AS3020: Aerospace Structures

Module 2: Aircraft Materials

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Dept. of Aerospace Engg., IIT-Madras, Chennai

August 15, 2024

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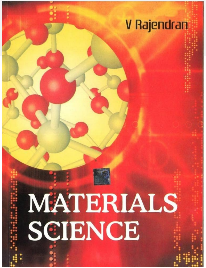
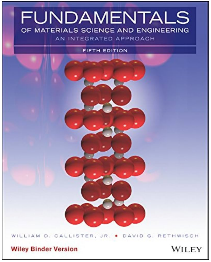
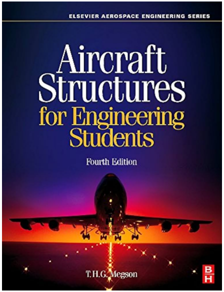


Chapters 2, 9, 11 in Rajendran [1]



Chapters 3, 5, 9-11 in Jr and Rethwisch [2]



Chapters 11, 15 in Megson [3]

1. Understanding the Stress-Strain Curve

The Uniaxial Tensile Test

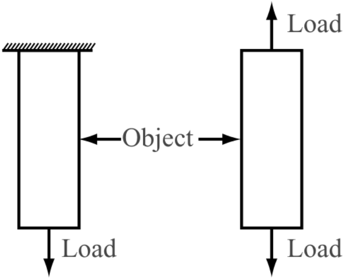


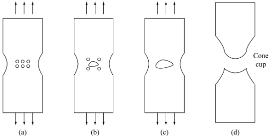
Figure from [1]

1. Understanding the Stress-Strain Curve

Terminology

1. Proportionality Limit;
2. Elastic Limit;
3. Yield Point;
4. Ultimate Strength;
5. Fracture Point;
6. Elongation at Failure;

Ductile Fracture



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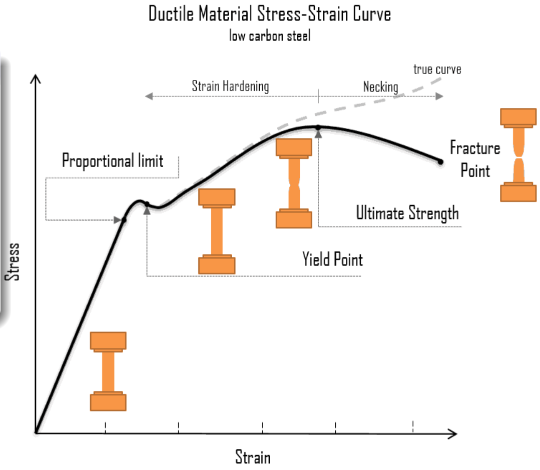

Figure from [4]

1. Understanding the Stress-Strain Curve

Terminology

① Proportionality Limit;

② Elastic Limit;

③ Yield Point;

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⑤ Fracture Point;

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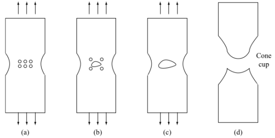

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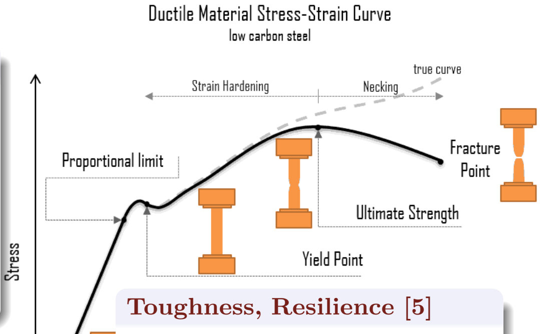
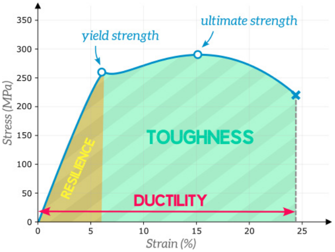


Ductile Material Stress-Strain Curve

low carbon steel

Toughness, Resilience [5]



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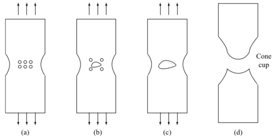
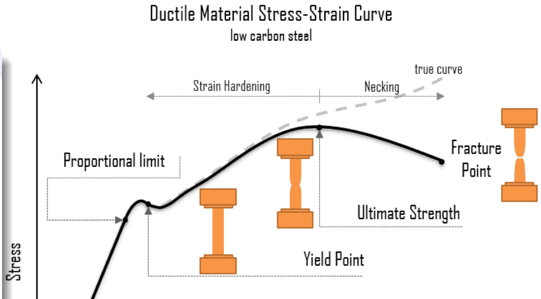


Figure from [1]


Ductile Material Stress-Strain Curve

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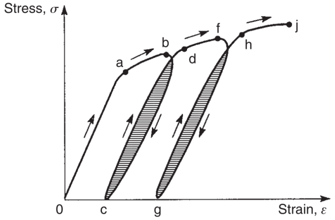
Strain Hardening [3]



1. Understanding the Stress-Strain Curve

Terminology

1. Proportionality Limit;
2. Elastic Limit;
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Classifications

- Brittle, Ductile
- Non-dissipative: Elastic, Hyper-elastic
- Dissipative: Elastic-perfectly plastic, Bi-linear elastoplastic, etc.

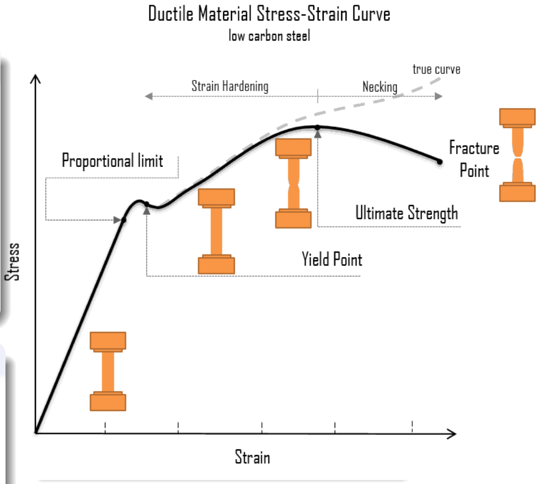

Figure from [4]

1.1. Failure Mechanisms: Fracture

1. Understanding the Stress-Strain Curve

“Griffith Theory” of brittle fracture

- Theoretical fracture stress $\sim \frac{E}{5} - \frac{E}{30}$ (steel $\sim \frac{E}{1000}$)
- Fracture occurs when $E_{strain} = E_{surface}$
- Crack propagates when $\frac{dE_{strain}}{dL} = \frac{dE_{surface}}{dL}$

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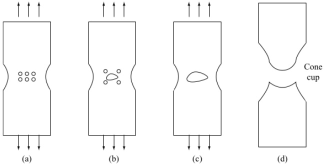

Ductile Fracture [1]

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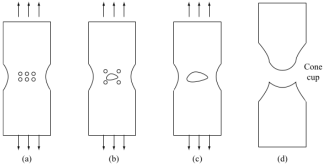
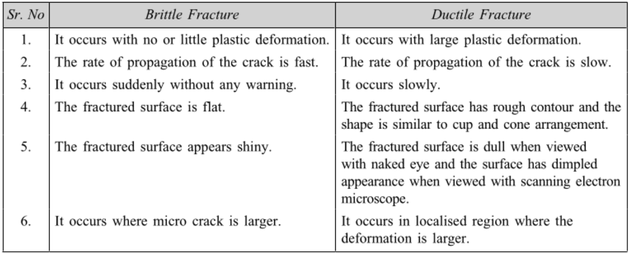


Ductile Fracture [1]



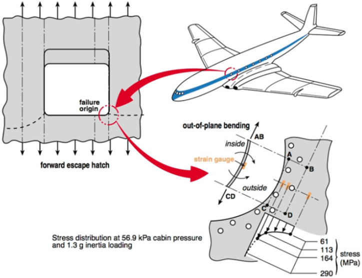
Sr. No	*Brittle Fracture*	*Ductile Fracture*
1.	It occurs with no or little plastic deformation.	It occurs with large plastic deformation.
2.	The rate of propagation of the crack is fast.	The rate of propagation of the crack is slow.
3.	It occurs suddenly without any warning.	It occurs slowly.
4.	The fractured surface is flat.	The fractured surface has rough contour and the shape is similar to cup and cone arrangement.
5.	The fractured surface appears shiny.	The fractured surface is dull when viewed with naked eye and the surface has dimpled appearance when viewed with scanning electron microscope.
6.	It occurs where micro crack is larger.	It occurs in localised region where the deformation is larger.

Ductile vs Brittle Fracture [1]

1.1. Failure Mechanisms: Fatigue

1. Understanding the Stress-Strain Curve

..over 90% of mechanical failures are caused because of metal fatigue [6]...



The De Havilland Comet [7] [lecture]

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1. Understanding the Stress-Strain Curve

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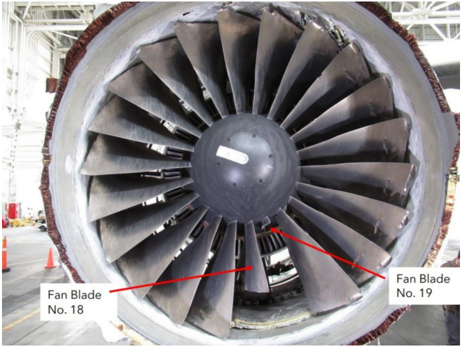
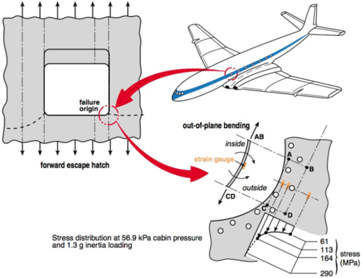


A more recent example (2021 United Airlines Boeing 777) [8]. [video]



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1. Understanding the Stress-Strain Curve

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A more recent exam
Boeing 7

Fatigue Crack Propagation: Beech Marks

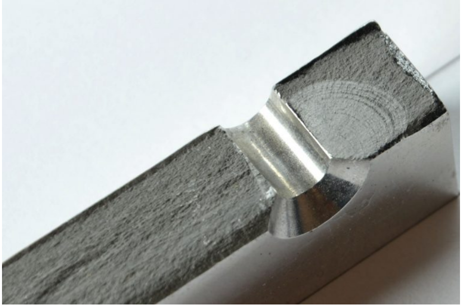
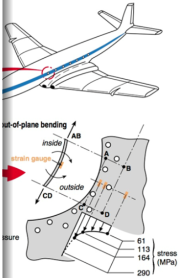


Figure from [9]



Comet [7] [*lecture*]

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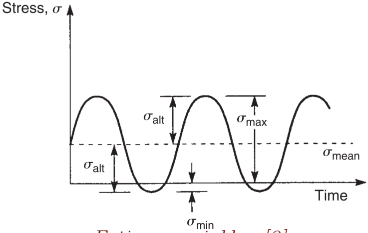
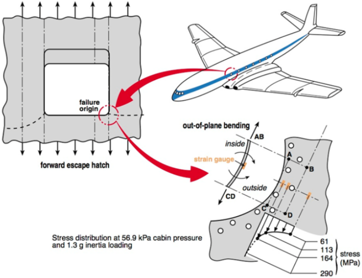


Fatigue variables [3]



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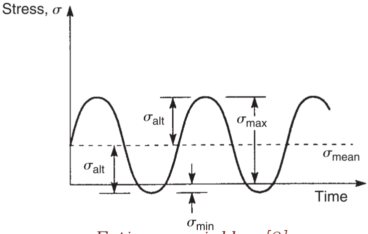

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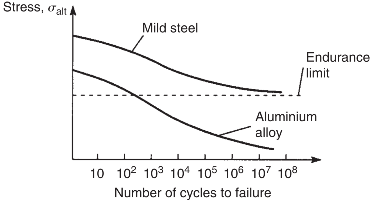
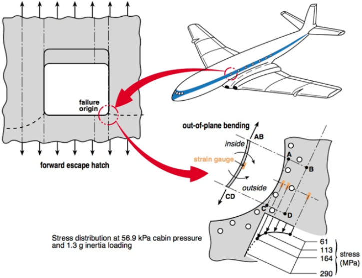


The S-n Diagram [3]



Stress distribution at 56.9 kPa cabin pressure and 1.3 g inertia loading

The De Havilland Comet [7] [lecture]

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S-N Curves for Common Metals [2]

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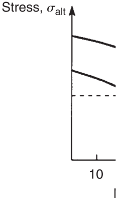

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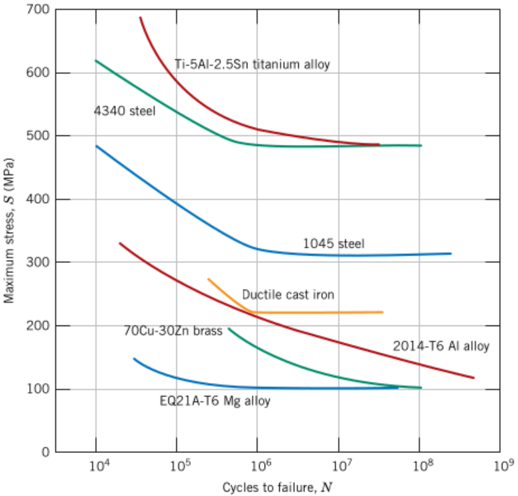
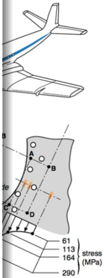


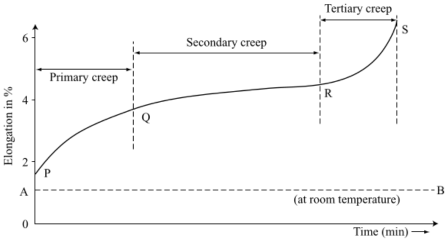


7] *[lecture]*

1.1. Failure Mechanisms: Creep

1. Understanding the Stress-Strain Curve

- Constant stress applied over a long time
- High temperature phenomenon ($>\sim 30 - 45\%$ of melting point)



Creep curve [1]

1.1. Failure Mechanisms: Creep

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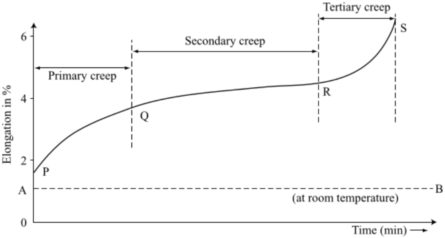
Examples

Zinc Melts at ~ 420° C ($T_{creep} \sim 145°$ C)



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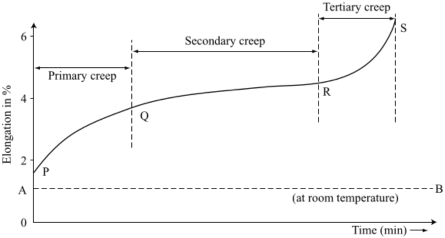

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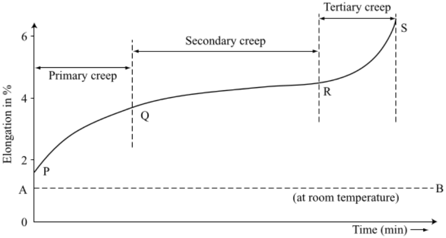
Titanium $T_{creep} \sim 650°$ C



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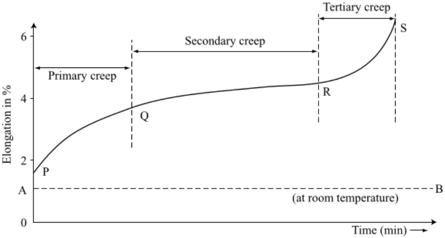

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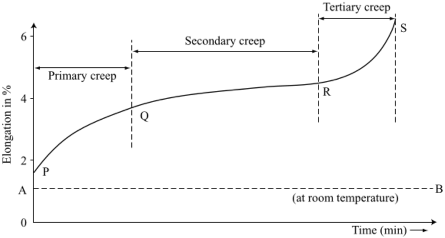
Steel, AA	$T_{creep} \sim 400^\circ$ C



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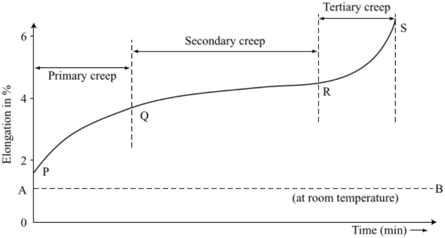
Nickel	Melts at ~ 900° C



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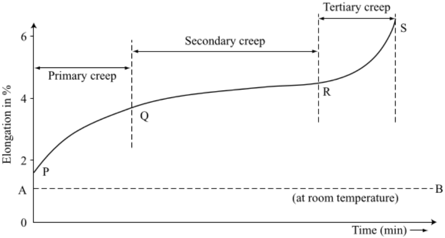
Nickel	Melts at $\sim 900^\circ$ C **Super-Alloys**



Creep curve [1]

- Fundamentally related to grain dislocation movement
- Single crystal solutions: **Super-Alloys**: $T_{creep} > 1000^\circ$ C

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1. Understanding the Stress-Strain Curve

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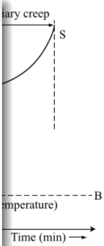
Steel

Nickel Melts at ~ 900° C
Super-Alloys



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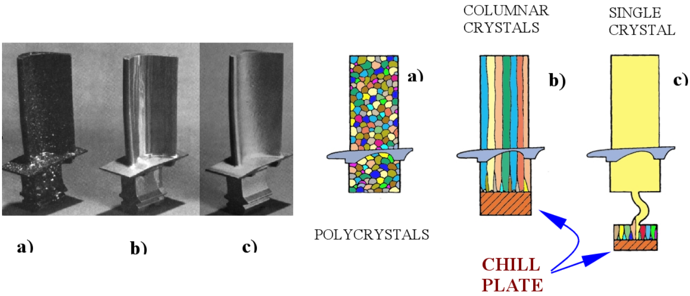
Super-Alloys: $T_{creep} > 1000°$ C

Single Crystal Casting [10]



DMRL developed this capability in 2021 [11]

- $T_{melting} \uparrow \implies E_{Young} \uparrow, d_{grain} \uparrow \impliedby$ creep resistance $\uparrow$

2. Materials Used in Aircrafts

2.1. Metallic Alloys

Main Considerations

- Strength-to-weight ratio;
- Stiffness, Strength;
- Toughness, resistance to fast crack propagation;
- Fatigue life;
- Thermal behavior ("Superalloys")

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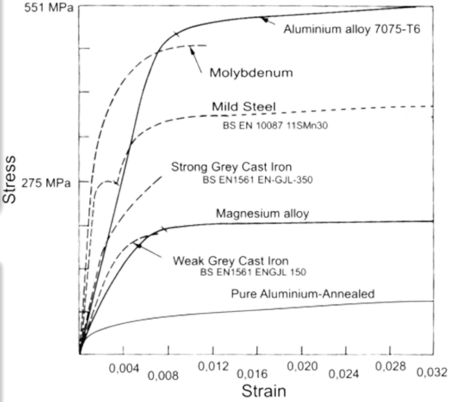
Metallic Alloys/"Solutions"

Fe Alloys C, Ni, Co, Mo, Ti, Mn, Si, S, P (C ↑, Ductility↓)



Stress strain curve of common metals [12]

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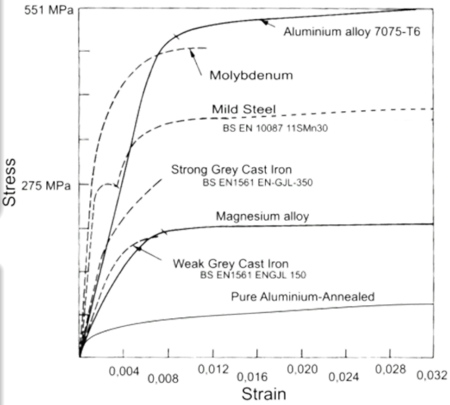
Al Alloys Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti



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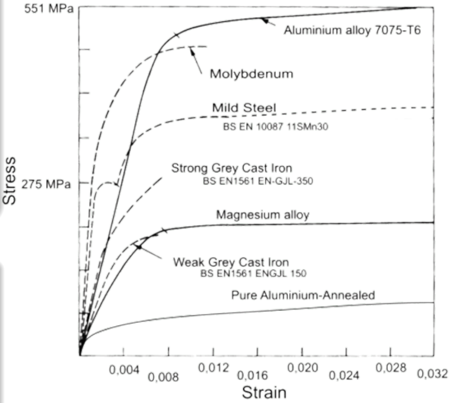
Al Alloys	Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti
Ti Alloys	Al, V



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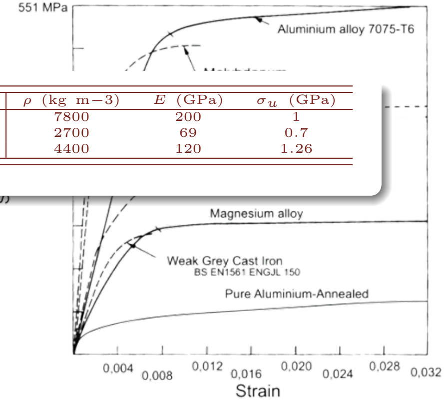
- Thermal behavior (“Superalloy)

Alloy	ρ (kg m-3)	E (GPa)	σ_u (GPa)
Fe	7800	200	1
Al	2700	69	0.7
Ti	4400	120	1.26

Metallic Alloys/“Solutions”

Fe Alloys	C, Ni, Co, Mo, Ti, Mn, Si, S, P (C ↑, Ductility↓)
Al Alloys	Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti
Ti Alloys	Al, V
Ni Superalloys	Cr, Al



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2.1. Metallic Alloys

Main Considerations

- Strength-to-weight ratio;
- Stiffness,
- Toughne
  propagat
- Fatigue l
- Thermal

Metallic All

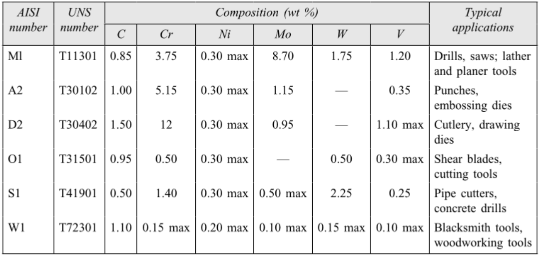
Fe Alloys

Al Alloys Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti

Ti Alloys Al, V

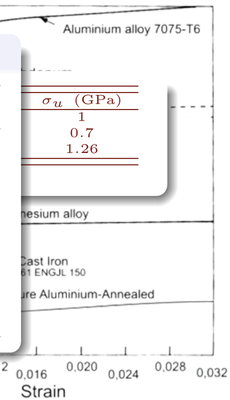
Ni Superalloys Cr, Al

Steel Alloys [1]



AISI number	*UNS number*	*Composition (wt %)*						*Typical applications*
		C	*Cr*	*Ni*	*Mo*	*W*	*V*	
Ml	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lather and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, woodworking tools

σ_u (GPa)
1
0.7
1.26

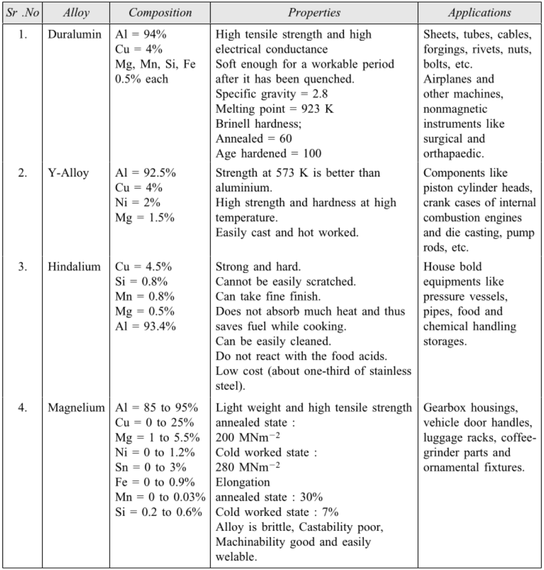


Stress strain curve of common metals [12]

2. Materials Used in Aircrafts

2.1. Metallic Allo

Aluminum Alloys [1]



Sr .No	Alloy	Composition	Properties	Applications
1.	Duralumin	Al = 94% Cu = 4% Mg, Mn, Si, Fe 0.5% each	High tensile strength and high electrical conductance Soft enough for a workable period after it has been quenched. Specific gravity = 2.8 Melting point = 923 K Brinell hardness; Annealed = 60 Age hardened = 100	Sheets, tubes, cables, forgings, rivets, nuts, bolts, etc. Airplanes and other machines, nonmagnetic instruments like surgical and orthapaedic.
2.	Y-Alloy	Al = 92.5% Cu = 4% Ni = 2% Mg = 1.5%	Strength at 573 K is better than aluminium. High strength and hardness at high temperature. Easily cast and hot worked.	Components like piston cylinder heads, crank cases of internal combustion engines and die casting, pump rods, etc.
3.	Hindalium	Cu = 4.5% Si = 0.8% Mn = 0.8% Mg = 0.5% Al = 93.4%	Strong and hard. Cannot be easily scratched. Can take fine finish. Does not absorb much heat and thus saves fuel while cooking. Can be easily cleaned. Do not react with the food acids. Low cost (about one-third of stainless steel).	House bold equipments like pressure vessels, pipes, food and chemical handling storages.
4.	Magnelium	Al = 85 to 95% Cu = 0 to 25% Mg = 1 to 5.5% Ni = 0 to 1.2% Sn = 0 to 3% Fe = 0 to 0.9% Mn = 0 to 0.03% Si = 0.2 to 0.6%	Light weight and high tensile strength annealed state : 200 MNm^{-2} Cold worked state : 280 MNm^{-2} Elongation annealed state : 30% Cold worked state : 7% Alloy is brittle, Castability poor, Machinability good and easily welable.	Gearbox housings, vehicle door handles, luggage racks, coffee-grinder parts and ornamental fixtures.

Main Consi

- Strength
- Stiffness,
- Toughne propagat
- Fatigue l
- Thermal

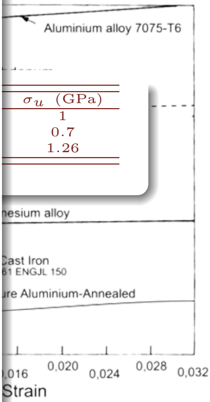
Metallic All

Fe Alloys

Al Alloys

Ti Alloys

Ni Superall



σ_u (GPa)
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0.7
1.26

common metals [12]

2. Materials Used in Aircrafts

2.1. Metallic Allo

Main Consi

- Strength
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Metallic All

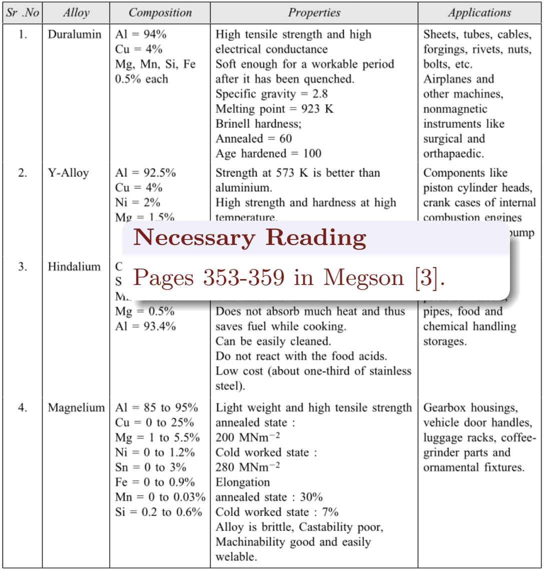
Fe Alloys

Al Alloys

Ti Alloys

Ni Superall

Aluminum Alloys [1]



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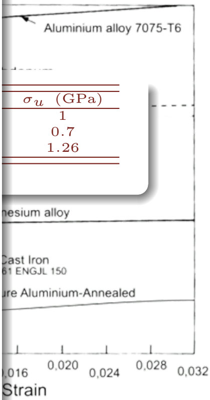
Necessary Reading

Pages 353-359 in Megson [3].

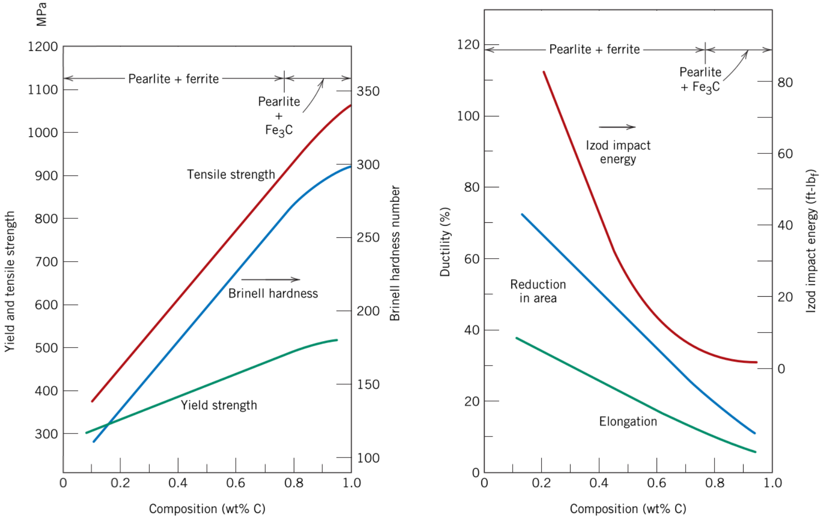


σ_u (GPa)
1
0.7
1.26

common metals [12]

Mechanical Behavior of Steel

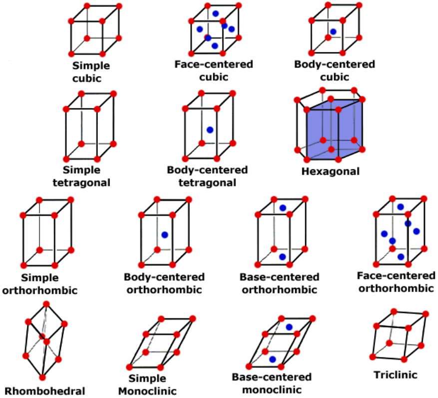
2. Materials Used in Aircrafts



As Carbon Content↑, Strength↑, but Ductility↓ [2]

3. Introduction to Material Science

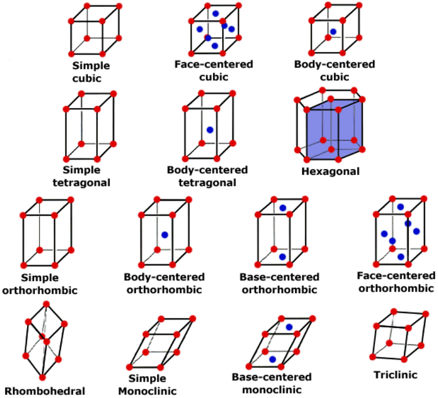
3.1. Metallic Crystal Structure



Types of crystal structures in metals [13]

3. Introduction to Material Science

3.1. Metallic Crystal Structure



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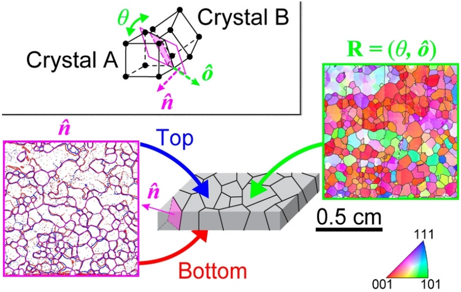
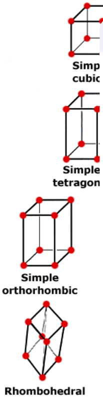


Crystal and Grain Structures [14].
"Polycrystallinity"

3. Introduction to Material Science

3.1. Metallic Crystal Structure



Dislocations and their "motion" under load

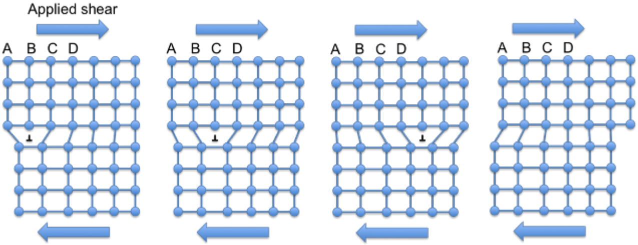
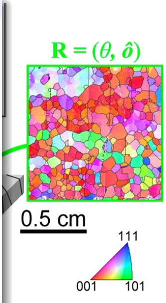


Figure from [13]



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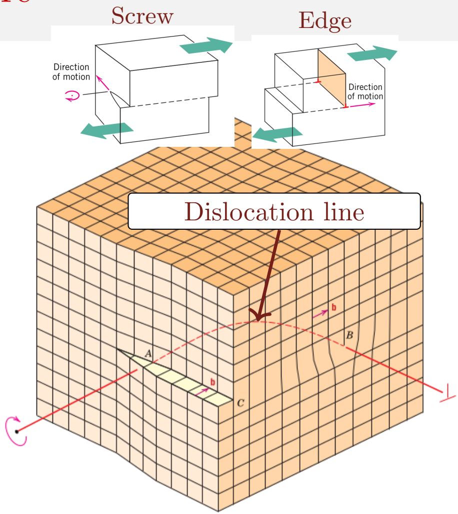
Types of crystal structures in metals [13]

3.1. Metallic Crystal Structure

3. Introduction to Material Science

- The ability of a metal to deform plastically depends on the ability of its disloications to *move.*
- Restricting or hindering dislocation motion renders a material harder and stronger.



Figures from [2]

3.1. Metallic Crystal Structure

3. Introduction to Material Science

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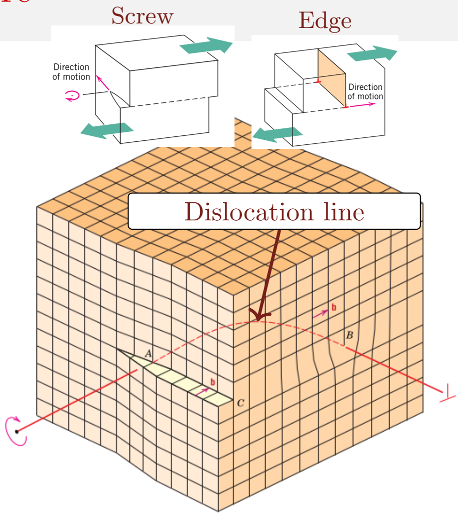
Material Strengthening

1. Grain size reduction
2. Solid-solution (alloys)
3. Strain hardening



Figures from [2]

3.1. Metallic Crystal Structure

3. Introduction

Screw

Grain Size Reduction

- Grain boundaries act as barriers to dislocation movement

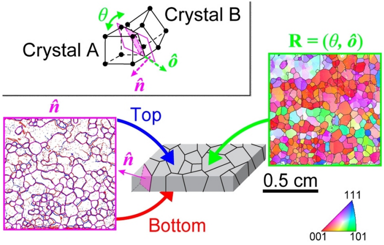


Figure from [14]

- **Hall-Petch Equation**:

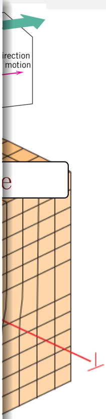
$$\sigma_y = \sigma_0 + k_y d^{-\frac{1}{2}}$$

- Controlled by heat-treatment (rate of solidification, etc.)

- The a plastic of its
- Restri disloc mater

Material S

1. Grain
2. Solid-s
3. Strain

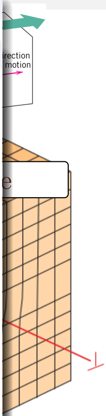


3.1. Metallic Crystal Structure

3. Introduction

Screw

Ed



- The a
  plastic
  of its
- Restri
  disloc
  mater

Material S

1. Grain
2. Solid-s
3. Strain

Grain Size Reduction

Solid-Solution Alloying

- Substitutional/interstitial impurity addition
- Impurities redistribute lattice strains

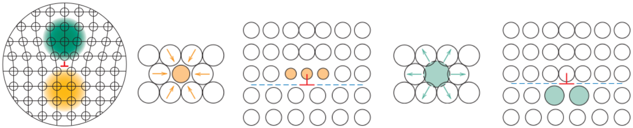


Figure from [2]

- Solutes have a tendency to distribute around imperfections in host lattice
- Greater stress necessary for dislocation movement $\Longrightarrow$ Greater strength and hardness

- Controlled by heat-treatment (rate of solidification, etc.)

3.1. Me

3. Introduction

Strain/Work Hardening aka Cold Working

- Increased yield stress with plastic deformation
- The “price” that we pay is reduced ductility

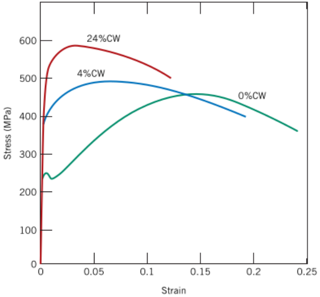


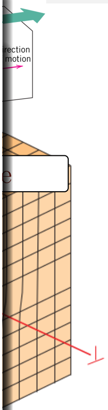
Figure from [2]

- As plastic work is done, dislocations increase in size/move closer. It takes higher stress to *move* bigger/more numerous dislocations.
- *Annealing* undoes this.

- The a
  plastic
  of its
- Restri
  disloca
  mater

Material S

1. Grain
2. Solid-s
3. Strain



3.2. Phase Diagrams

3. Introduction to Material Science

Mechanical properties are a direct consequence of microstructures, which are direct consequences of thermal histories.

3.2. Phase Diagrams

3. Introduction to Material Science

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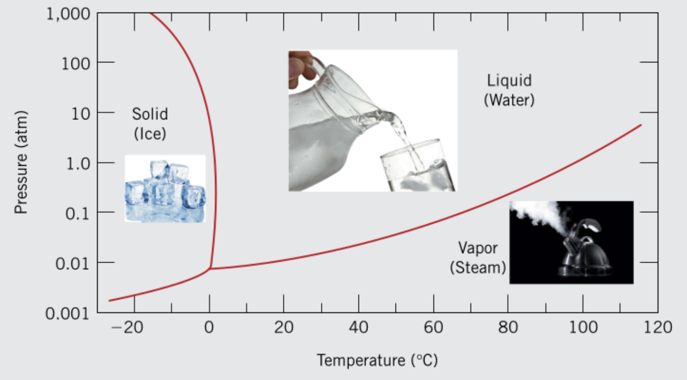
What is a phase diagram? [2]



3.2. Phase Diagrams

3. Introduction to Material Science

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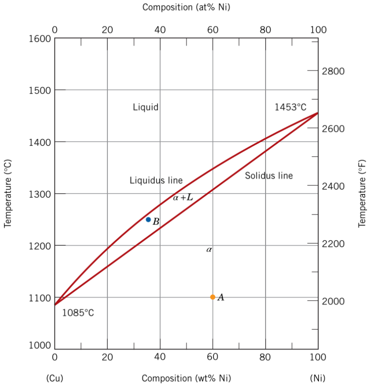
The Copper-Nickel Phase Diagram [2]

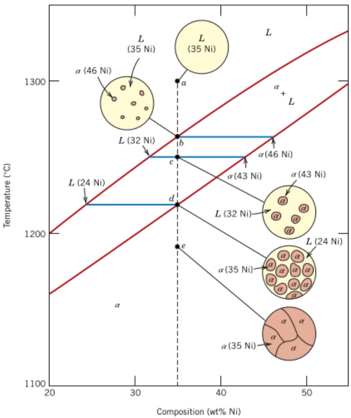


3.2. Phase Diagrams

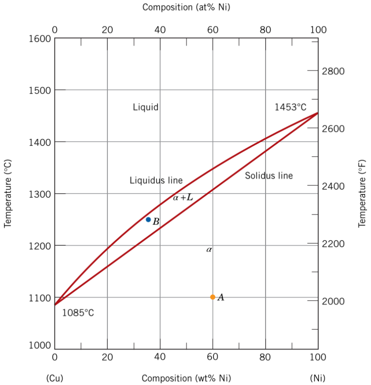
3. Introduction to Material Science

Mechanical properties are a direct consequence of microstructures, which are direct consequences of thermal histories.

Equilibrium Cooling [2]



The Copper-Nickel Phase Diagram [2]

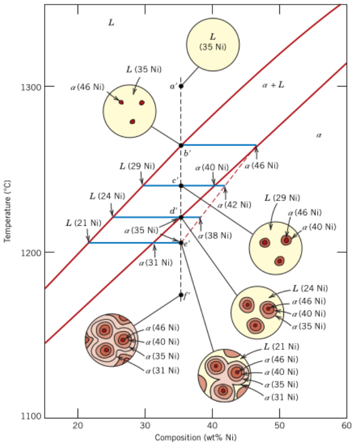


3.2. Phase Diagrams

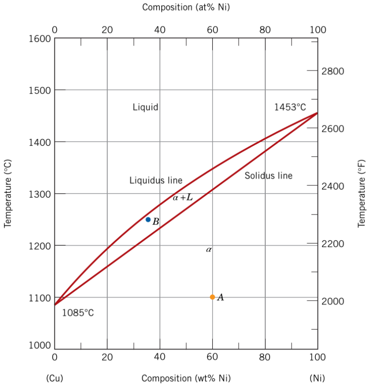
3. Introduction to Material Science

Mechanical properties are a direct consequence of microstructures, which are direct consequences of thermal histories.

Non-Equilibrium Cooling [2]



The Copper-Nickel Phase Diagram [2]



3.2. Phase Diagrams

3. Introduction to Material Science

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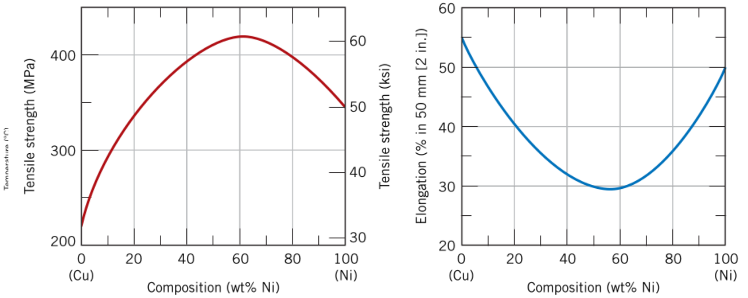
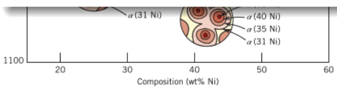
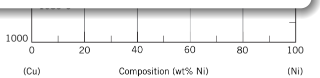
Non-Equilibrium Cooling [2]

The Copper-Nickel Phase

Mechanical Ramifications [2]



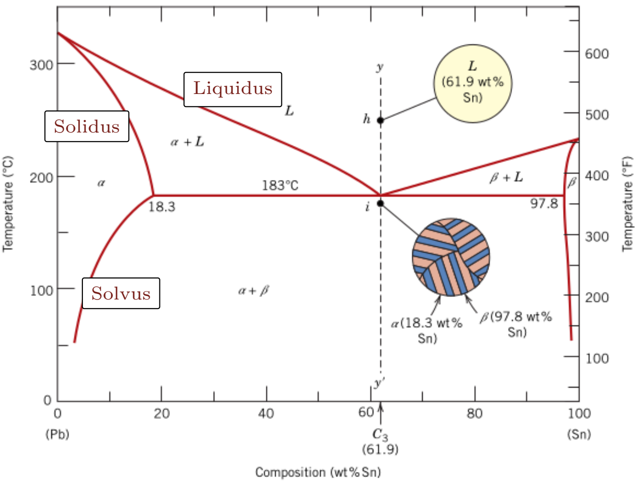




3.2. Phase Diagrams: Eutectic Systems

3. Introduction to Material Science

The Lead-Tin System [2]



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3. Introduction to Material Science

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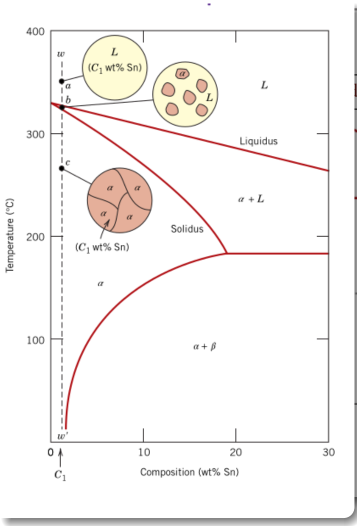

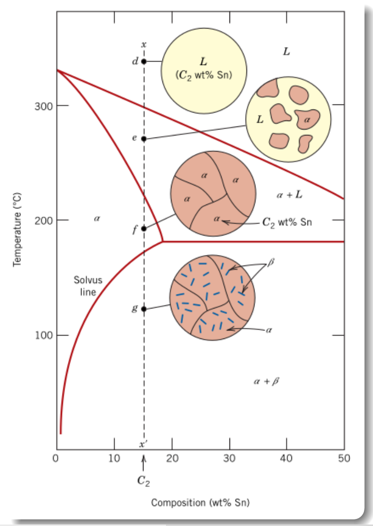

3.2. Phase Diagrams: Eutectic Systems

3. Introduction to Material Science

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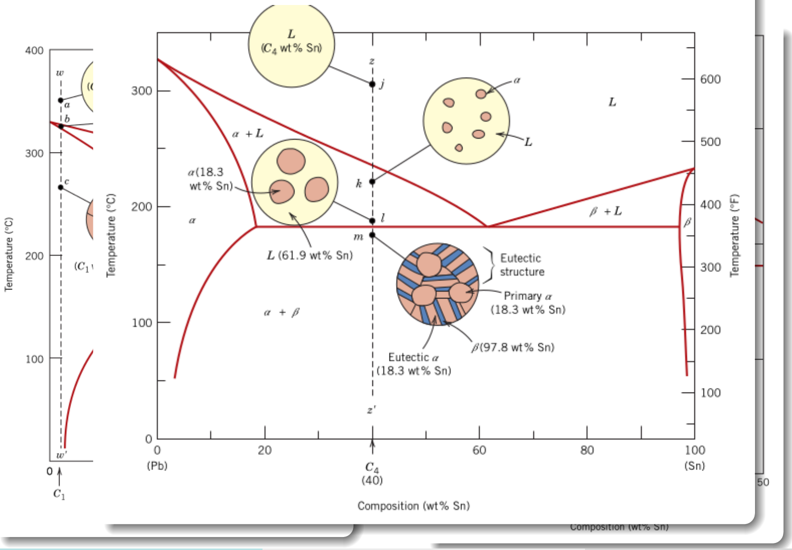

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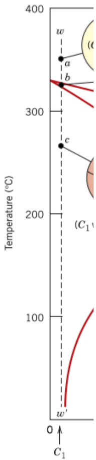
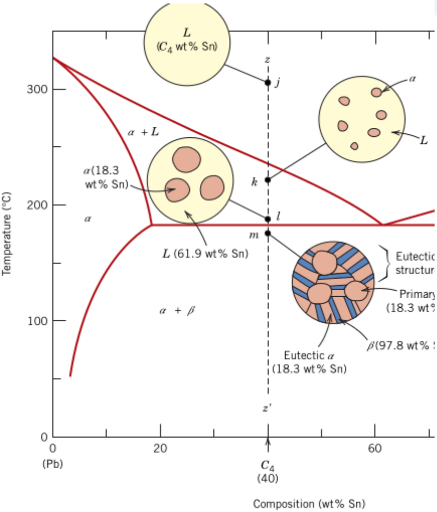
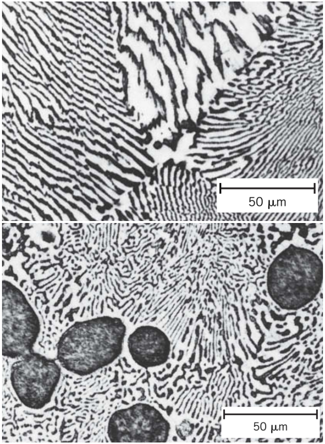
3. Introduction to Material Science



The Lead-Tin System [2]



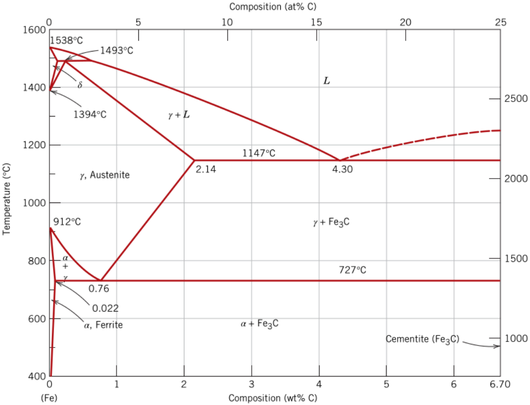
Some Pictures [2]

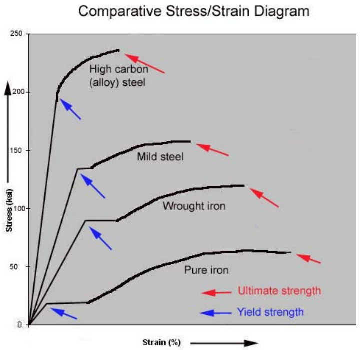


3.2. Phase Diagrams

3. Introduction to Material Science

The Iron Carbon System [2]

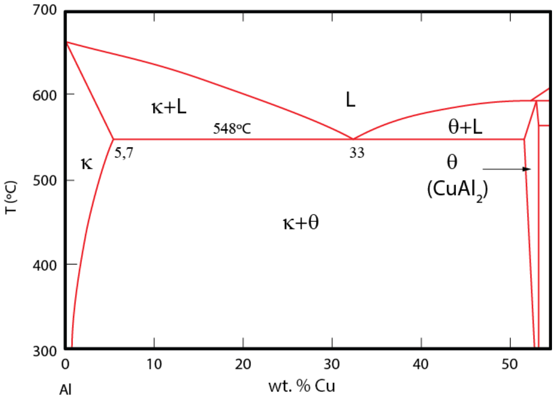


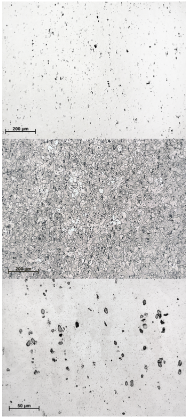


3.2. Phase Diagrams

3. Introduction to Material Science

The Al-Cu-Mg System (2024 AA) [15]

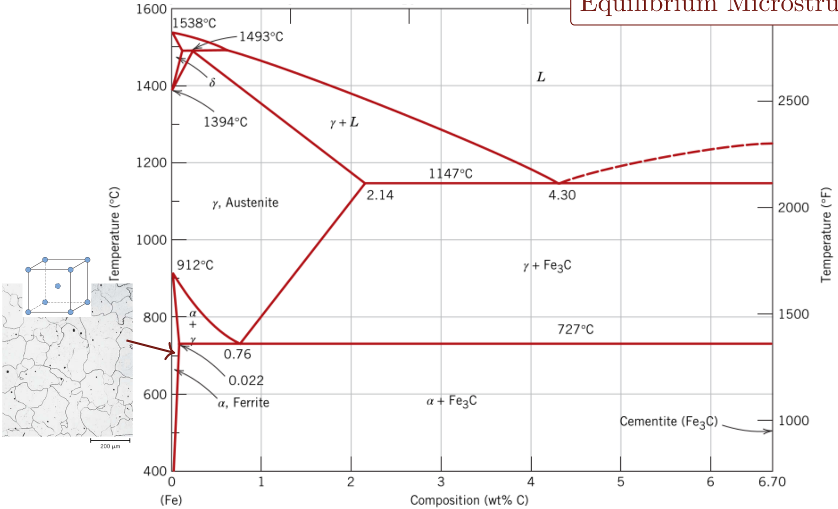




3.2. Phase Diagrams: The Iron-Carbon System [2]

3. Introduction to Material Science

Equilibrium Microstructure



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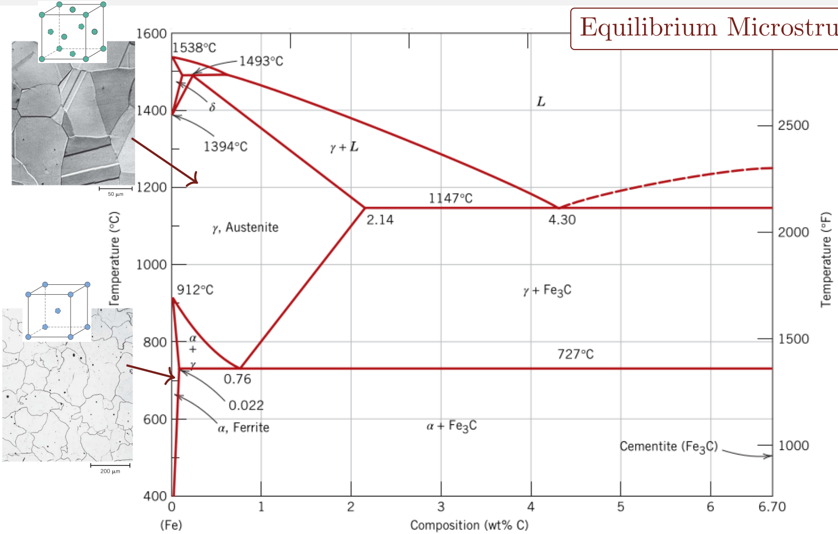
3. Introduction to Material Science

Equilibrium Microstructure



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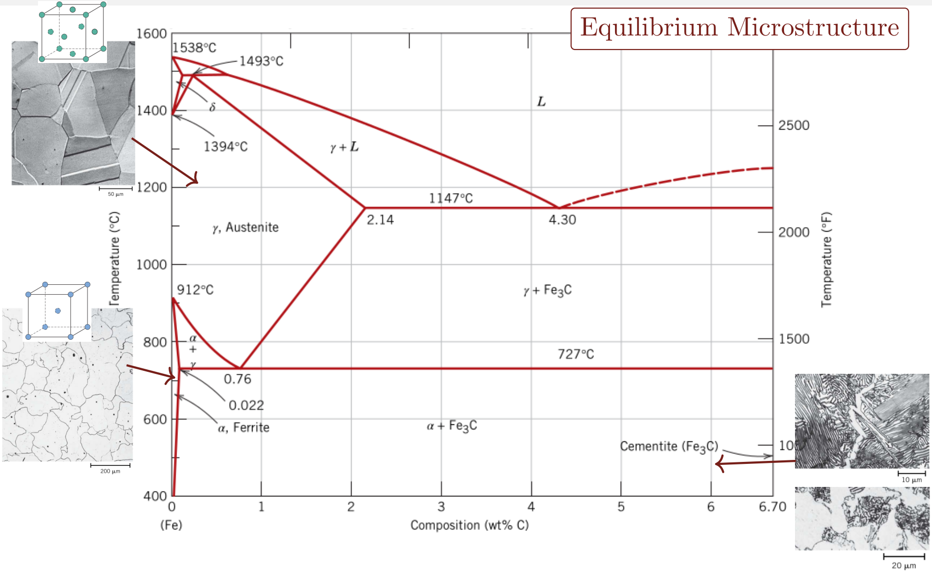
3. Introduction to Material Science

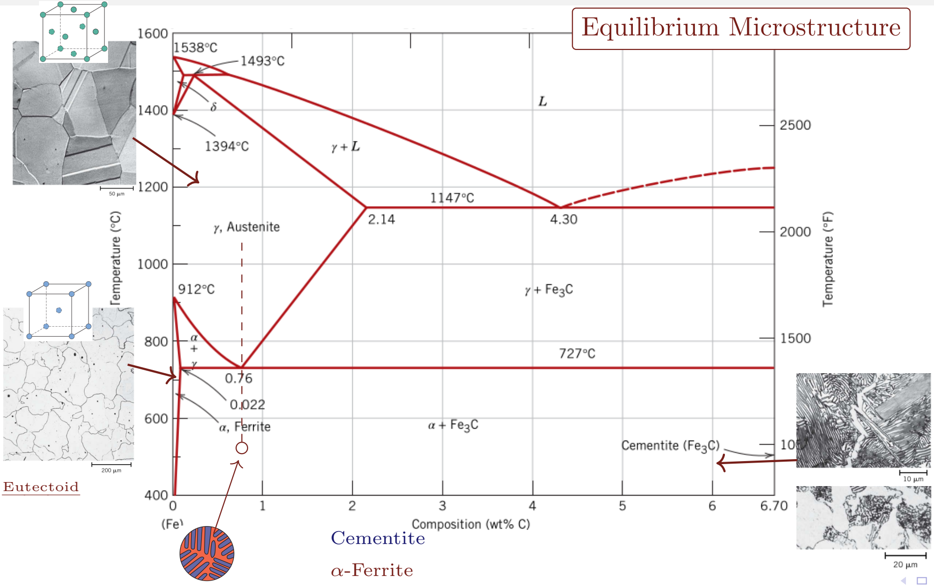
Equilibrium Microstructure



3.2. Phase Diagrams: The Iron-Carbon System [2]

3. Introduction to Material Science

Equilibrium Microstructure



Eutectoid

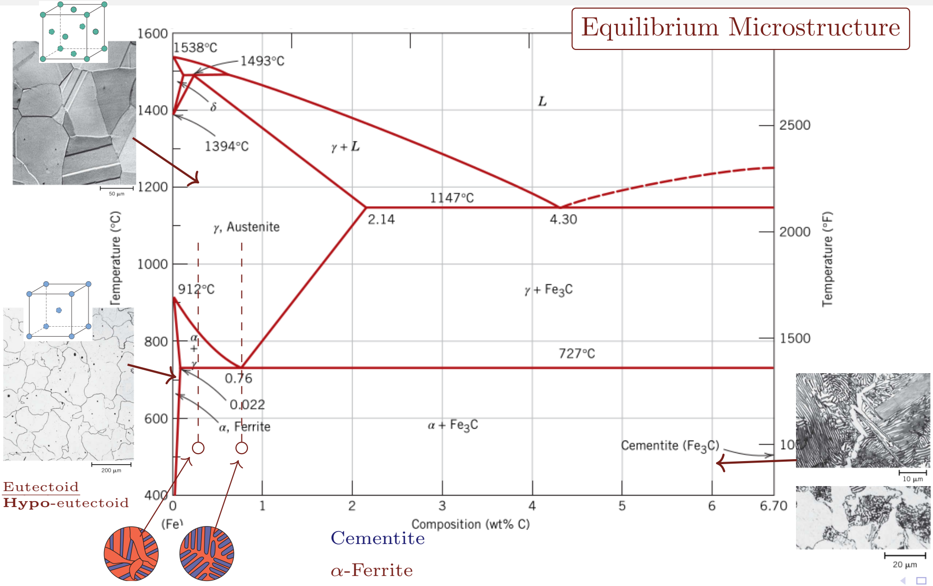
Cementite

α-Ferrite

3.2. Phase Diagrams: The Iron-Carbon System [2]

3. Introduction to Material Science

Equilibrium Microstructure



Eutectoid

Hypo-eutectoid

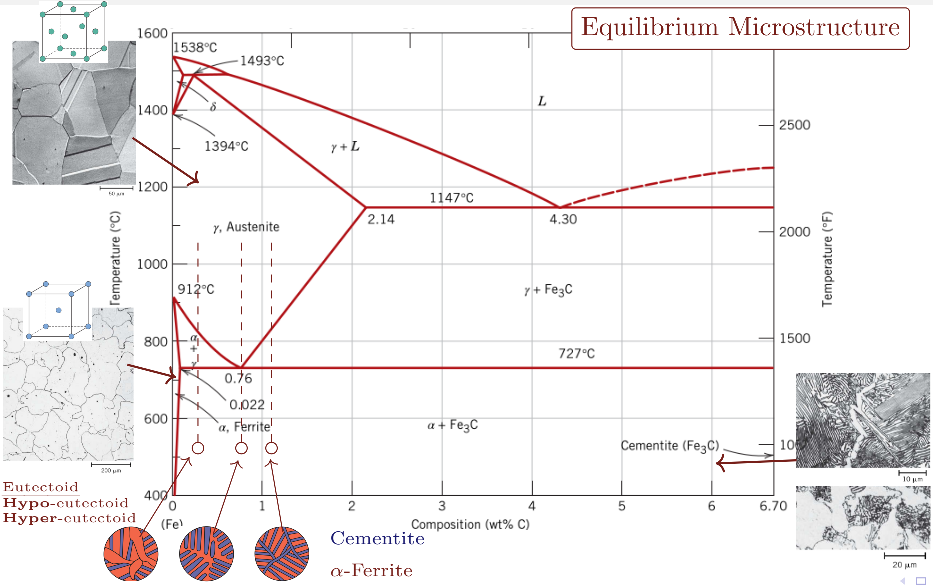
Cementite

α-Ferrite

3.2. Phase Diagrams: The Iron-Carbon System [2]

3. Introduction to Material Science

Equilibrium Microstructure



Eutectoid
Hypo-eutectoid
Hyper-eutectoid

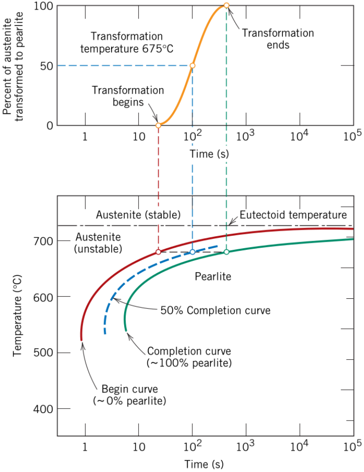
Cementite
α-Ferrite

3.2. The Fe-Fe_3C System: Heat Treatment

3. Introduction to Material Science

- Although a phase may be unstable (eg., Austenite for $T < 727°$ C), phase-change takes time, especially when solid.

Isothermal transformation diagram [2]



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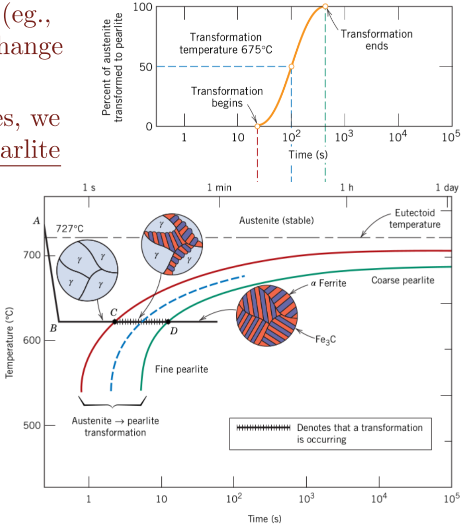

3.2. The Fe-Fe$_3$C System: Heat Treatment

3. Introduction to Material Science

Isothermal transformation

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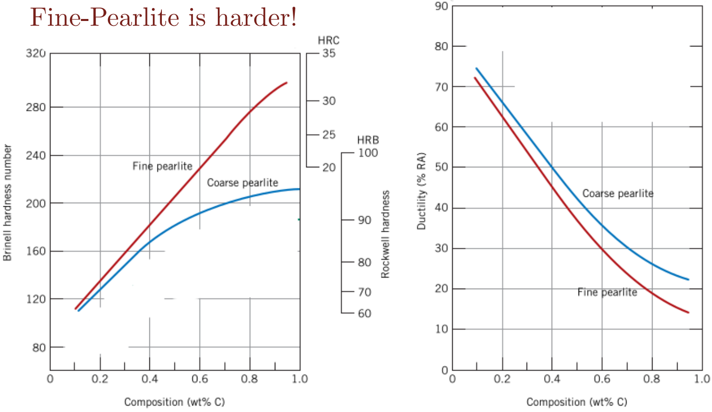
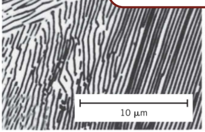
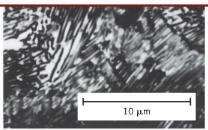
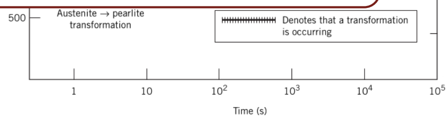
Fine-Pearlite is harder!









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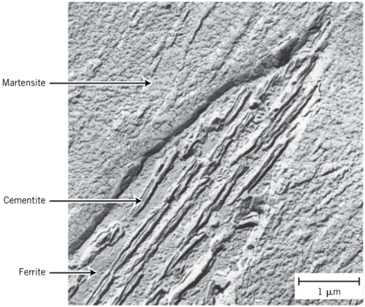

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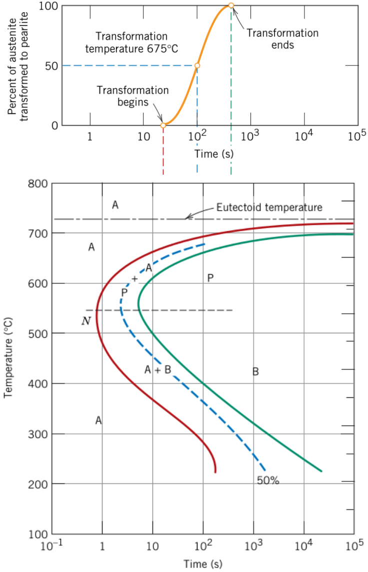

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Isothermal transformation diagram [2]

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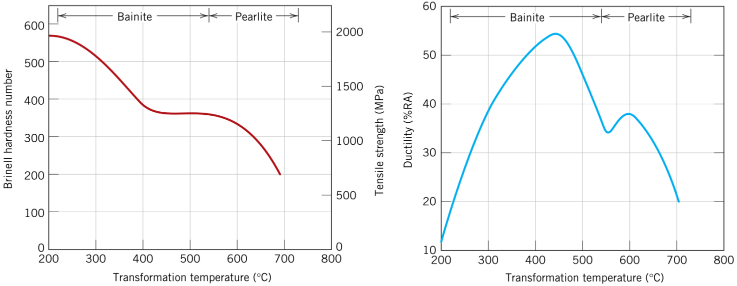
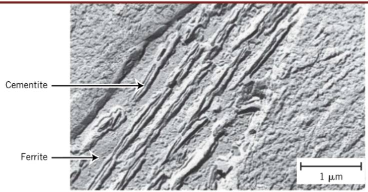
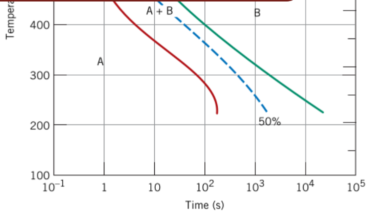
Bainite is harder than Pearlite!







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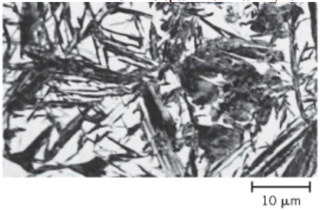
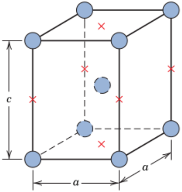
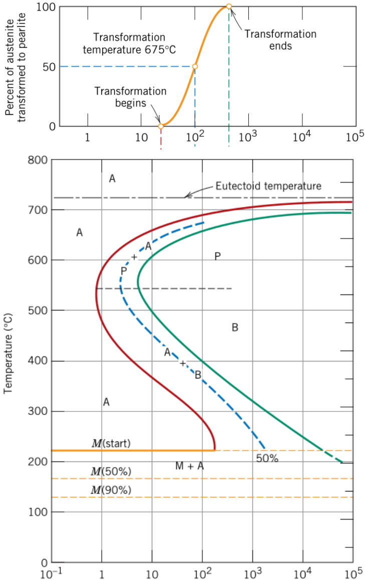
    - "Diffusion-less" transformation
    - Super-saturated carbon solution
    - Non-equilibrium, time-independent





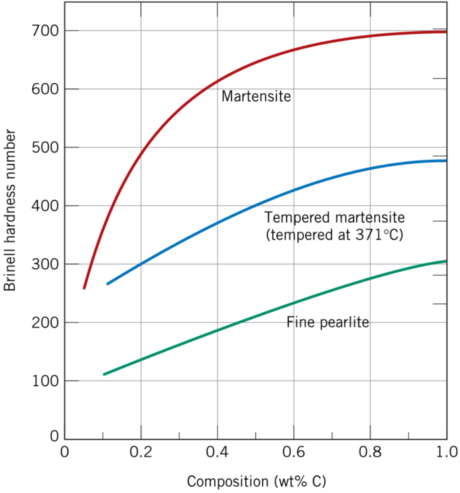
Isothermal transformation diagram [2]



3.2. The Fe-Fe_3C System: Heat Treatment

- Although a phase may be unstable (eg.,

Martensite is **the hardest!**



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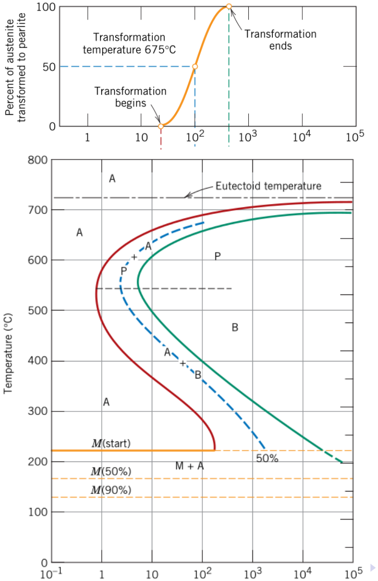

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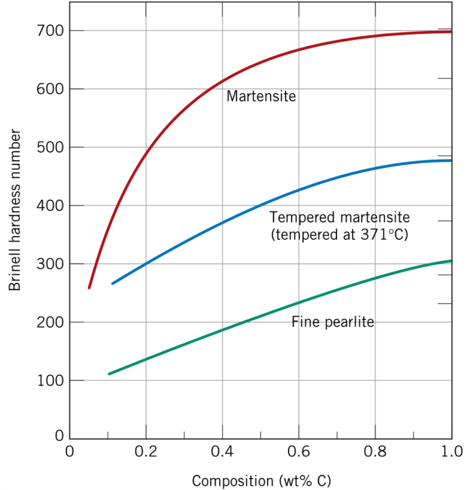

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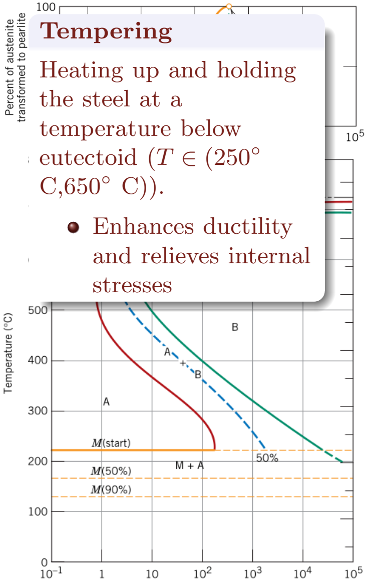

Tempering

Heating up and holding the steel at a temperature below eutectoid ($T \in (250^\circ \text{C}, 650^\circ \text{C})$).

- Enhances ductility and relieves internal stresses

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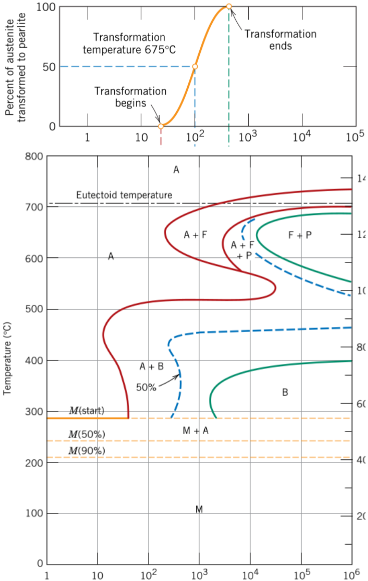
- When quenched to ∼ambient, Martensite
  - "Diffusion-less" transformation
  - Super-saturated carbon solution
  - Non-equilibrium, time-independent
- The presence of other alloy content changes these curves

Isothermal transformation diagram [2]



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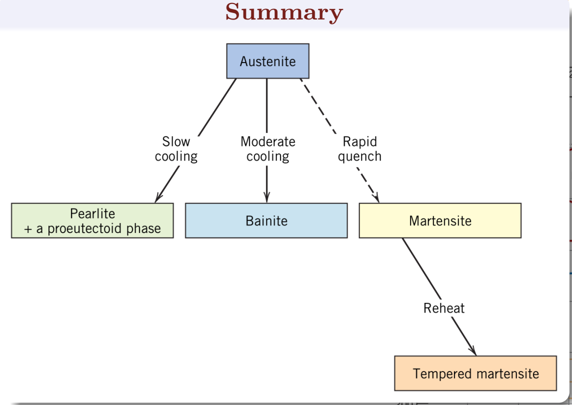


Summary

Austenite

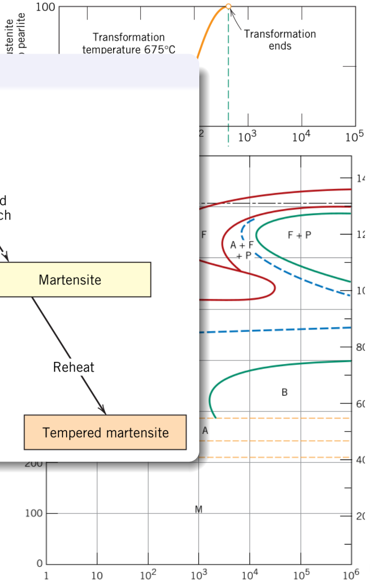
Slow cooling → Pearlite + a proeutectoid phase

Moderate cooling → Bainite

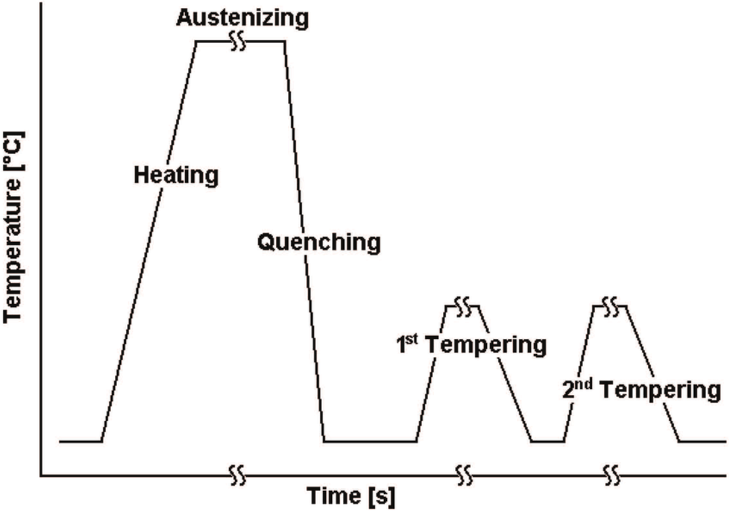
Rapid quench → Martensite

Martensite → Reheat → Tempered martensite

Isothermal transformation diagram [2]



3.2. The Fe-Fe_3C System: The Heat Treatment Process



A typical heat treatment process involving Austenizing, quenching and tempering

Summary

Module 2: Aircraft Materials

1. Understanding the Stress-Strain Curve
   - Failure Mechanisms
2. Materials Used in Aircrafts
   - Metallic Alloys
3. Introduction to Material Science
   - Metallic Crystal Structure
   - Phase Diagrams

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