AS3020: Aerospace Structures

Module 2: Aircraft Materials

Instructor: Nidish Narayanaa Balaji

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

August 11, 2025

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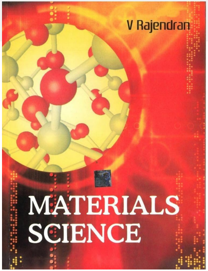
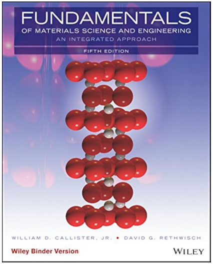
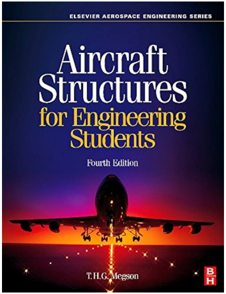


Chapters 2, 9, 11 in Rajendran (2011)



Chapters 3, 5, 9-11 in Jr and Rethwisch (2012)



Chapters 11, 15 in Megson (2013)

1. Understanding the Stress-Strain Curve

The Uniaxial Tensile Test

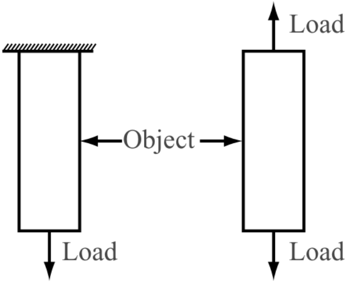


Figure from Rajendran 2011

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

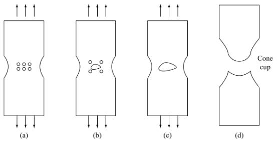


Figure from Rajendran 2011

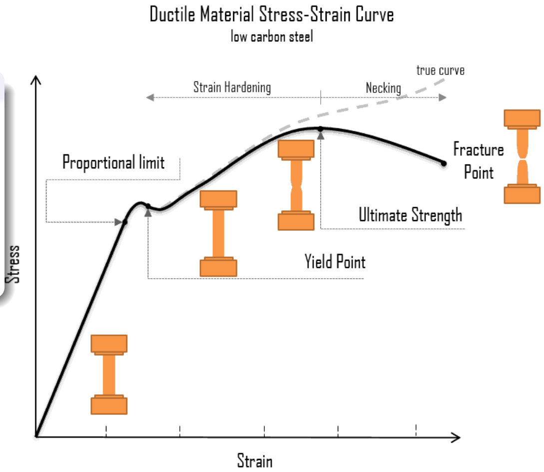
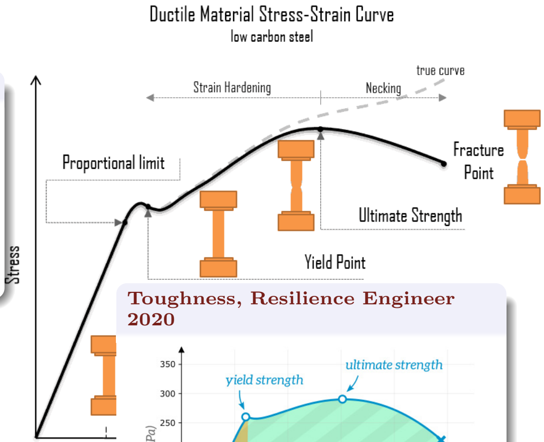


Figure from Connor 2020

1. Understanding the Stress-Strain Curve



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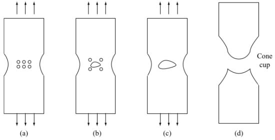
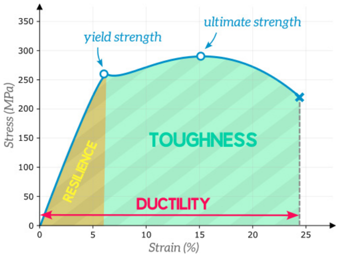


Figure from Rajendran 2011

Toughness, Resilience Engineer 2020



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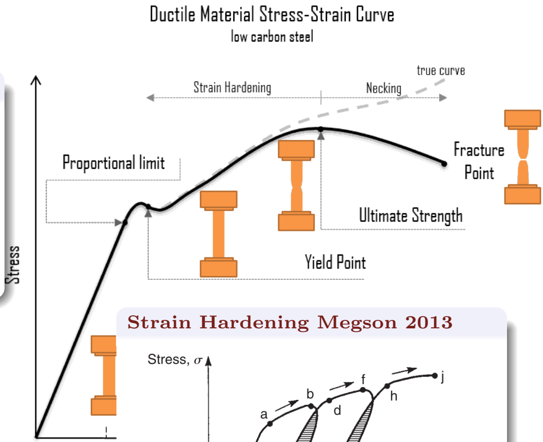


Ductile Fracture

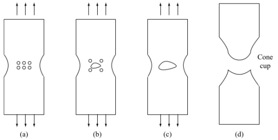
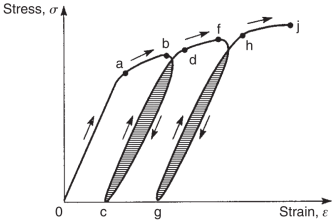


Figure from Rajendran 2011

Strain Hardening Megson 2013



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Classifications

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

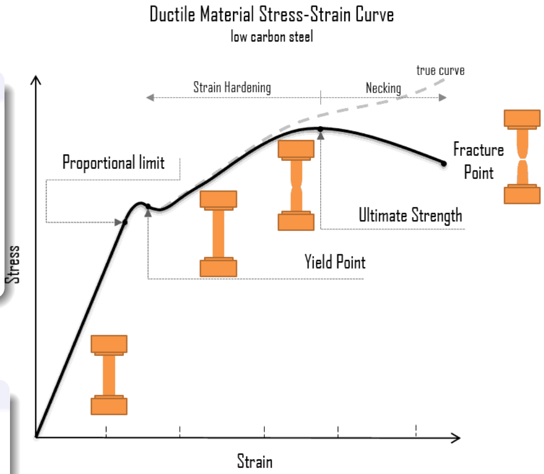

Figure from Connor 2020

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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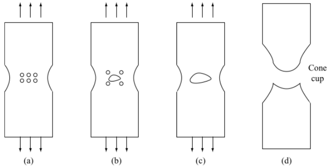

Ductile Fracture Rajendran 2011

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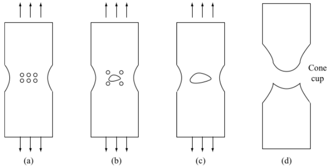


Ductile Fracture Rajendran 2011

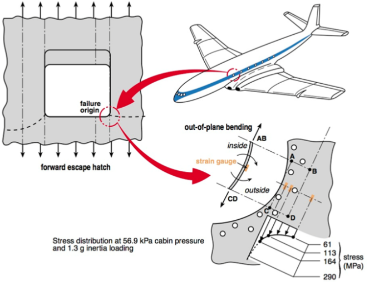
Sr. No	*Brittle Fracture*	*Ductile Fracture*
1.	It occurs with no or little plastic deformation.	It occurs with large plastic deformation.
2.	The rate of propagation of the crack is fast.	The rate of propagation of the crack is slow.
3.	It occurs suddenly without any warning.	It occurs slowly.
4.	The 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 Rajendran 2011

1.1. Failure Mechanisms: Fatigue

1. Understanding the Stress-Strain Curve

..over 90% of mechanical failures are caused because of metal fatigue *What Is Metal Fatigue?* 2021...



The De Havilland Comet The deHavilland Comet Disaster 2019 [lecture]

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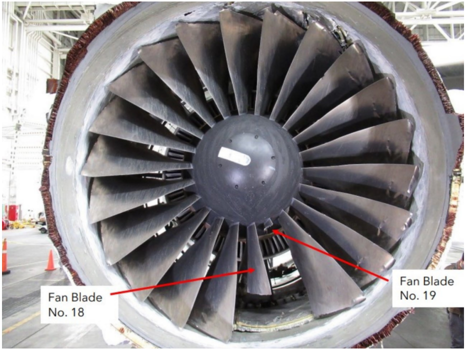
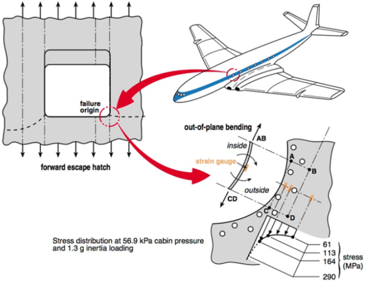


A more recent example (2021 United Airlines Boeing 777) DCA21FA085.Aspx 2024. *[video]*



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Fatigue Crack Propagation: Beech Marks

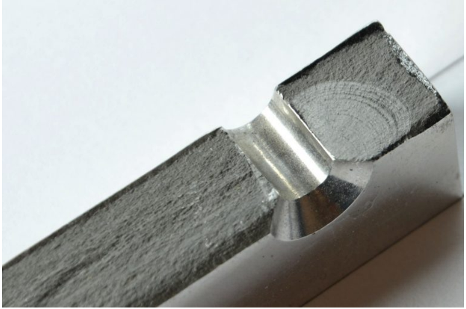
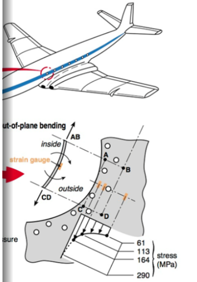


Figure from Fatigue Physics 2024



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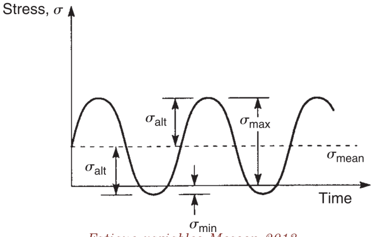
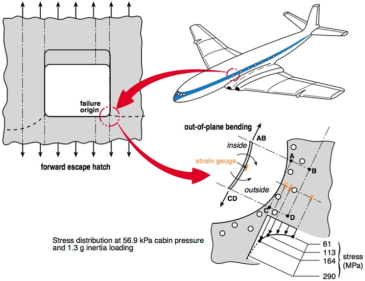


Fatigue variables Megson 2013



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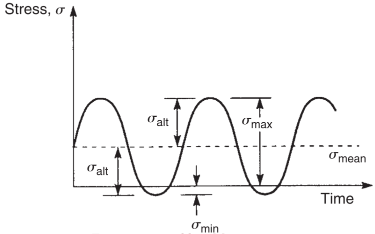
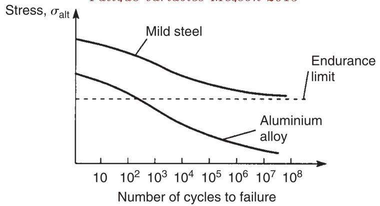
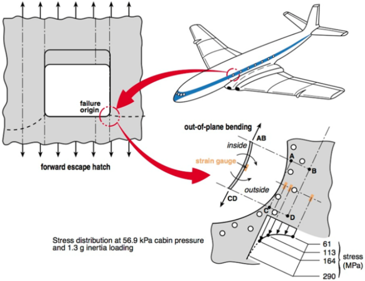


Fatigue variables Megson 2013



The S-n Diagram Megson 2013



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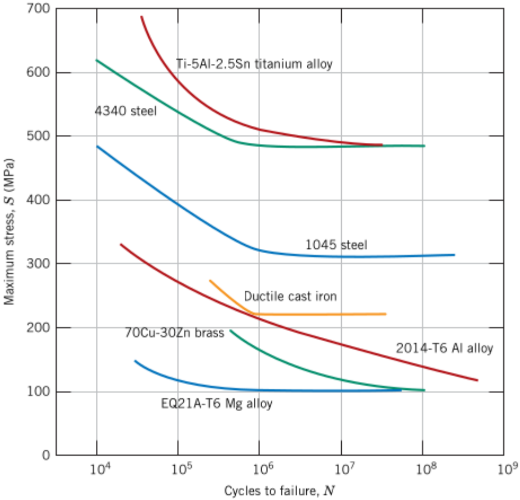
S-N Curves for Common Metals Jr and Rethwisch 2012



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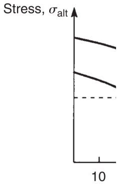

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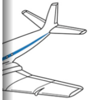

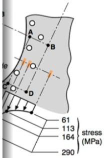

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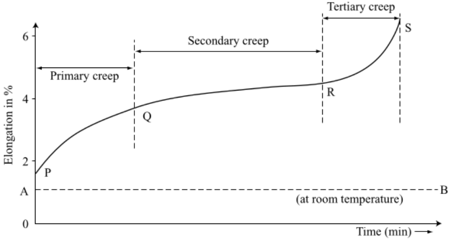
- Constant stress applied over a long time
- High temperature phenomenon ($>\sim 30-45\%$ of melting point)



Creep curve Rajendran 2011

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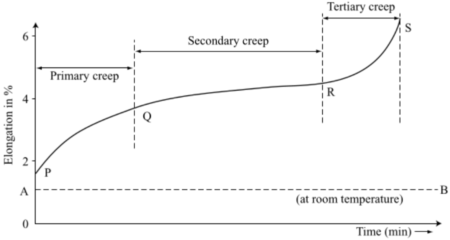
Examples

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



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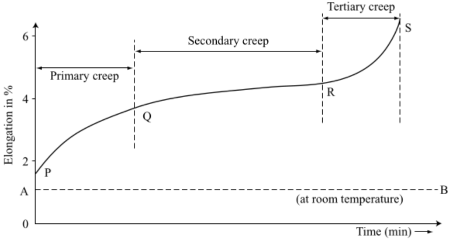

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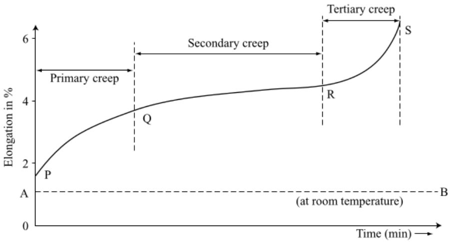

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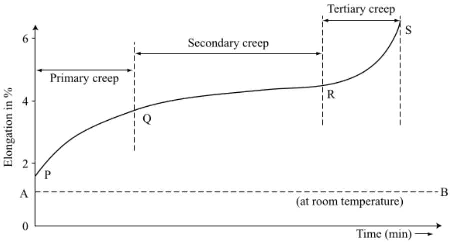

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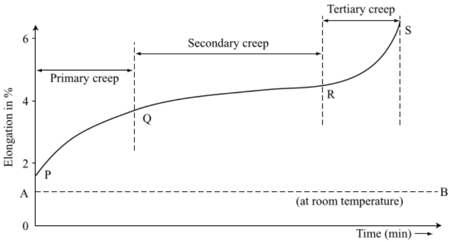

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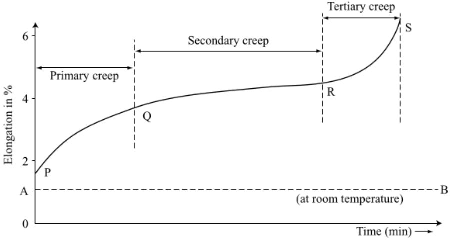

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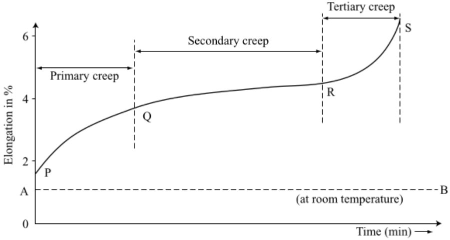

Creep curve Rajendran 2011

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

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- Cons time
- High (>∼

Example

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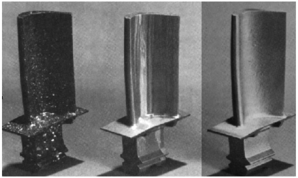
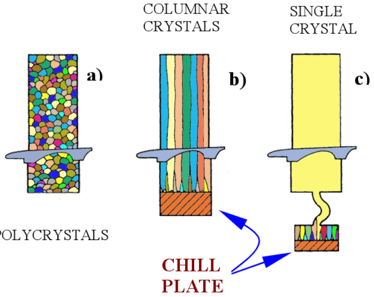
Single Crystal Casting SingleCrystalCasting2008

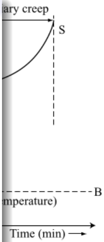


a) b) c)



DMRL developed this capability in 2021 DRDO Develops Single Crystal Blades for Helicopter Engine Application 2024

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



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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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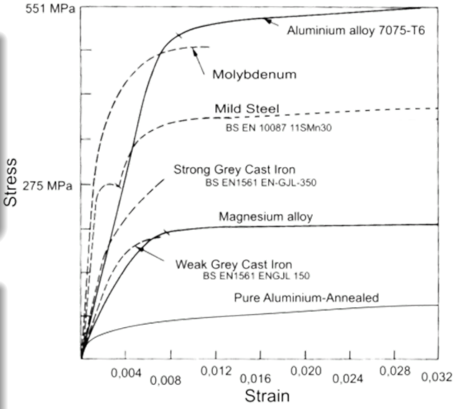
Metallic Alloys/"Solutions"

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



Stress strain curve of common metals What Is a Stress-Strain Curve? 2024

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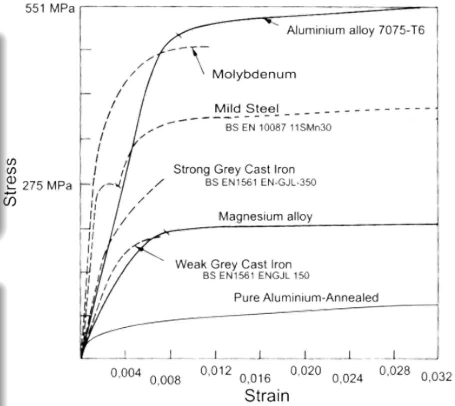
Al Alloys Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti



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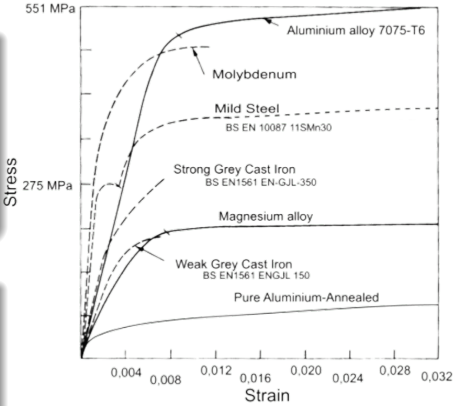
Al Alloys Cu, Mg, Mn, Si, Fe, Zn, Ni, Ti

Ti Alloys Al, V



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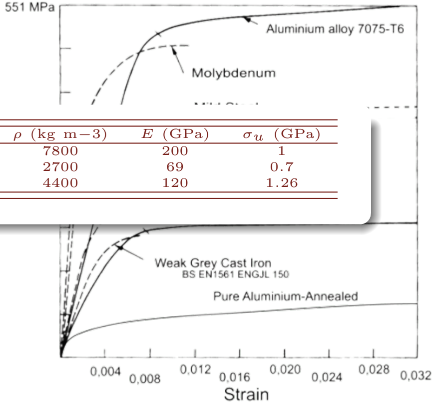

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Alloy	ρ (kg m-3)	E (GPa)	σ_u (GPa)
Fe	7800	200	1
Al	2700	69	0.7
Ti	4400	120	1.26

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

2. Materials Used in Aircrafts

2.1. Metallic Alloys

Main Considerations

- Strength-to-weight ratio:
- Stiffness, S
- Toughness, propagatio
- Fatigue life
- Thermal b

Metallic Alloy

Fe Alloys

Al Alloys

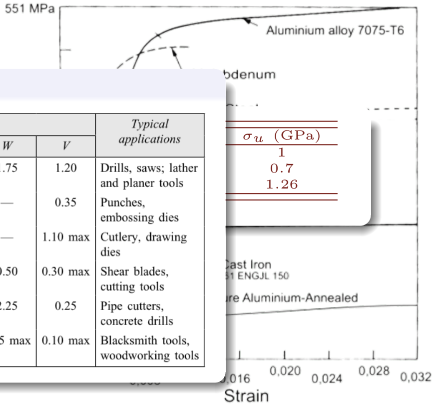
Ti Alloys Al, V

Ni Superalloys Cr, Al

Steel Alloys Rajendran 2011

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 What Is a Stress-Strain Curve? 2024

2. Materials Used in Aircrafts

2.1. Metallic Allo

Aluminum Alloys Rajendran 2011

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 Conside

- Strength-tc
- Stiffness, S
- Toughness, propagatio
- Fatigue life
- Thermal be

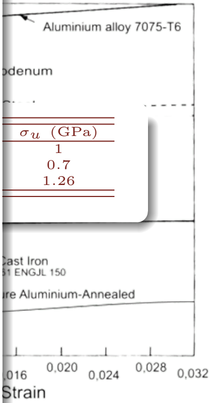
Metallic Alloy

Fe Alloys

Al Alloys

Ti Alloys

Ni Superalloys



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1
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etals What Is a Stress-Strain
2024

2. Materials Used in Aircrafts

2.1. Metallic Allo

Main Conside

- Strength-to
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Metallic Alloy

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Al Alloys

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Aluminum Alloys Rajendran 2011

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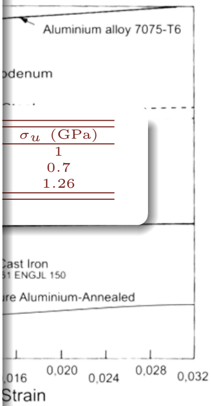
Necessary Reading

Pages 353-359 in Megson 2013.

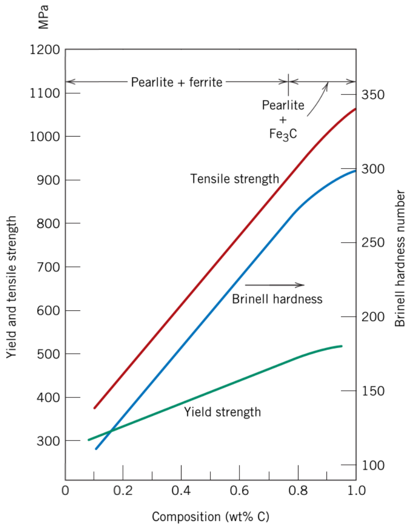


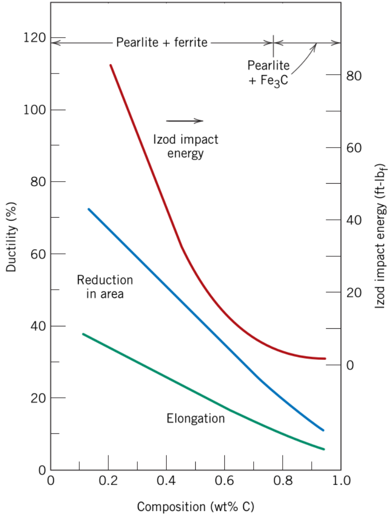
	σ_u (GPa)
	1
	0.7
	1.26

etals What Is a Stress-Strain 2024

Mechanical Behavior of Steel

2. Materials Used in Aircrafts

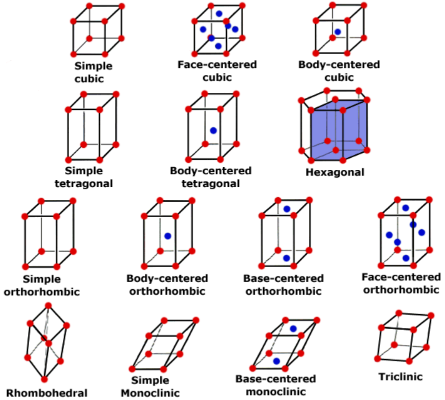




As Carbon Content↑, Strength↑, but Ductility↓ Jr and Rethwisch 2012

3. Introduction to Material Science

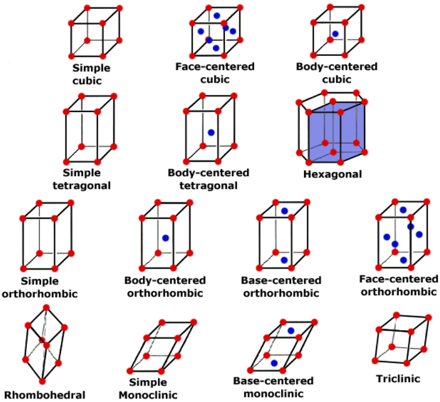
3.1. Metallic Crystal Structure



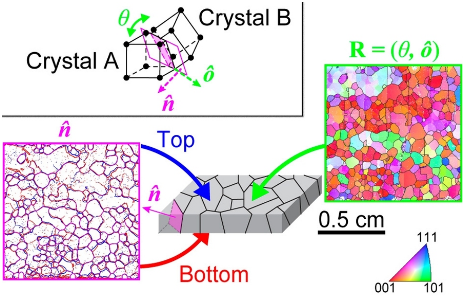
Types of crystal structures in metals Sparky 2013

3. Introduction to Material Science

3.1. Metallic Crystal Structure



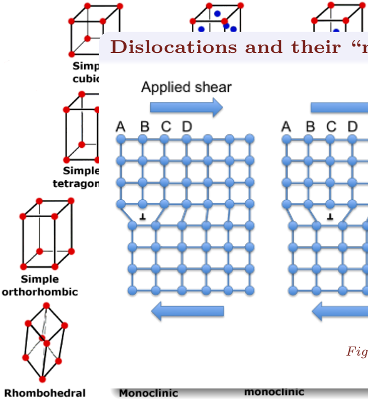
Types of crystal structures in metals Sparky 2013



Crystal and Grain Structures New Technique Provides Detailed Views of Metals' Crystal Structure 2016. "Polycrystallinity"

3. Introduction to Material Science

3.1. Metallic Crystal Structure



Dislocations and their “motion” under load

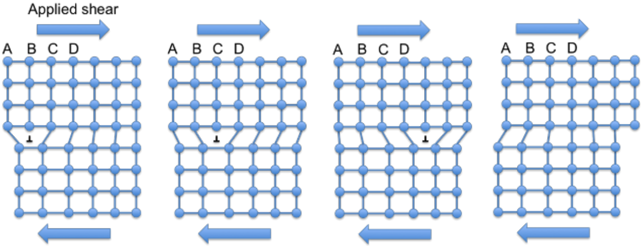
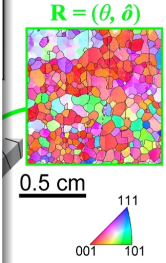


Figure from Sparky 2013



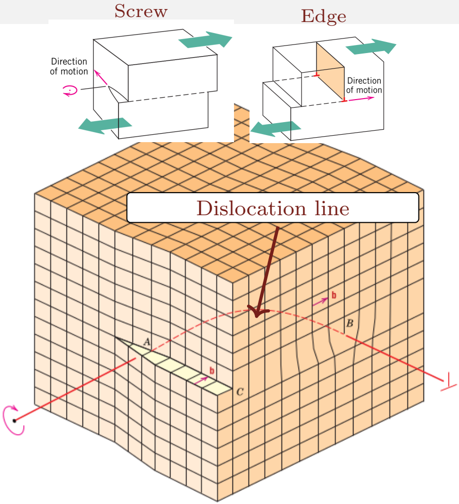
...que Provides Detailed Views of Metals' Crystal Structure 2016. “Polycrystallinity”

Types of crystal structures in metals Sparky 2013

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 Jr and Rethwisch 2012

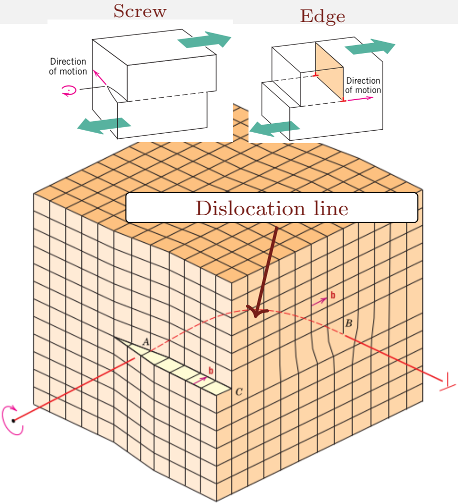
3.1. Metallic Crystal Structure

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.

Material Strengthening

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

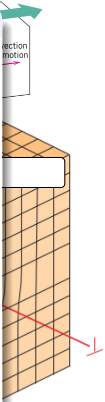


Figures from Jr and Rethwisch 2012

3.1. Metallic Crystal Structure

3. Introduction to Material Science

Screw　　Edge



- The abi plastica disloicat
- Restrict motion stronger

Material St

1. Grain si
2. Solid-sol
3. Strain h

Grain Size Reduction

- Grain boundaries act as barriers to dislocation movement

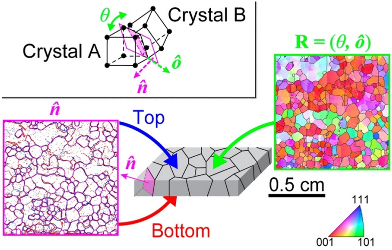


Figure from New Technique Provides Detailed Views of Metals' Crystal Structure 2016

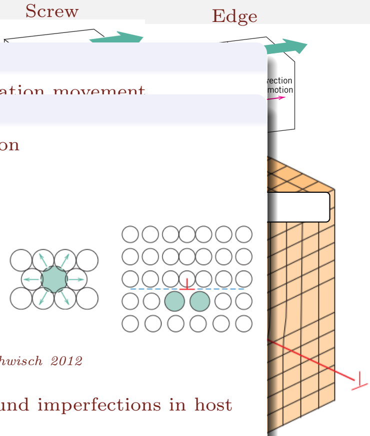
- **Hall-Petch Equation**:

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

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

3.1. Metallic Crystal Structure

3. Introduction to Material Science



- The abi
  plastica
  disloica
- Restrict
  motion
  stronge

Material St

1. Grain si
2. Solid-sol
3. Strain h

Grain Size Reduction

- Grain boundaries act as barriers to dislocation movement

Solid-Solution Alloying

- Substitutional/interstitial impurity addition
- Impurities redistribute lattice strains

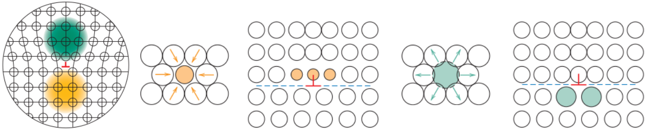


Figure from Jr and Rethwisch 2012

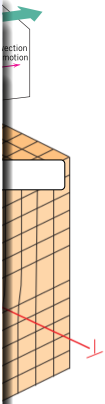
- Solutes have a tendency to distribute around imperfections in host lattice
- Greater stress necessary for dislocation movement $\implies$ Greater strength and hardness

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

3.1. Metallic Crystal Structure

3. Introduction to Material Science

Screw



- The abi plastica disloica
- Restrict motion stronge

Material St

1. Grain si
2. Solid-sol
3. Strain h

Strain/Work Hardening aka Cold Working

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

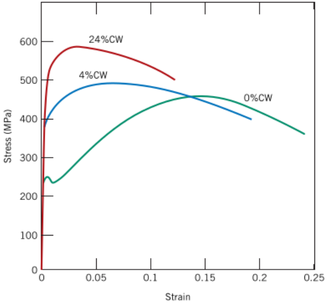


Figure from Jr and Rethwisch 2012

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

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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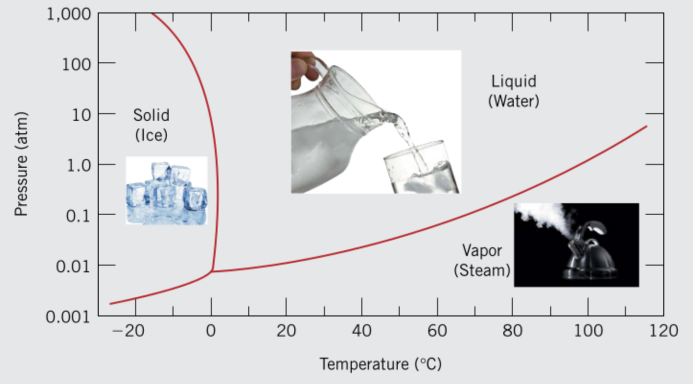
What is a phase diagram? Jr and Rethwisch 2012

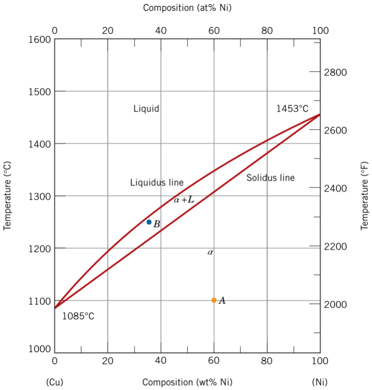


3.2. Phase Diagrams: Isomorphous Alloys

3. Introduction to Material Science

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

The Copper-Nickel Phase Diagram Jr and Rethwisch 2012



3.2. Phase Diagrams: Isomorphous Alloys

3. Introduction to Material Science

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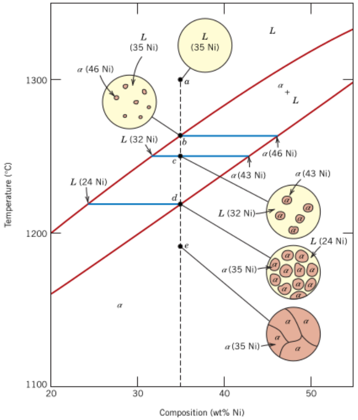
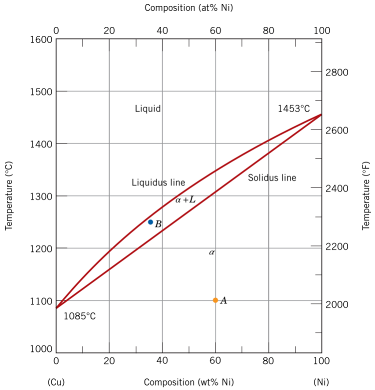
Equilibrium Cooling Jr and Rethwisch 2012



The Copper-Nickel Phase Diagram Jr and Rethwisch 2012



3.2. Phase Diagrams: Isomorphous Alloys

3. Introduction to Material Science

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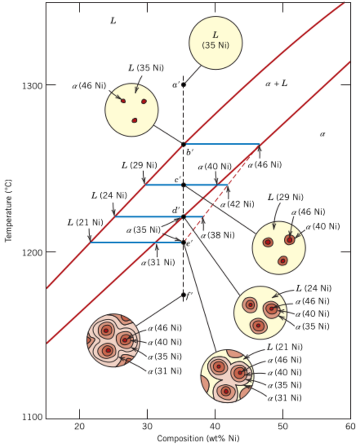
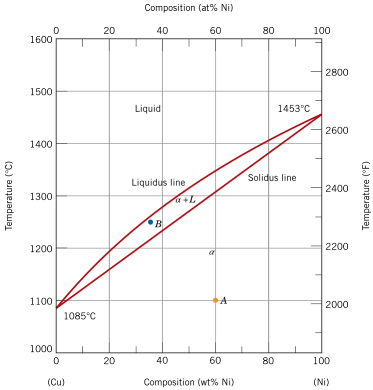
Non-Equilibrium Cooling Jr and Rethwisch 2012



The Copper-Nickel Phase Diagram Jr and Rethwisch 2012



3.2. Phase Diagrams: Isomorphous Alloys

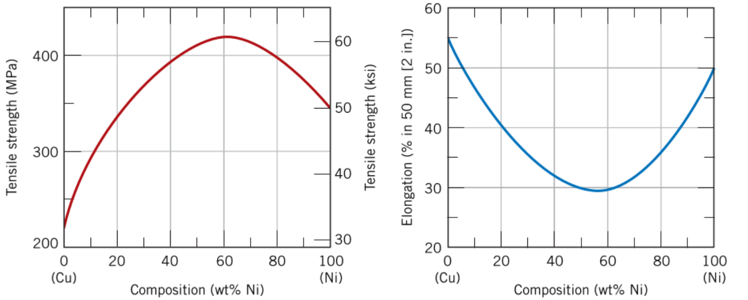
3. Introduction to Material Science

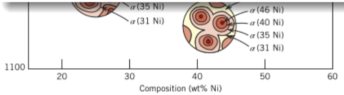
Mechanical properties are a direct consequence of microstructures, which are direct consequences of thermal histories.

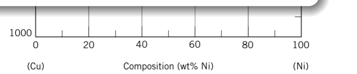
Non-Equilibrium Cooling Jr and Rethwisch 2012

The Copper-Nickel Phase

Mechanical Ramifications Jr and Rethwisch 2012



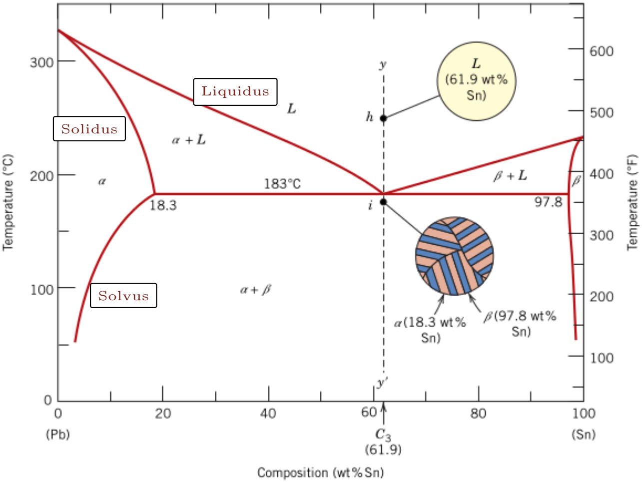




3.2. Phase Diagrams: Eutectic Systems

3. Introduction to Material Science

The Lead-Tin System Jr and Rethwisch 2012



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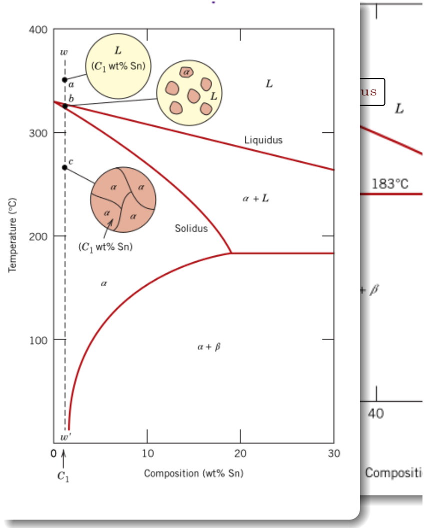
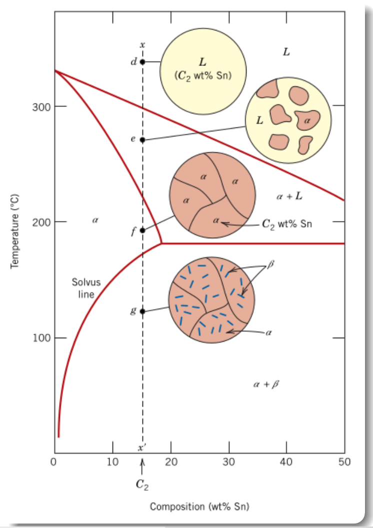
3. Introduction to Material Science

The Lead-Tin System Jr and Rethwisch 2012





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3. Introduction to Material Science

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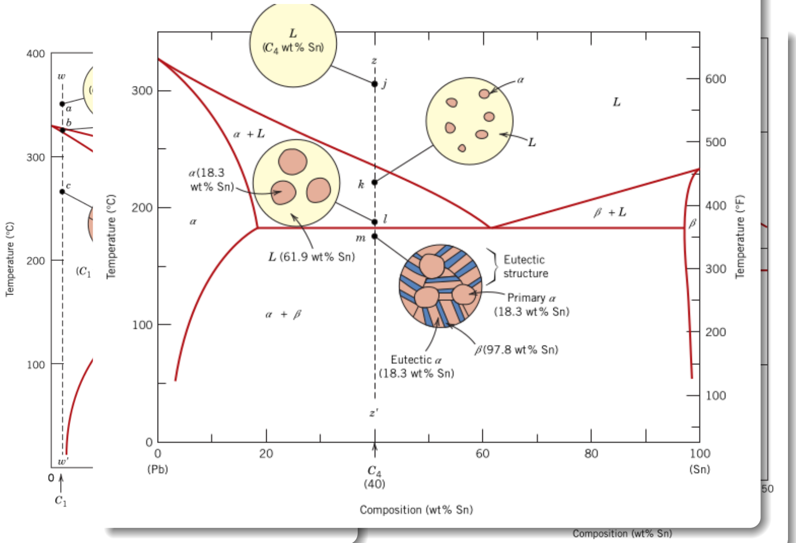

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3. Introduction to Material Science

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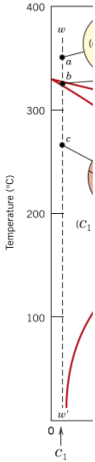
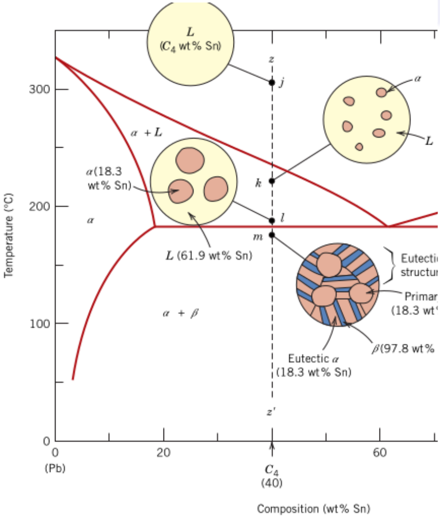
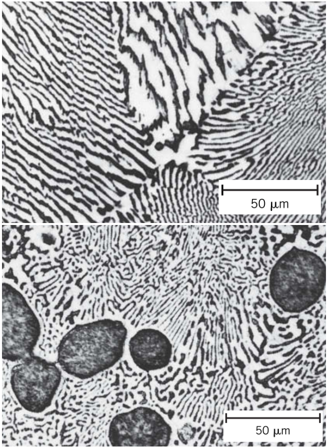




Composition (wt% Sn)

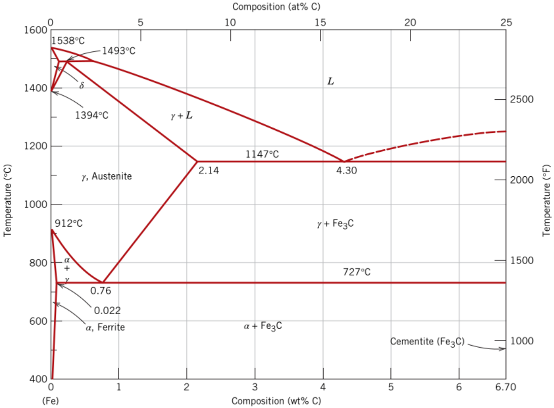
Some Pictures Jr and Rethwisch 2012

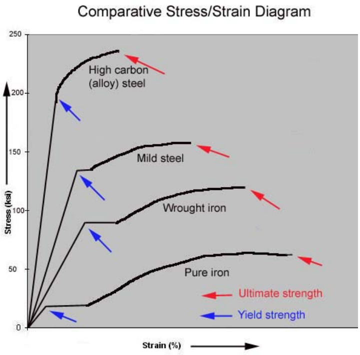


3.2. Phase Diagrams

3. Introduction to Material Science

The Iron Carbon System Jr and Rethwisch 2012

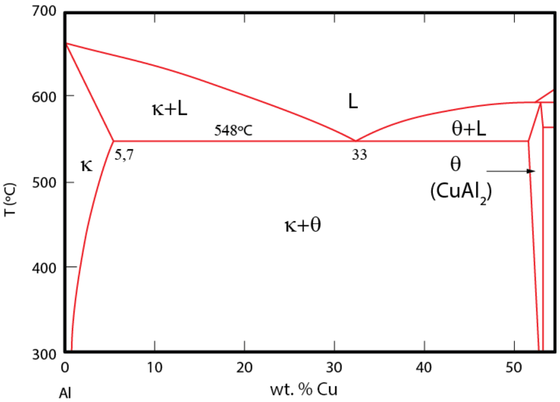


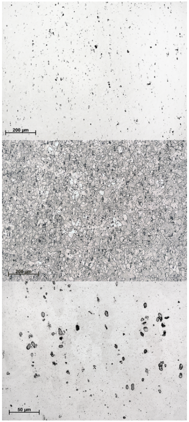


3.2. Phase Diagrams

3. Introduction to Material Science

The Al-Cu-Mg System (2024 AA) *2024 — Innovation Project Metallographic Atlas* **2024**

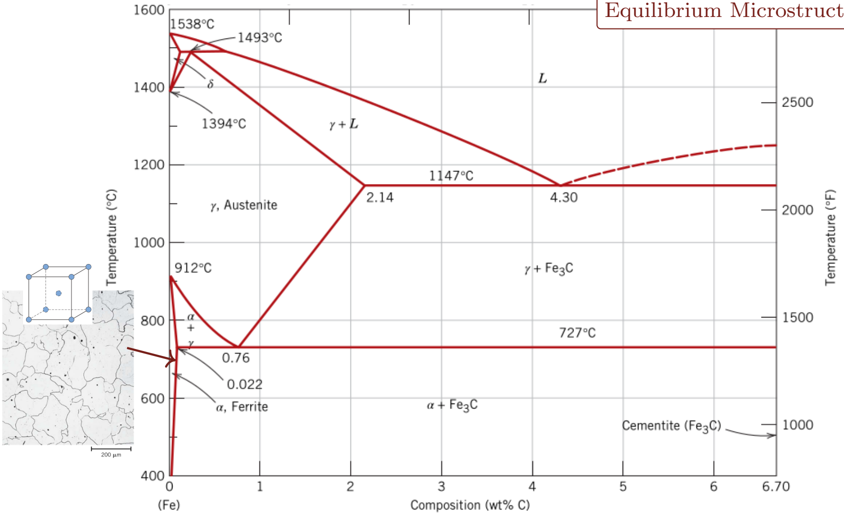




3.2. Phase Diagrams: The Iron-Carbon System Jr and Rethwisch 2012

3. Introduction to Material Science

Equilibrium Microstructure



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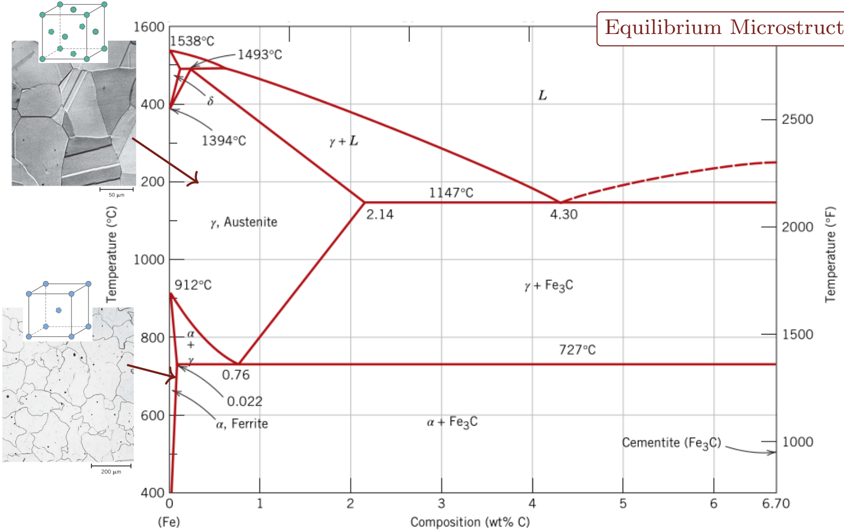
3. Introduction to Material Science

Equilibrium Microstructure



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3. Introduction to Material Science

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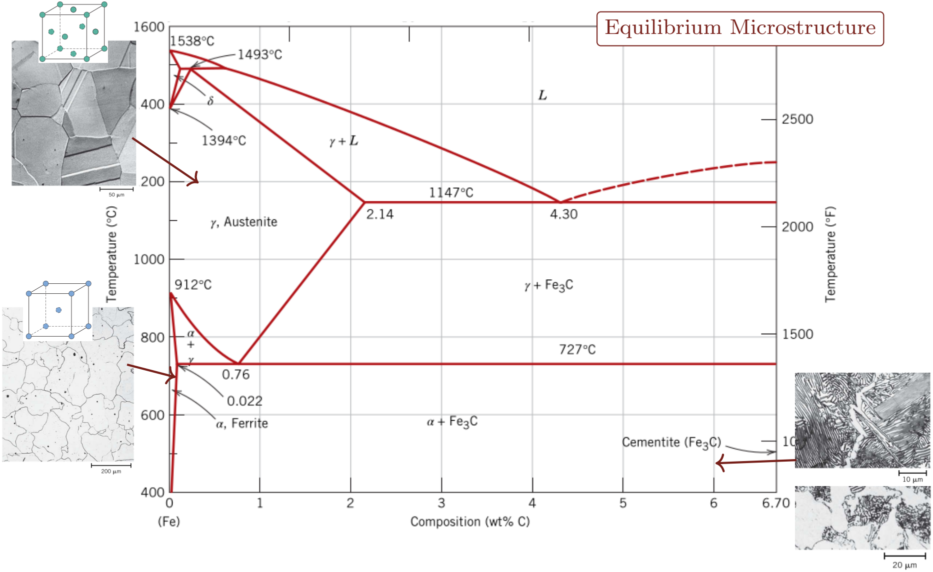

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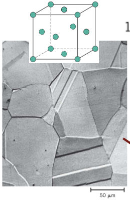
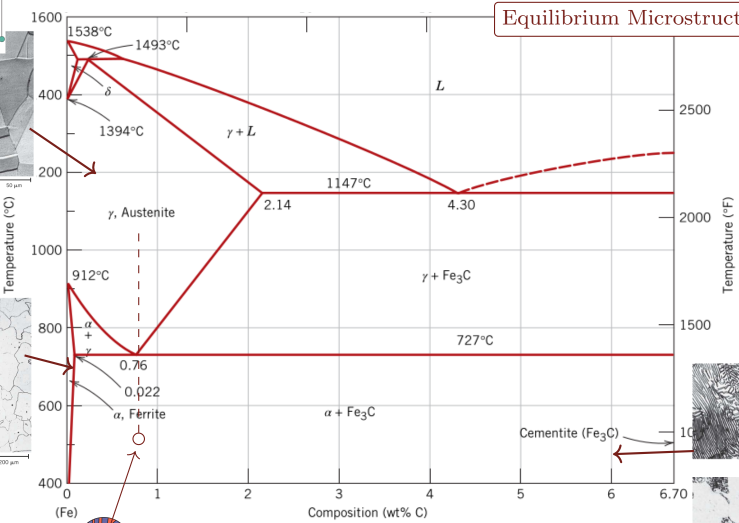
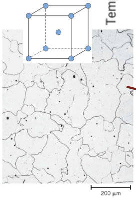
3. Introduction to Material Science

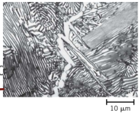
Equilibrium Microstructure

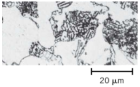






Eutectoid





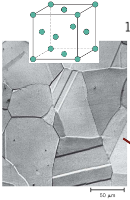
Cementite

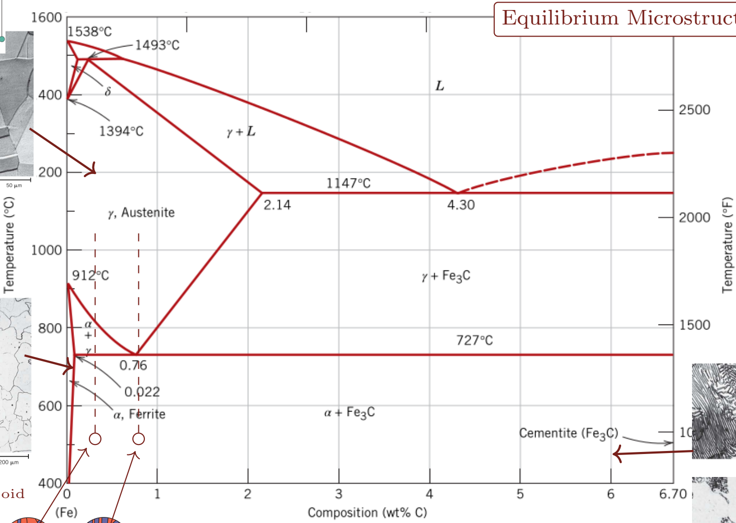
α-Ferrite

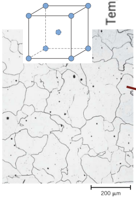
3.2. Phase Diagrams: The Iron-Carbon System Jr and Rethwisch 2012

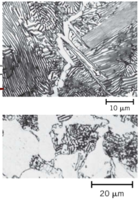
3. Introduction to Material Science

Equilibrium Microstructure

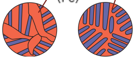








Eutectoid
Hypo-eutectoid



Cementite

α-Ferrite

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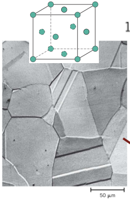
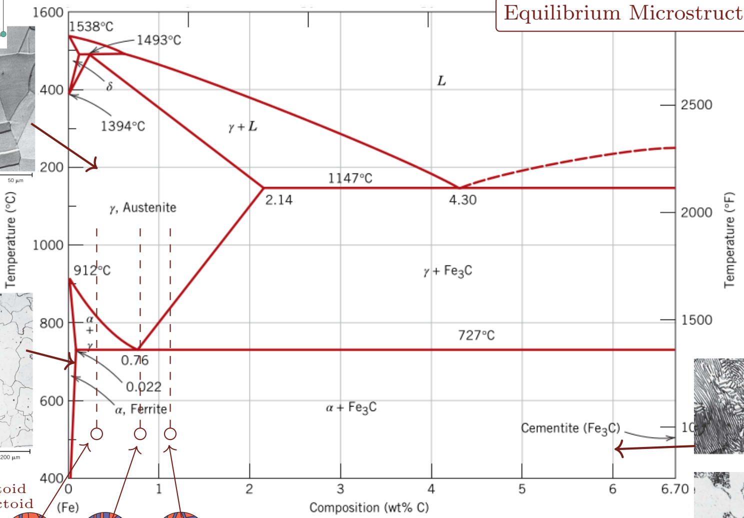
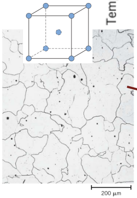
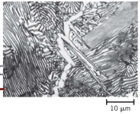
3. Introduction to Material Science

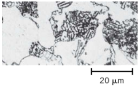




Equilibrium Microstructure







Eutectoid
Hypo-eutectoid
Hyper-eutectoid

Cementite

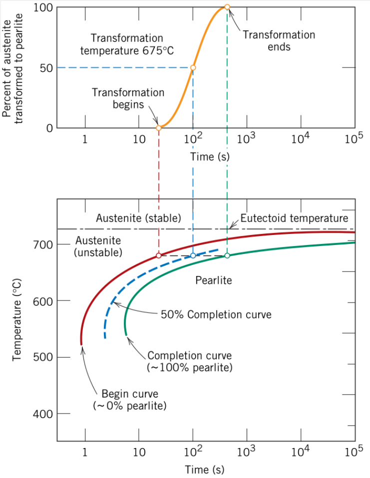
α-Ferrite

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 Jr and Rethwisch 2012



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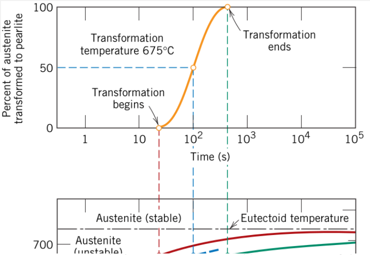

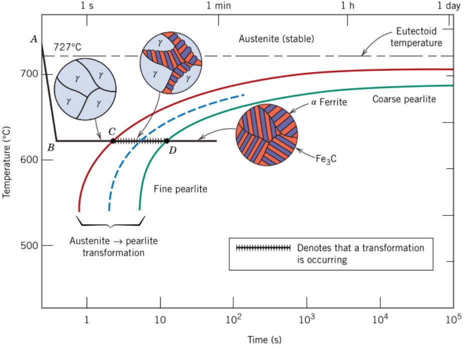

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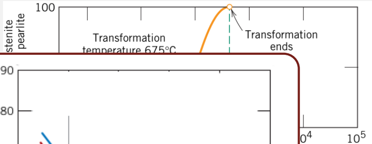

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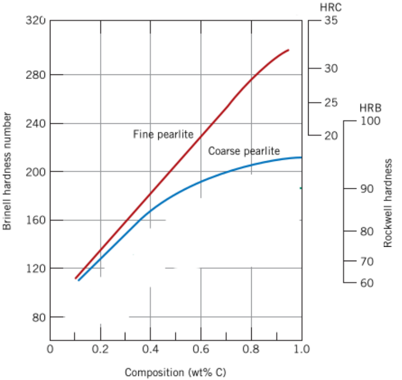
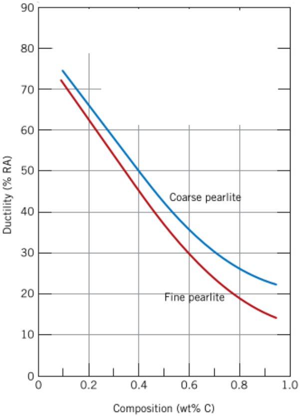
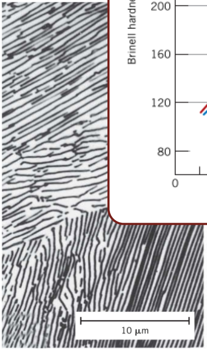
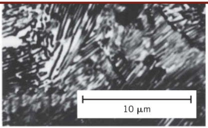
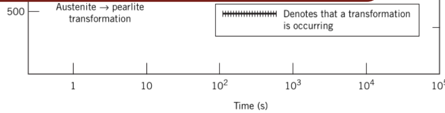
Fine-Pearlite is harder!











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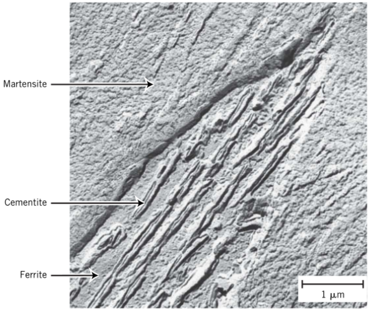
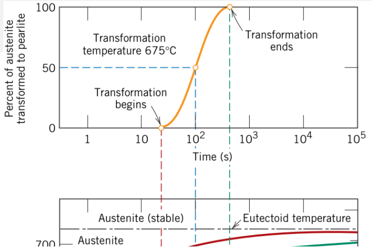
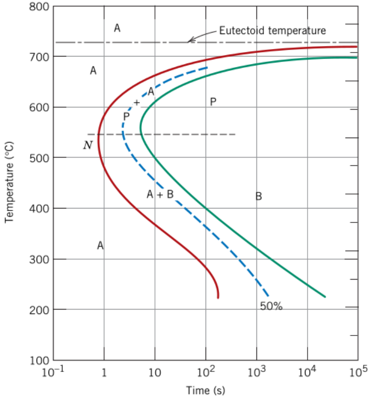


Isothermal transformation diagram Jr and Rethwisch 2012





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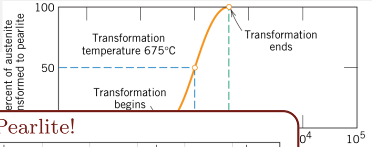

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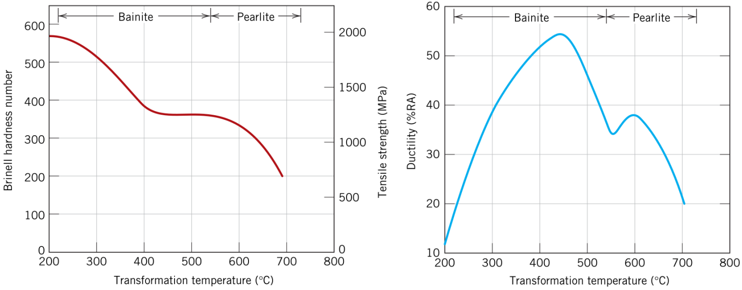
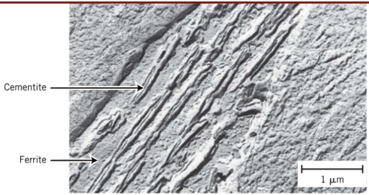
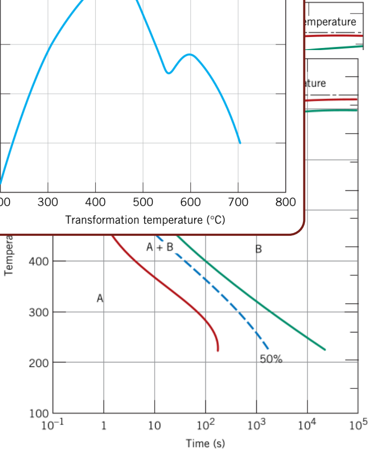
- When lamell
- For T Cemen

Bainite is harder than Pearlite!







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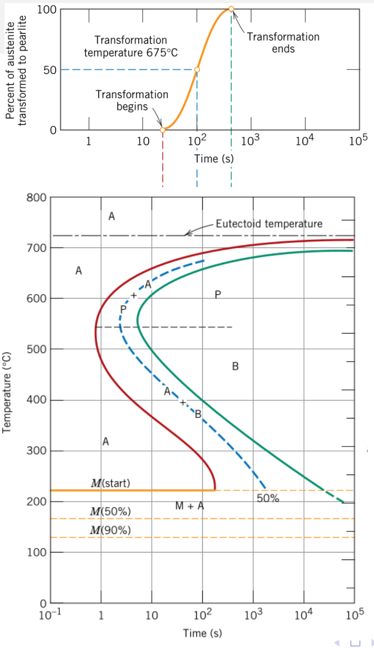
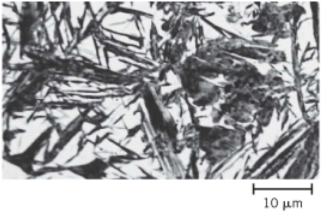
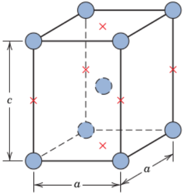
- When quenched to ~ambient, Martensite
  - "Diffusion-less" transformation
  - Super-saturated carbon solution
  - Non-equilibrium, time-independent

Isothermal transformation diagram Jr and Rethwisch 2012



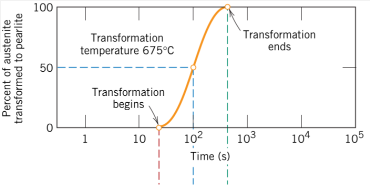




3.2. The Fe-Fe_3C System: Heat Treatment

3. Introduction to Material Science

Isothermal transformation diagram Jr and Rethwisch 2012



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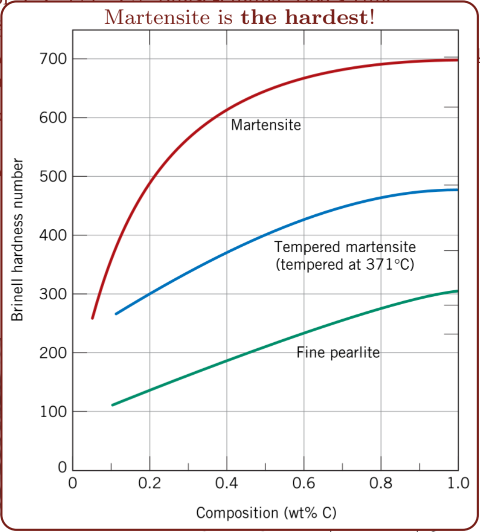
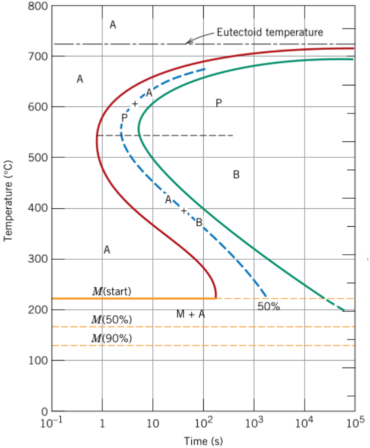


10 µm

a

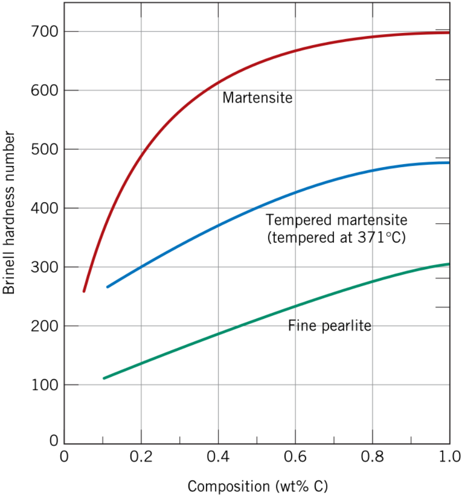


3.2. The Fe-Fe_3C System: Heat Treatment

3. Introduction to Material Science

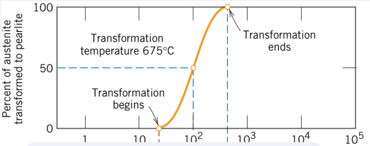
- Although a phase may be unstable (eg., Austenite for $T < 727°$ C), phase-change takes time
  es
- W ... k
  la
- F
  C
- W

Martensite is **the hardest!**



10 µm

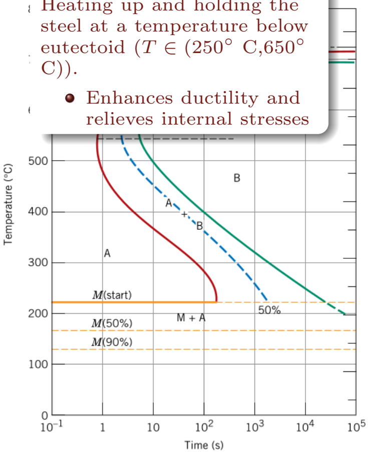
Isothermal transformation diagram Jr and Rethwisch 2012



Tempering

Heating up and holding the steel at a temperature below eutectoid ($T \in (250°$ C,$650°$ C)).

- Enhances ductility and relieves internal stresses



3.2. The Fe-Fe_3C System: Heat Treatment

3. Introduction to Material Science

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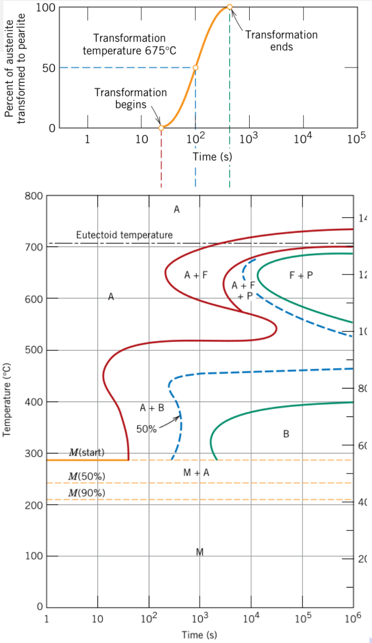
- When quenched to ∼ambient, Martensite
  - "Diffusion-less" transformation
  - Super-saturated carbon solution
  - Non-equilibrium, time-independent
- The presence of other alloy content changes these curves

Isothermal transformation diagram Jr and Rethwisch 2012



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3. Introduction to Material Science

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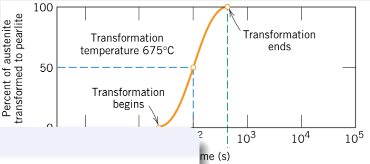

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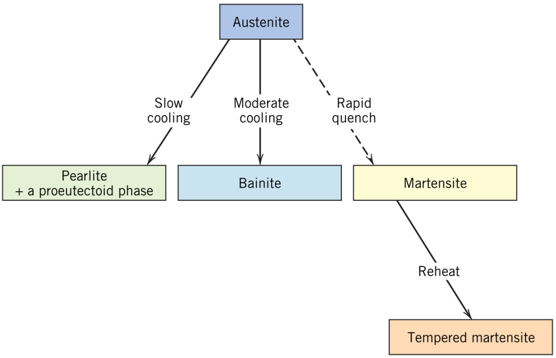
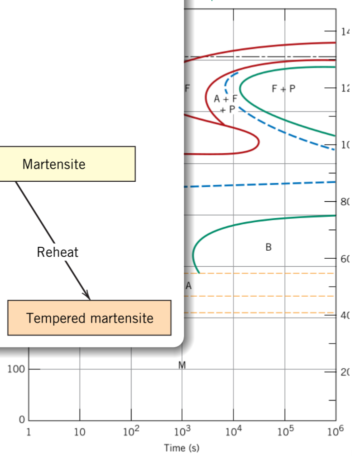
- For $T \in (215°$ Cementite) is f
- When quenche
  - "Diffusion-
  - Super-satu
  - Non-equilil
- The presence o curves

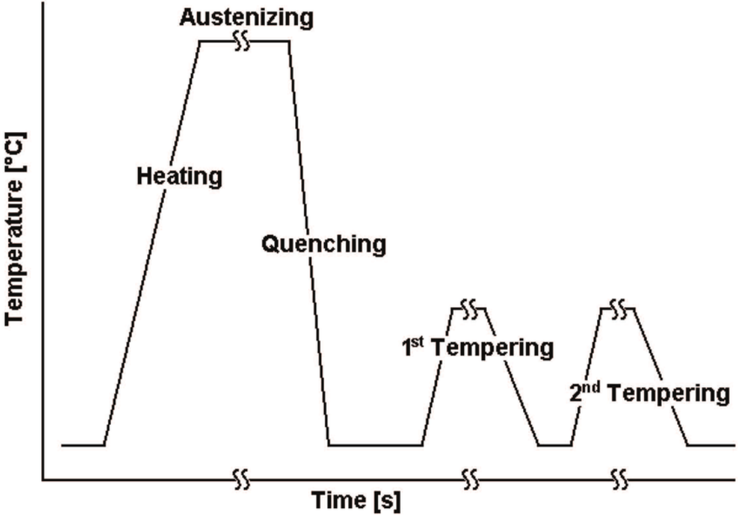
Summary





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

3. Introduction to Material Science



A typical heat treatment process involving Austenizing, quenching and tempering

3.3. Aluminum and its Alloys

Introduction to Material Science

Aluminum Association Number	UNS Number	Composition (wt%)[a]	Condition (Temper Designation)	Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications/ Characteristics
			Wrought, Non–Heat-Treatable Alloys				
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
			Wrought, Heat-Treatable Alloys				
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat-treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat-treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
			Cast, Heat-Treatable Alloys				
295.0	A02950	4.5 Cu, 1.1 Si	Heat-treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat-treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
			Aluminum–Lithium Alloys				
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat-treated, cold worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat-treated, cold worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

[a]The balance of the composition is aluminum.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

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Designation	Description
	Basic Tempers
F	As-fabricated–by casting or cold working
O	Annealed–lowest strength temper (wrought products only)
H	Strain-hardened (wrought products only)
W	Solution heat-treated–used only on products that precipitation harden naturally at room temperature over periods of months or years
T	Solution heat-treated–used on products that strength stabilize within a few weeks–followed by one or more digits
	Strain-Hardened Tempers[a]
H1	Strain-hardened only
H2	Strain-hardened and then partially annealed
H3	Strain-hardened and then stabilized
	Heat-Treating Tempers[b]
T1	Cooled from an elevated-temperature shaping process and naturally aged
T2	Cooled from an elevated-temperature shaping process, cold worked, and naturally aged
T3	Solution heat treated, cold worked, and naturally aged
T4	Solution heat treated and naturally aged
T5	Cooled from an elevated-temperature shaping process and artificially aged
T6	Solution heat treated and artificially aged
T7	Solution heat treated and overaged or stabilized
T8	Solution heat treated, cold worked, and artificially aged
T9	Solution heat treated, artificially aged, and cold worked
T10	Cooled from an elevated-temperature shaping process, cold worked, and artificially aged

[a]Two additional digits may be added to denote degree of strain hardening.
[b]Additional digits (the first of which cannot be zero) are used to denote variations of these 10 tempers.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reproduced with permission of ASM International, Materials Park, OH, 44073.

Temper Designations (Table 13.7 from Jr and Rethwisch 2012)

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
   - Aluminum and its Alloys

References I

[1] V Rajendran. Materials Science, Tata McGraw-Hill Education, 2011. ISBN: 978-1-259-05006-0 (cit. on pp. 2–10, 17–33).

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