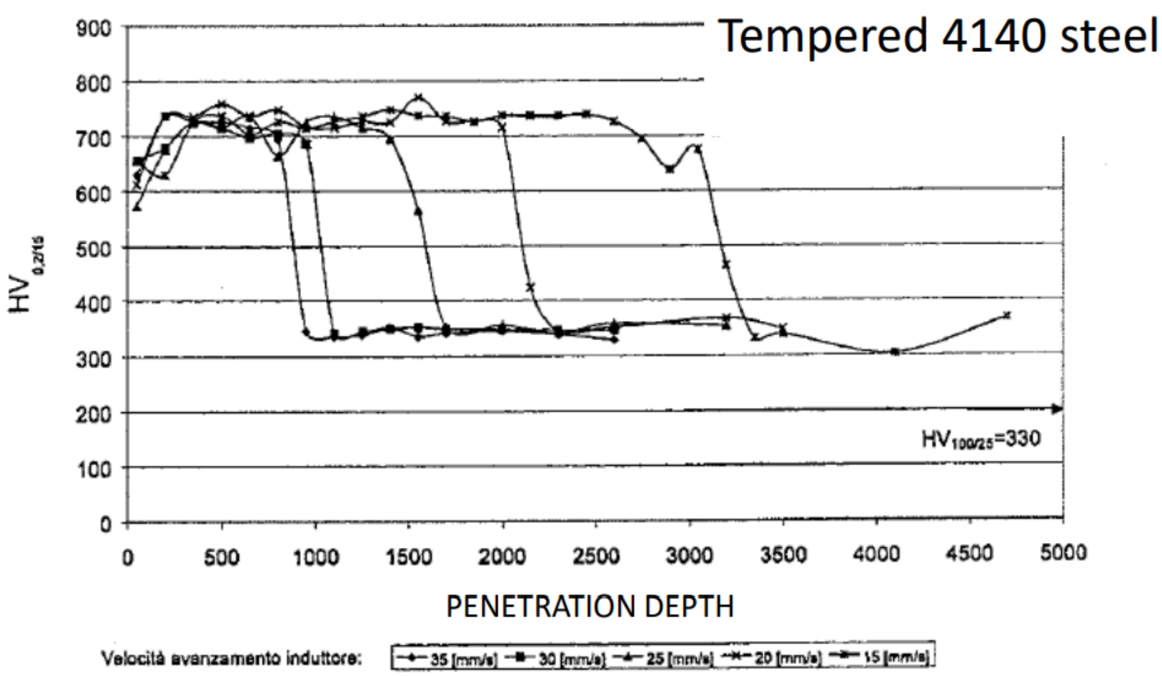
- Single-shot coils for cylindrical parts.
- Shaped coils for slideways or gears.

Slideways vs Coils



Hardness Profiles

Induction hardening creates a sharp transition in hardness. For example, in Tempered 4140 steel, hardness holds steady around 700 HV before dropping sharply to the core hardness ($\sim$ 330 HV) at a specific depth determined by the induction frequency and speed.



Heat vs. Chemical Surface Treatments Overview

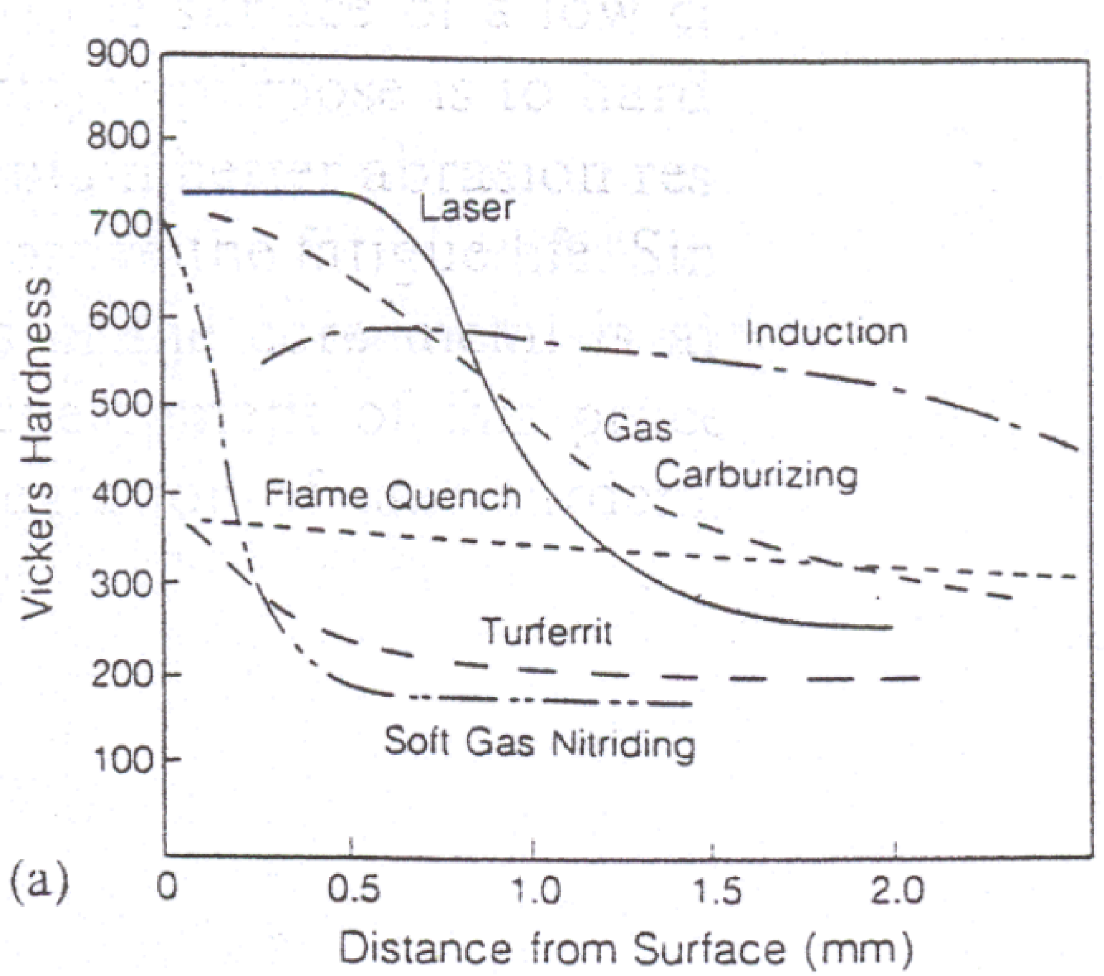
All surface heat treatments generally confer a **compressive stress state** on the surface, which increases fatigue resistance.

Process Comparison Table

Process	Steel Type	Component	Conditions
Induction (3 kHz)	0.38% C	Axle	Water Quenched, Tempered at $210^{\circ}C$
Flame Hardening	0.67% C	Wheel	Water Quenched, Tempered at $490^{\circ}C$
Carburizing	0.2% C (Ni-Cr-Mo alloy)	Gear	Oil Quenched, Tempered at $200^{\circ}C$
Laser (15 kW)	0.43% C (Mn alloy)	Gear	Self Quenched
Nitriding	0.2% C (Cr-V-Al alloy)	Gear	Process carried out at $570^{\circ}C$

Residual Stress Profiles

- **Nitriding (Turferrit/Soft Gas):** Creates the highest compressive residual stress (-600 to -1000 MPa) right at the surface.
- **Induction:** Creates deep compressive stress, but lower magnitude at the surface compared to nitriding.
- **Laser:** High surface hardness but shallower stress profile.



Weldability and Heat Affected Zone (HAZ)

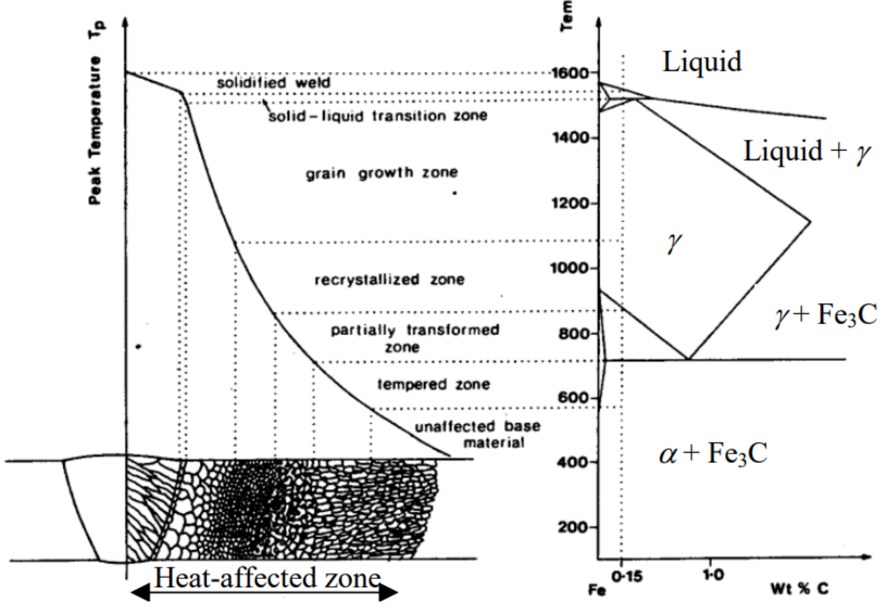
When welding steels, the thermal cycle alters the microstructure adjacent to the weld. This is the Heat Affected Zone (HAZ).

Structure of the Welding Zone

1. **Solidified Weld:** The melt zone.
2. **Grain Growth Zone:** Liquid + γ (austenite) transition.
3. **Recrystallized Zone:** γ region.
4. **Partially Transformed Zone:** $\gamma + Fe_3C$.
5. **Tempered Zone:** Below A_1 temperature.
6. **Unaffected Base Material:** Original microstructure.

Welding of hypoeutectoid steel (0.15 wt% C) vs Fe-Fe_3C diagram

(*From K. Easterling, Introduction to the Physical Metallurgy of Welding, Butterworths, (1983)*)



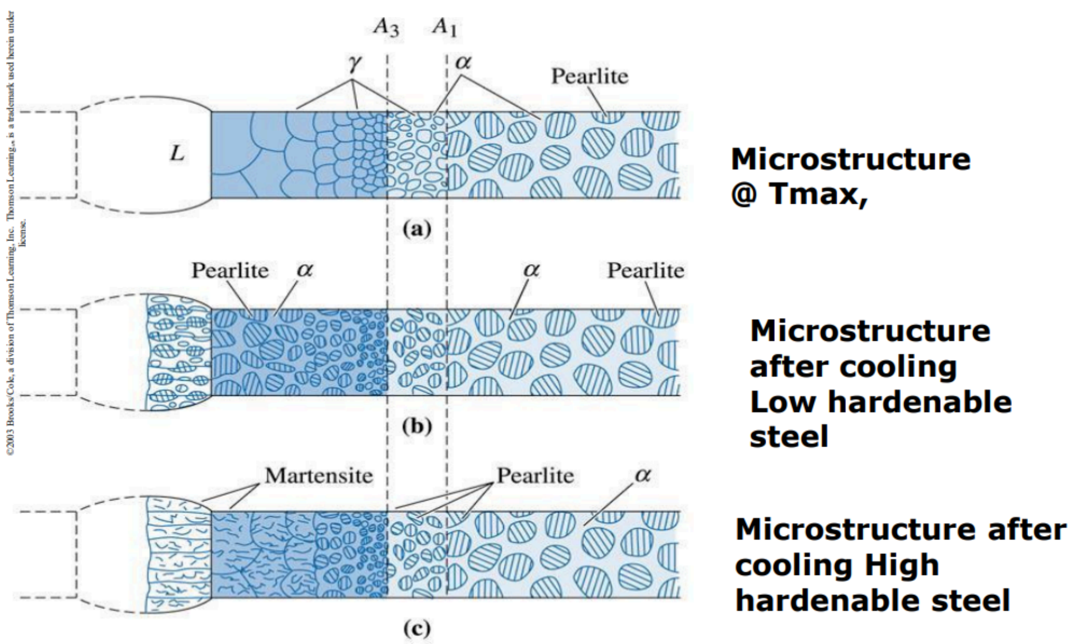
Microstructural Evolution

The final structure depends heavily on the hardenability of the steel.

- **At T_{max}:** The structure becomes Austenite (γ) near the melt line.
- **Cooling (Low Hardenable Steel):** Reverts to Pearlite and Ferrite (α).
- **Cooling (High Hardenable Steel):** Forms **Martensite**, which is brittle and prone to cracking.

Weldability Criteria

- To be weldable, steel must have **low hardenability** (low alloying elements).
- Steels up to $0.4\%C$ are weldable, but caution is needed for higher carbon contents.
- **Risk:** Cracks can form underneath the welding bead in the HAZ.



Summary Tables

Chemical Surface Treatments Summary

Process	Compound	Temp ($^\circ C$)	Time (h)	Thickness (μm)	Hardness (HV)	Distortion
Nitriding	Fe-N	500-550	1-70	50-100	700-1000	Min
Nitro-carb.	Fe-(C,N)	550-650	1-6	50-200	700-1000	Min
Boriding	Fe-B	600-1000	1-4	50-500	1000-1800	High
Carburizing	Fe-C	700-1050	1-46	100-7000	750-950	High
Process QUAD	CrCN, VCN, TiCN	400-700	1-8	5-20	1200-2500	Min

Wear Resistant Ceramic Coatings

Process	Surface Layer	Method	Surface T ($^\circ C$)	Thickness (μm)	Hardness (HV)	Distortion
Cr hard	Cr	Electrolysis	50-80	20-50	700-800	Low
Thermal CVD	TiC, TiCN, TiN	Gas	800-1100	3-15	1500-2000	High
Plasma CVD	TiC, TiN	Arc in vacuum	300-600	1-6	1500-2000	Low
PVD	TiN, CrN	N in vacuum	300-600	1-6	2000-4000	Low
Flame coating	Ni, Cr, B, Si	Powder melting	1000-1100	500-2000	600-800	High
Stellite	Ni, Cr, B, Si	Melting (arc)	T_{fus}	2000-5000	300-900	High

Thermal Expansion

Thermal Expansion

$$\Delta L = L_0 \alpha_L \Delta T$$
$$\Delta V = V_0 \alpha_L \Delta T$$

$$\alpha_V = \frac{1}{V}\frac{dV}{dT} = \alpha_x + \alpha_y + \alpha_z$$
$$\alpha_L = \frac{1}{L}\frac{dL}{dT}$$

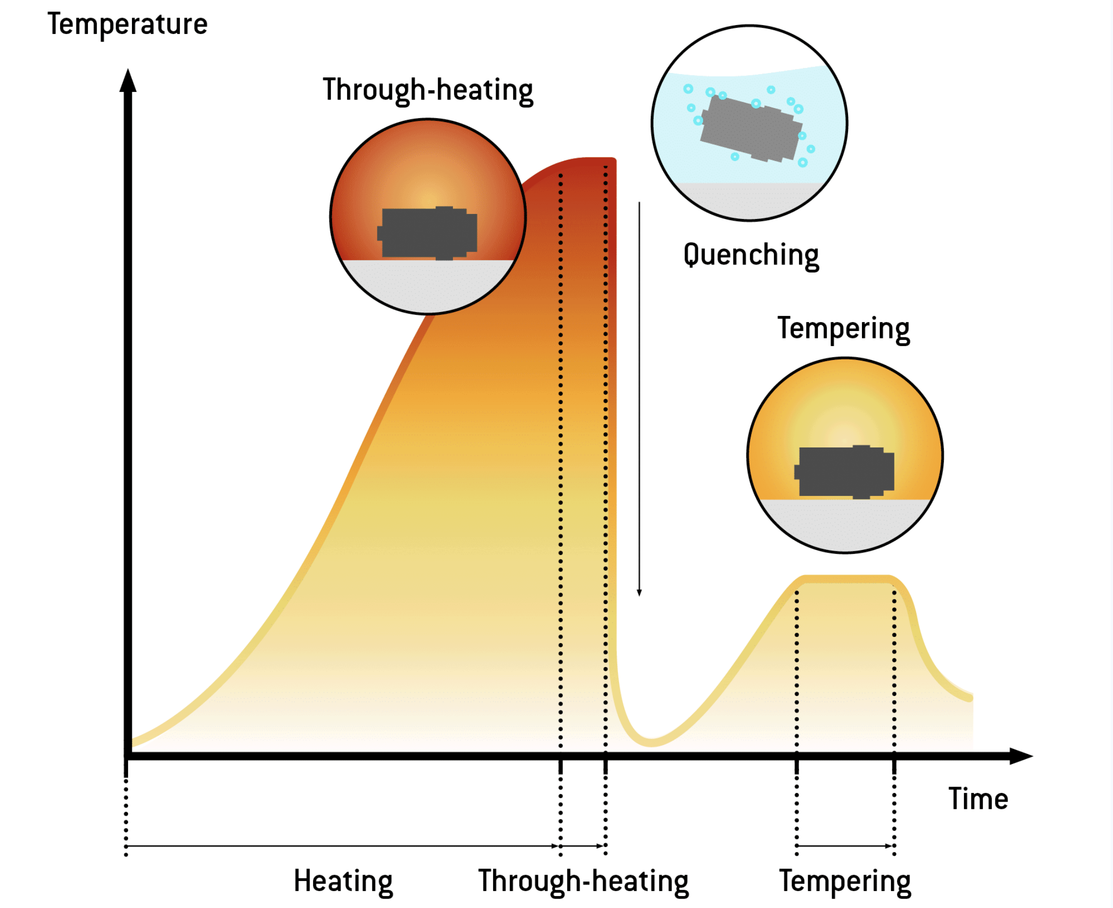
Treatment

Treatment

Quenching

The process of rapidly cooling a material, disallowing the crystal structure to realign as a result of the change in temperature.

Optional Diagram!

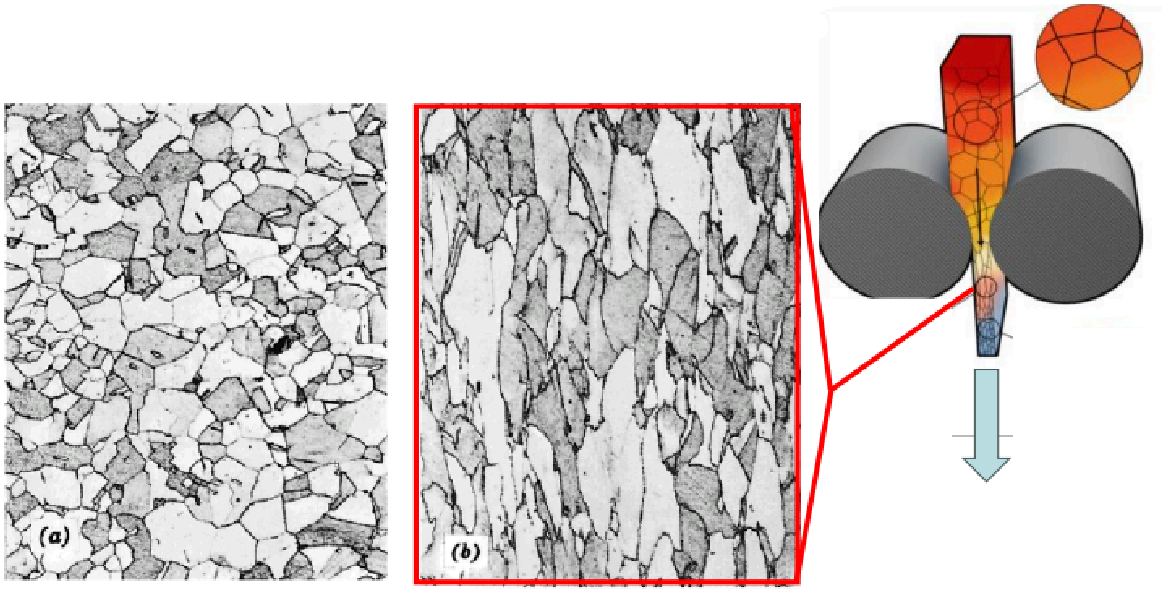


Work Hardening

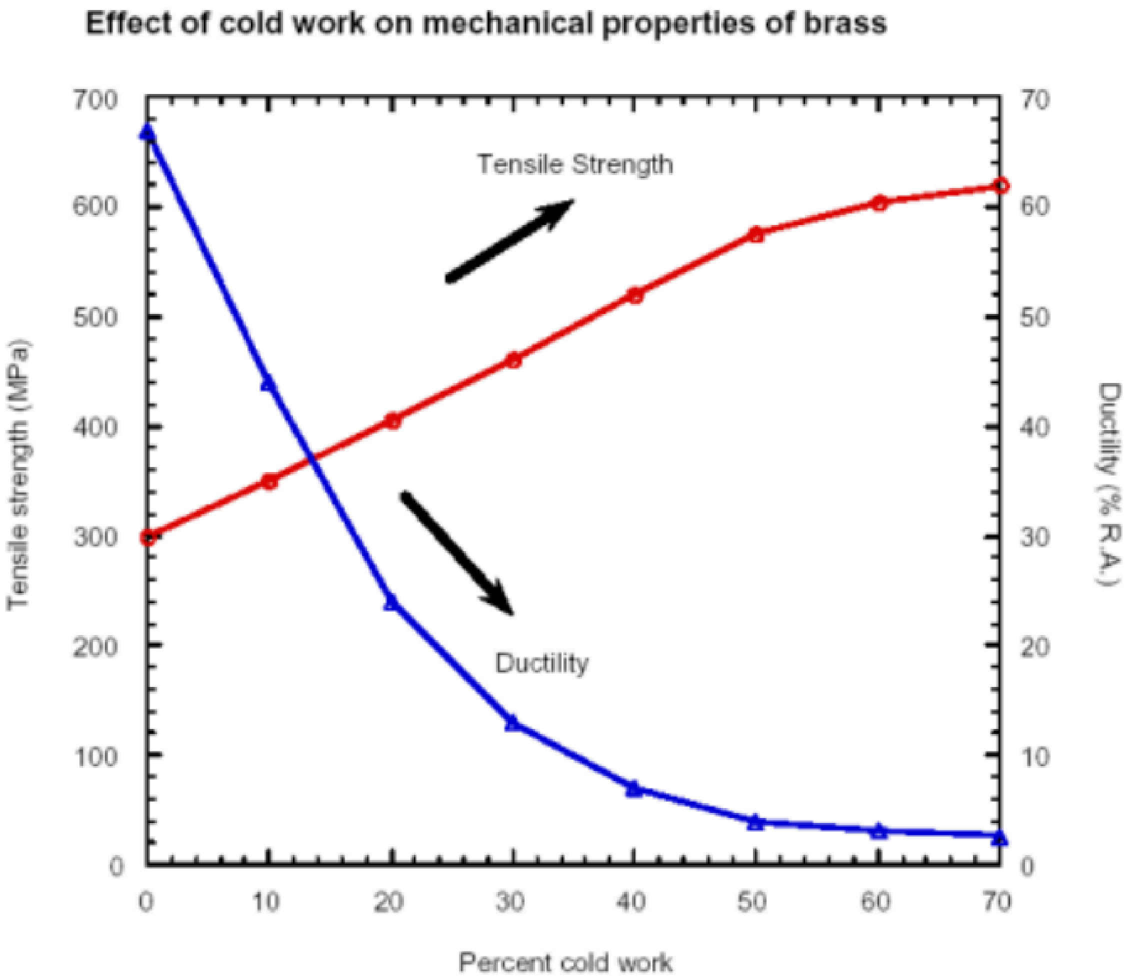
Work hardening (cold working is the process and work hardening is the result), or strain hardening, is the process of strengthening metal or polymer materials through plastic deformation (e.g., rolling, drawing, bending) below their recrystallization temperature.

This increases dislocation density, making further deformation more difficult, which boosts strength and hardness while decreasing ductility. It is common in steels, aluminium, and copper.

Work hardening will create “dislocation forests” which slow down further dislocations, therefore increasing strength of the material, but a drop in toughness and resilience.



before after



For stretching:

$$\%\text{CW} = \frac{A_0 - A_d}{A_0} \times 100\%$$

- A_0: Initial area of the cross-section
- A_d: Final area of the cross-section

For rolling:

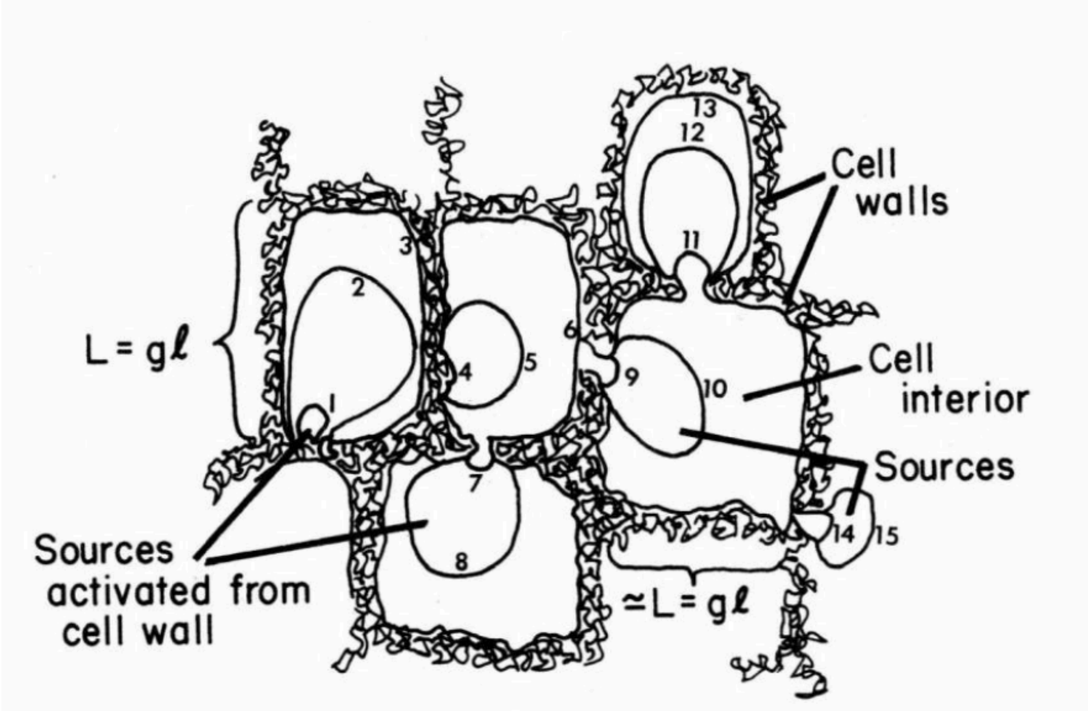
$$\%\text{CW} = \frac{D_0 - D_f}{D_0} \times 100\%$$

- D_0: Initial thickness
- D_f: Final thickness

By deforming, we create more dislocations via Frank-Read Dislocation Sources. The process is reversible via Technology of Metallic Materials/Treatment > Annealing.

	K, Mpa	n
Aluminum, 1100-0 Industrial purity	180	0.2
2024-T4	690	0.16
5052-0	210	0.13
6061-0	205	0.2
6061-T6	410	0.05
7075-0	400	0.17
Brass,60-39-1 Pb, annealed	800	0.33
70-30, annealed	895	0.49
85-15, cold-rolled	580	0.34
Bronze (phosphor), annealed	720	0.46
Cobalt-base alloy, heat-treated	2070	0.5
Copper, annealed	315	0.54
Molybdenum, annealed	725	0.13
Steel, low-carbon annealed	530	0.26
1045 hot-rolled	965	0.14
1112annealed	760	0.19
1112 cold-rolled	760	0.08
4135 annealed	1015	0.17
4135 cold-rolled	1100	0.14
4340 annealed	640	0.15
17-4 P-H annealed Precipitation hardening steel	1200	0.05
52100annealed	1450	0.07
302 stainless, annealed	1300	0.3
304 stainless, annealed	1275	0.45
410 stainless, annealed	960	0.1

When the dislocation density gets high enough, we can observe that they cannot exist randomly any more, since they repel each other via their stress fields. Therefore, we get the following 'cell' structure:



Dislocations will end up clumping in cell walls, where certain ones will act as Frank-Read Dislocation Sources. Inside the cell interiors, the material is relatively free of defects.

Ludwik-Hollomon Law

$$\sigma_T = K\varepsilon_T^n$$

- σ_T, ε_T: True stress and true strain
  - $\varepsilon_T = \ln\left(\frac{L_i}{L_0}\right)$
- K: Strength coefficient. This is the value of σ_T when $\varepsilon_T = 1.0$.
- n: Strain Hardening Exponent
  - $n_{\text{FCC}} \approx 0.5$
  - $n_{\text{BCC}} \approx 0.2$
  - $n_{\text{HCP}} \approx 0.05$

> This is an approximation for a stress-strain curve.

When $\varepsilon_T = \varepsilon_u = n$, we can predict failure (necking) of the material.

Taylor Equation

The Taylor Equation describes how much stronger a material gets as you deform it (cold work). The more dislocations ρ are created, the more they interfere, making the material harder.

$$\sigma_i = \alpha G b \sqrt{\rho}$$
$$\tau_{\text{flow}} = \tau_0 + k\sqrt{\rho}$$

- σ_i: The increase in yield strength
- α: A material constant (usually between 0.2 and 0.5)
- G: Shear modulus (How stiff the material is in shear)
- b: Burgers Vector (Magnitude of the lattice distortion caused by one dislocation)
- ρ: Dislocation density (lines of dislocation per unit area)
- τ_{flow}: Flow stress

Solid Solutions

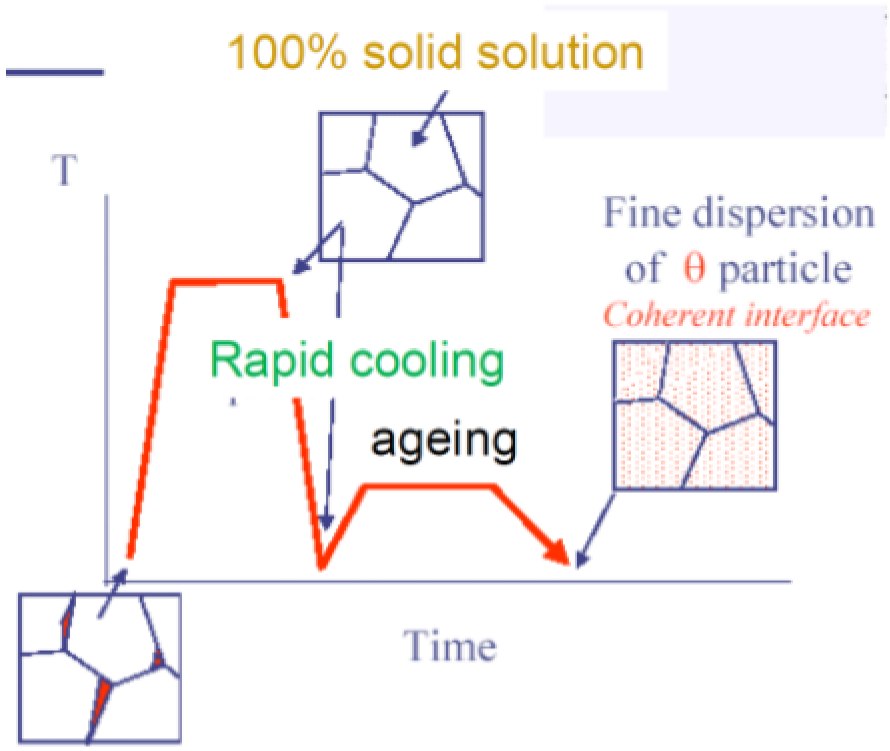
Ageing

The Orowan Loop

When second phases are present in a metal in the form of hard precipitate particles, dislocations need to “squeeze” through or around them to travel along the material. This leads to a harder material.

$$\sigma_{or} \approx \frac{Gb}{L}$$
$$\tau_{or} \approx \frac{G\,b}{2d}\sqrt{f}$$
$$\sigma \approx 3\tau$$

- G: Shear modulus (How stiff the material is in shear)
- b: Burgers Vector (Magnitude of the lattice distortion caused by one dislocation)
- L: Inter-particle spacing (distance between precipitates)
- σ, τ: Tensile and shear stresses
- d: Precipitate particle diameter
- f: volume fraction of precipitate



Via Technology of Metallic Materials/Treatment > Quenching the material, and warming it to a lower temperature than originally, we can then wait and the particles in the material will re-arrange (We therefore want the temperature just high enough to allow movement of particles).

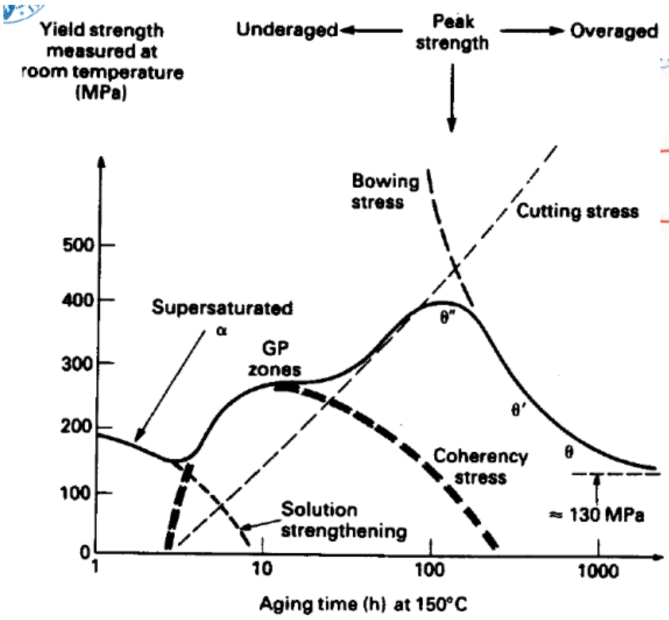
There are three main types of ageing results:

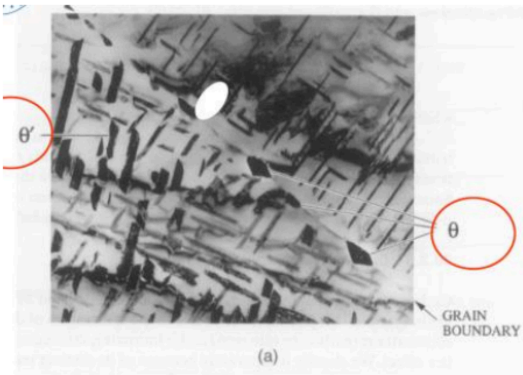
- Under-ageing: Impurities are very small, meaning that L (Orowan loop equation) is small, leading to a very strong but brittle material.
- Over-ageing: Impurities grow too large and dislocations move very freely, easily creating Orowan Loops around precipitates.
- In between the two, we have a point where we can achieve a good balance between ductility and strength.

Stages in the formation of the equilibrium precipitate θ phase (Ordered from the highest energy to lowest):

1. Supersaturated α solution solid (there is more solute than can actually be stored)
2. GP1 (Guinier-Preston) zones (Coherent precipitate, tiny precipitates start to form)
3. GP2 (Or phase θ'') zones (Coherent, ordered layers: Often max hardness occurs here or in the transition to the next phase)
4. Phase θ' (semi-coherent)
5. Phase $\theta \implies$ Equilibrium (incoherent, weak, over-aged, BCT structure in $CuAl_2$, while Al is FCC)

> - The material composed of aluminium matrix and $CuAl_2$ precipitate is called duralumin.





Precipitation Hardening

Sometimes, precipitates forming on grain boundaries can actually make the material more ductile. GBs act as attractors for impurities because of their high energy state, and therefore clean up the inner parts of grains, forming an almost pure second phase. The presence of two pure second phases makes the material more ductile compared to an impure material with one phase.

Solid Solution Strengthening (Size Misfit)

When a solid solution is formed between atoms with very different sizes, the material is in tension in some areas and in compression in others, creating a stress field that blocks dislocations. The increase in strength is approximately proportional to the size difference (As a percentage of the host's volume):

$$\sigma_{\text{Solid Solution}} \approx \text{const.} \frac{\Delta\Omega}{\Omega}$$

- $\Delta\Omega$: Difference in atomic volume between solute and solvent
- Ω: Atomic volume of host matrix

Solid solutions increase strength but slightly decreases ductility.

$$\Delta\tau \propto \sqrt{c}$$

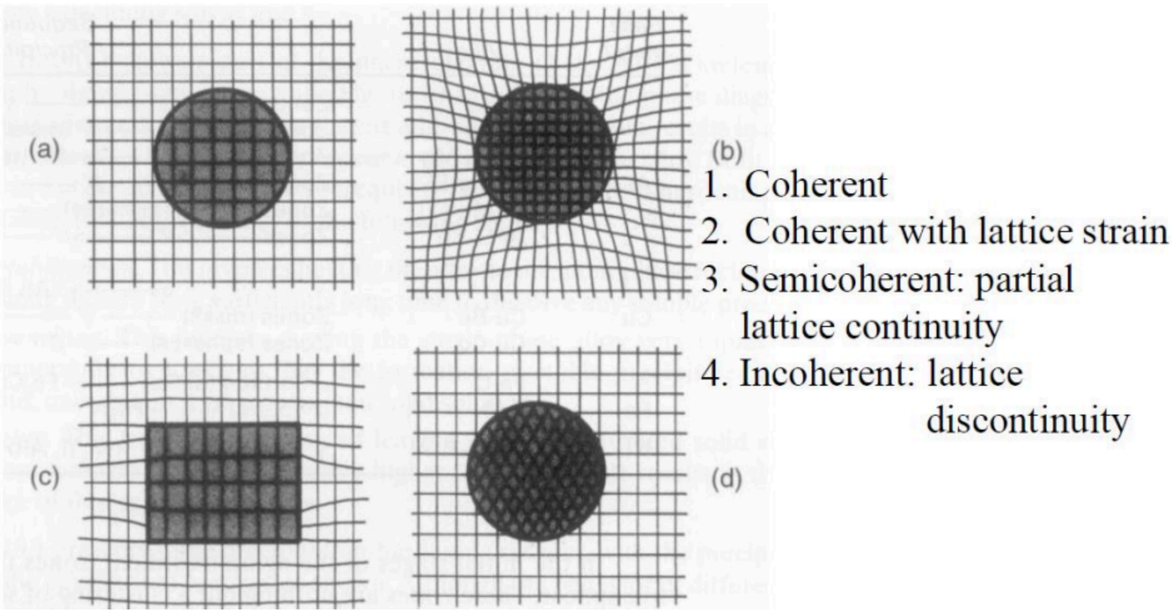
> Increase of internal shear stress $\Delta\tau$ is proportional to the square root of the concentration c of the added atoms, meaning that you get diminishing marginal returns as you add more solute.

Coherency Strain

When a precipitate does not interrupt the crystal structure (For example using a BCC solute in a BCC solvent with similar atomic sizes) and direction, we can consider it a coherent structure. Since the alignment is not perfect, there is a slight misfit in spacing, but the effect is much less than if the lattice structure was interrupted.

$$\sigma_{\text{coherency}} \approx \frac{\Delta a}{a} E = \varepsilon_{\text{misfit}} E$$

- a: Lattice parameter (grid size) of the matrix
- Δa: Difference between precipitate's grid size and matrix's grid size
- $\varepsilon_{\text{misfit}}$: Lattice misfit strain (How much this second phase strains the matrix)
- E: Young's Modulus



Annealing

Annealing is the process of warming up a metal close (but not over) T_m in order to remove dislocations. This increases ductility.

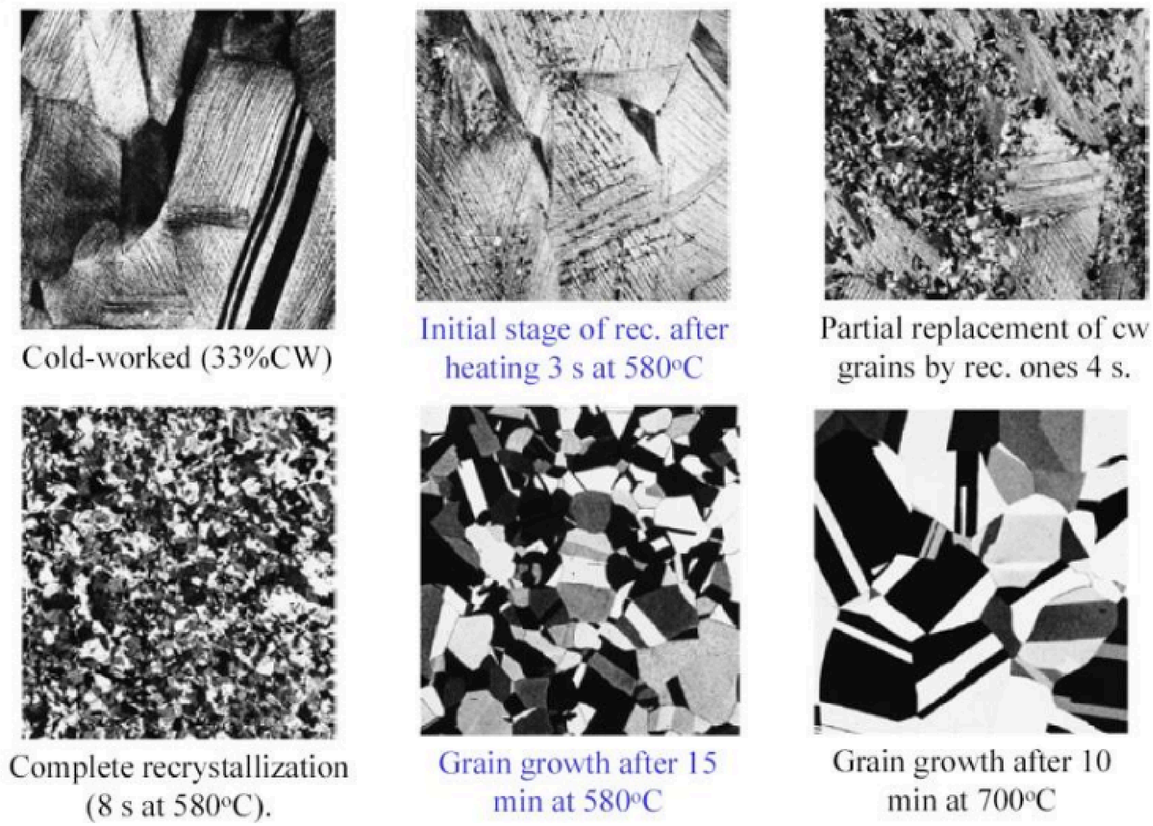
Strengthening by Hard Phase From Phase Transformation

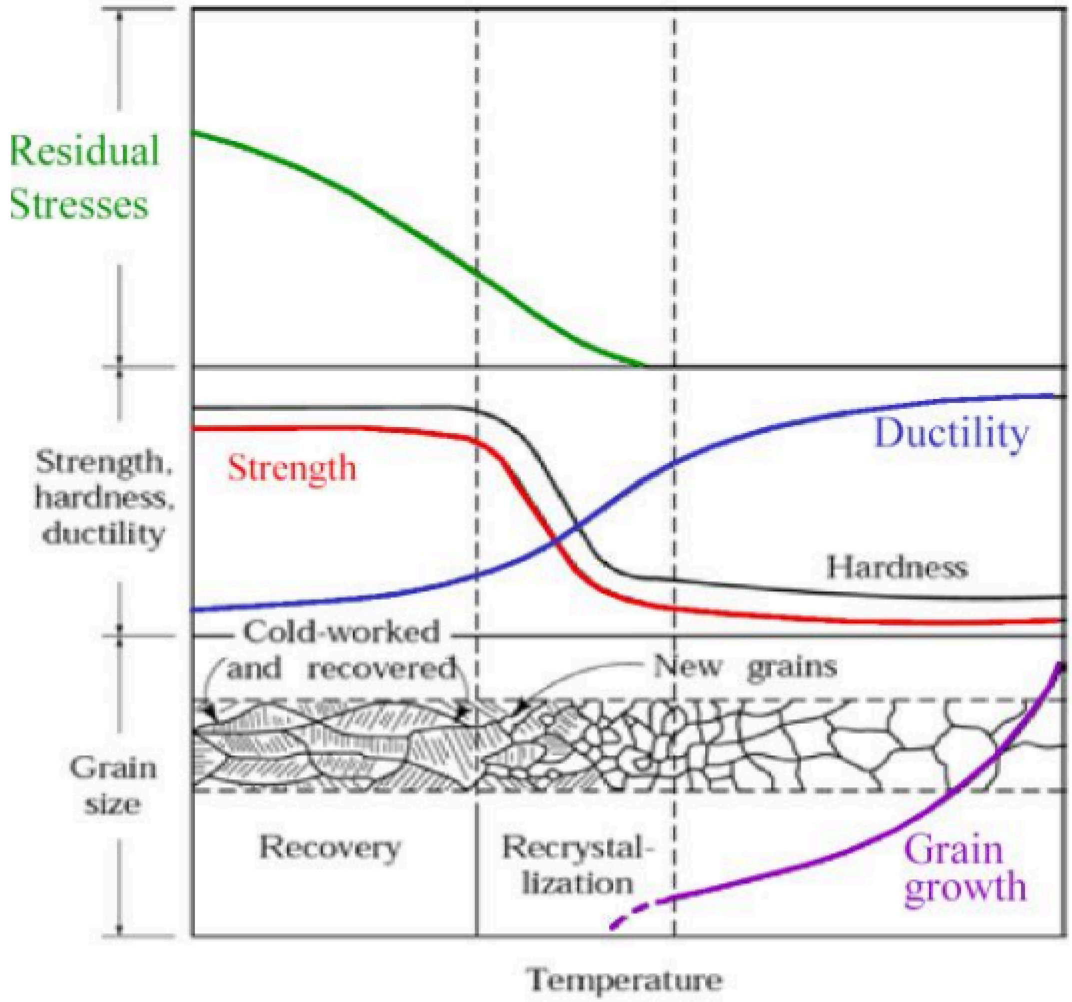
When a material cools down at eutectoid temperature ($723 - 727^{\circ}C, 0.76\,wt\%$ carbon austenite transforming into pearlite for steel) and therefore creates bands of different phases (For pearlite it is cementite and ferrite).

If steel is quenched, it will produce martensite instead, which is harder but more brittle than pearlite since it is in a meta-stable state.

Hot Rolling

Hot rolling is the process of rolling a metal under high temperatures (above re-crystallization temperatures) to allow for internal deformation forces to dissolve and to introduce dynamic recrystallization (constant formation of strain-free grains.).




Residual Stresses
Strength, hardness, ductility
Strength
Ductility
Hardness
Cold-worked and recovered
New grains
Grain size
Recovery
Recrystal-lization
Grain growth
Temperature