Aalto University
School of Engineering

Engineering metals and alloys

Selection of Engineering Materials 2022

Courses in the master programme

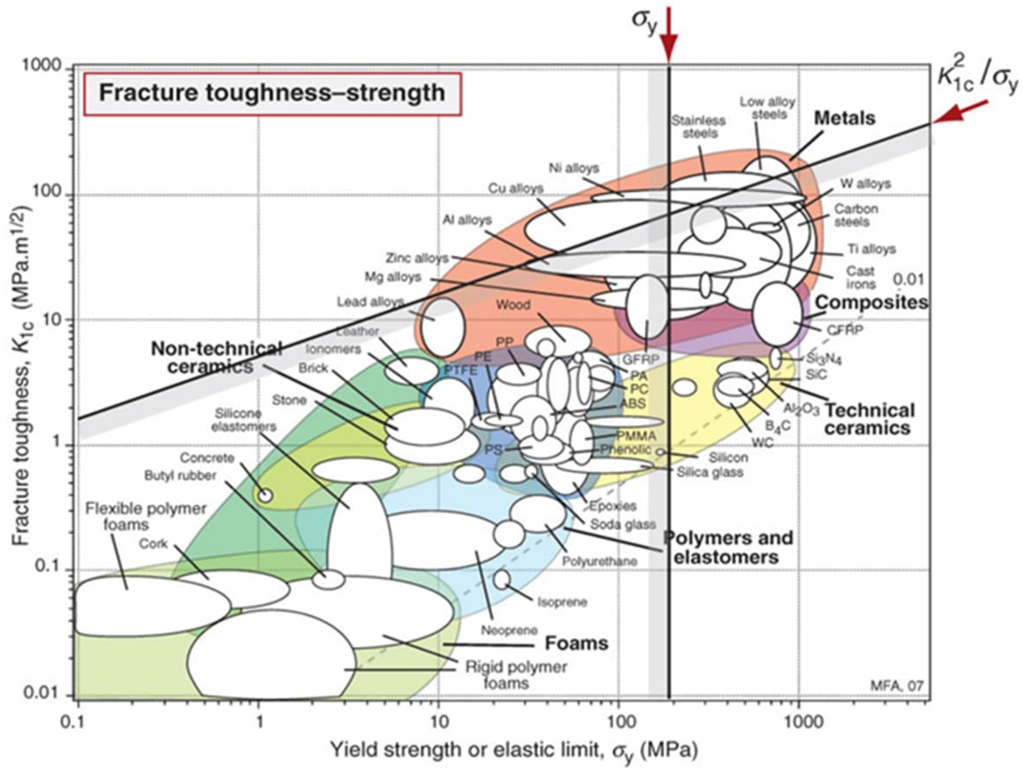
- **Engineering metals and alloys, 5 cr**
  - Period V
- **Engineering materials laboratory, 5 cr**
  - Periods I-II

Metals and alloys course content

- **Classification, properties and applications**
  - Steels, light alloys (Al, Mg, Ti), nickel and copper alloys
- **Steel metallurgy**
- **Heat treatments and strengthening**
  - Hardenability of steels
  - Thermomechanical treatments
  - Precipitation hardening (aluminium alloys)
- **Metal alloys in demanding applications**
  - High pressure, creep, corrosion, ...
- **Casting materials**
- **Assignments**

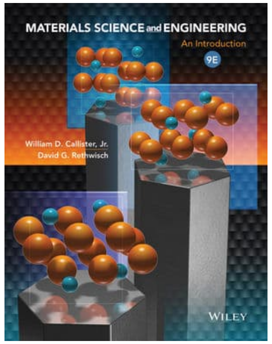
Motivation

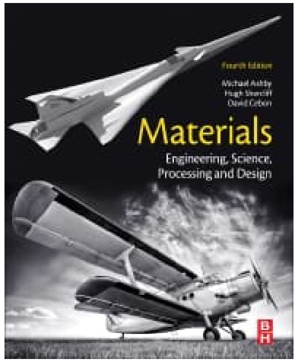
- **Metals, especially steels, are still the most important materials in mechanical engineering**
  - *have the best combination of strength, stiffness, and toughness*
  - *are relatively cheap*
  - *can be easily to shaped and joined*
  - *are good thermal and electrical conductors*
  - *are well known*

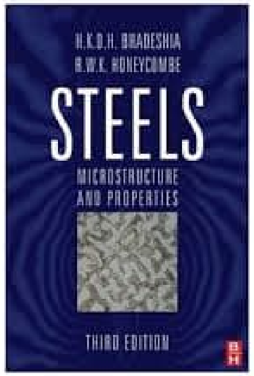


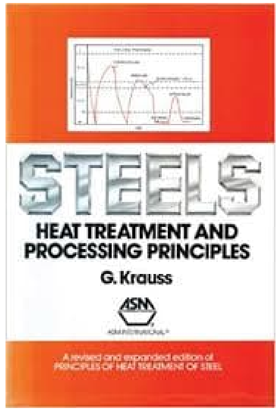
Literature

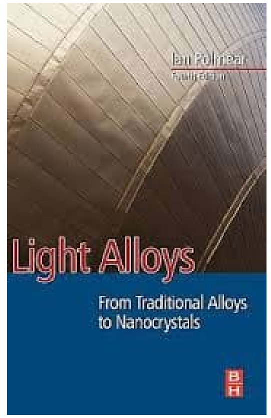
"Callister" "Ashby" "Honeycombe" ”Krauss" "Polmear"



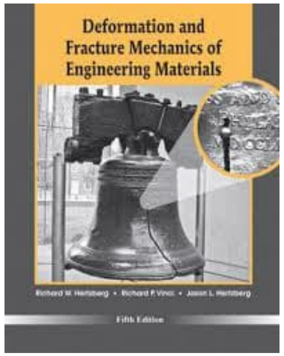


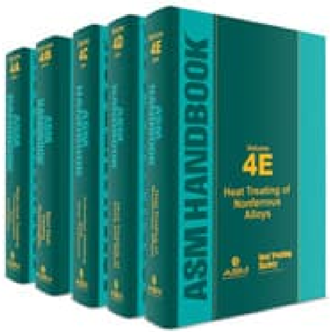






"Hertzberg" Metals Handbook "Chan-Haasen"





Ansys

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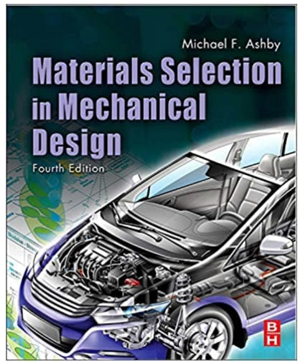
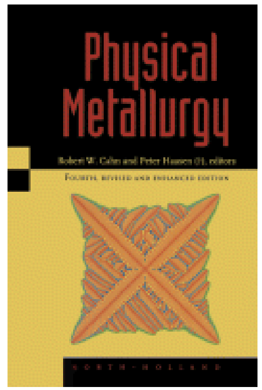
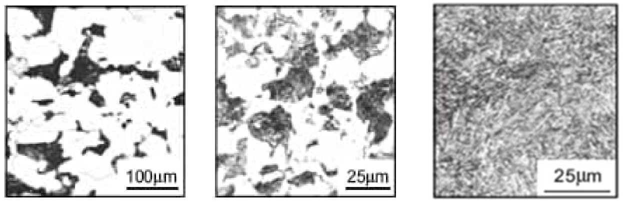




Composition + Processing → Microstructure + Properties

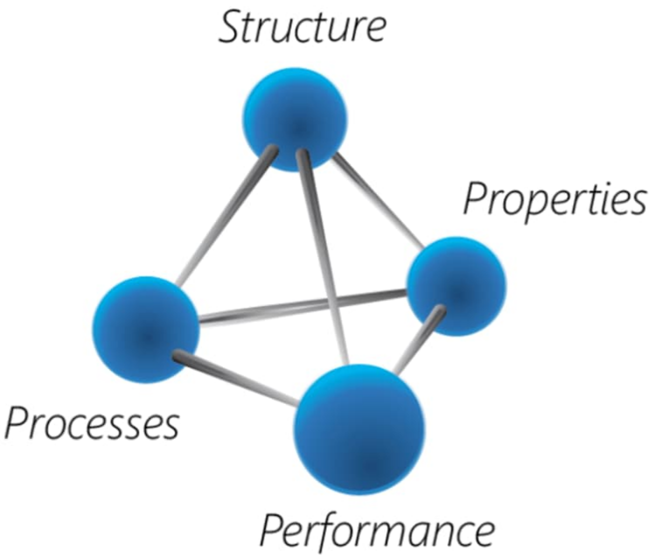
Phases, grain size, dislocation structure, …

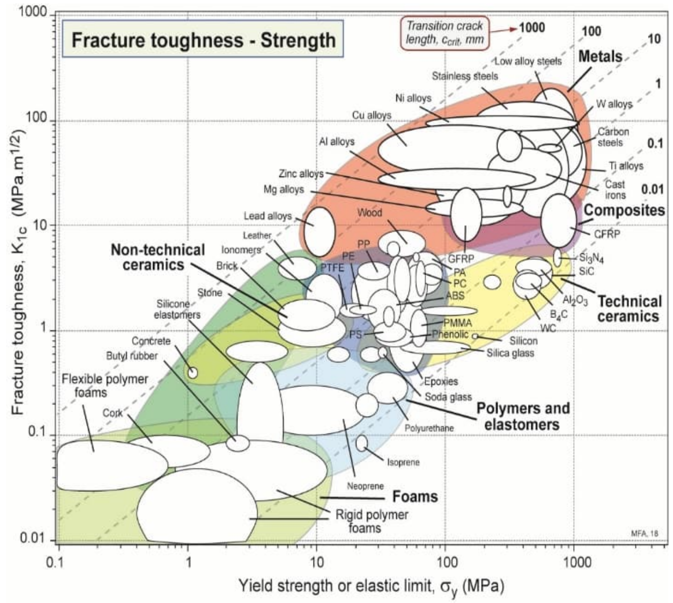
0.2wt% C steel, normalised	0.4wt% C steel, normalised	0.4wt% C steel, as-quenched



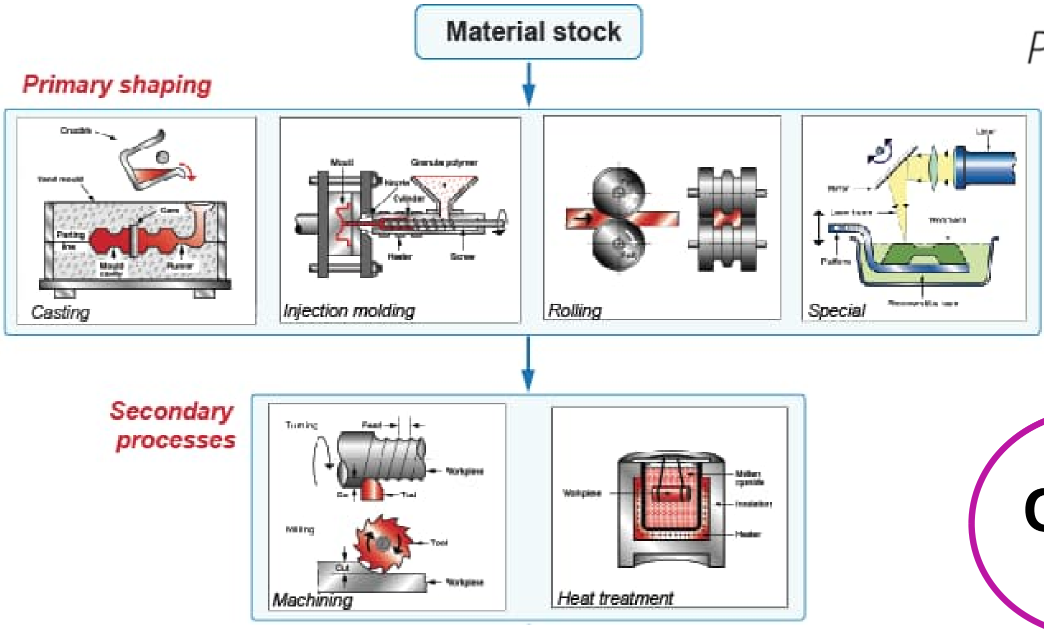
Ferrite + Pearlite | Martensite

Strength, stiffness, density, toughness,
corr. resistance, machinability, formability, weldability, …



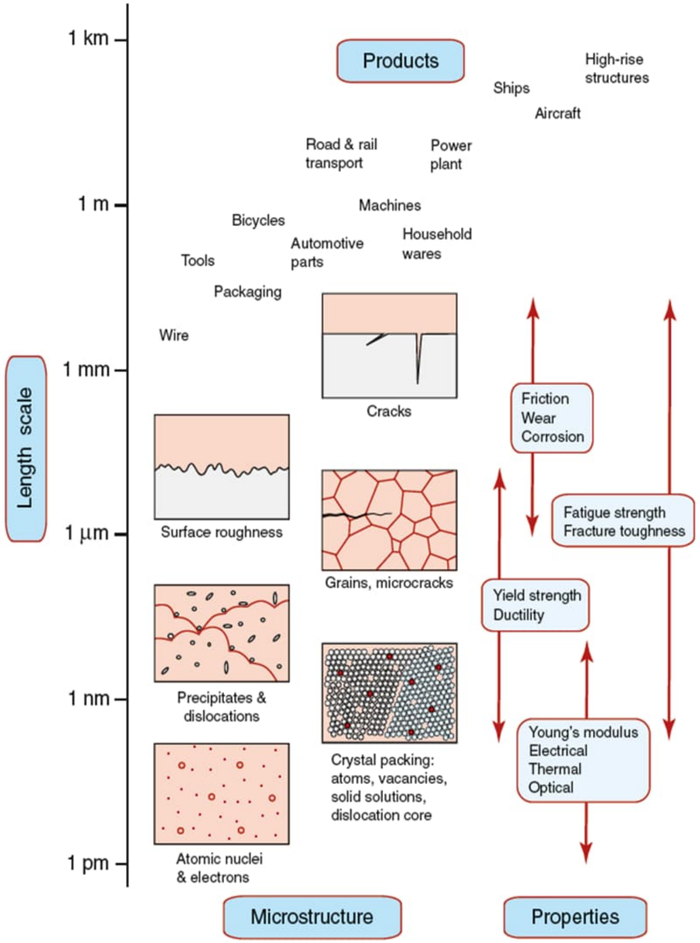


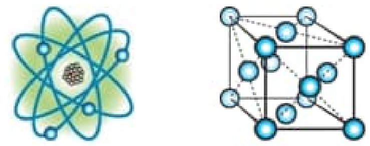
Heat treatment, forming,…



Cost

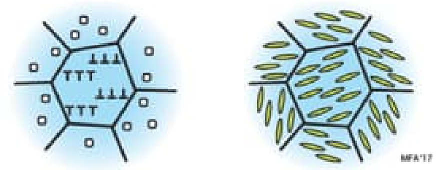
Properties, structure and scale





Microstructure-insensitive properties

- *Density*
- *Melting point*
- *Modulus*
- *Specific heat*
- *Expansion coefficient*
- *Heat of fusion, heat of vaporization*
- *Saturation magnetization*

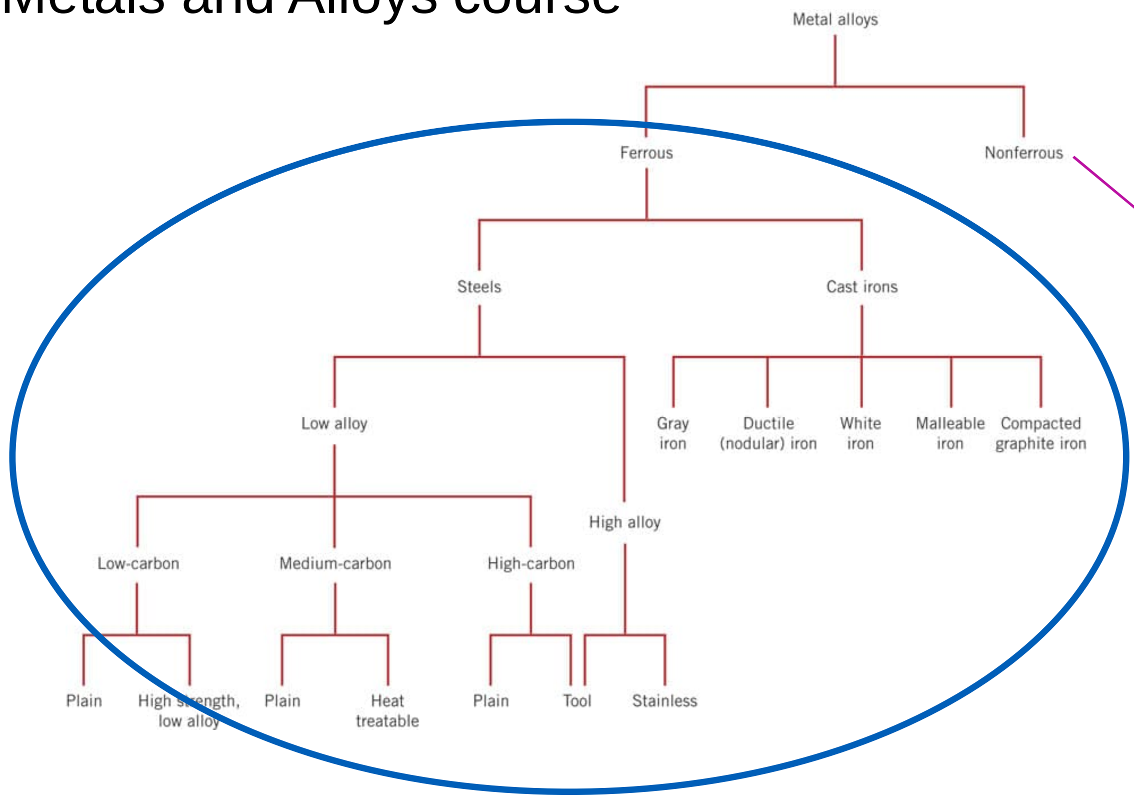


Microstructure-sensitive properties

- *Strength*
- *Toughness*
- *Elongation*
- *Thermal conductivity*
- *Electrical conductivity*
- *Coercive field*
- *Energy product*

Taxonomy of metals

Metals and Alloys course



Light alloys
- Aluminum
- Magnesium
- Titanium
- (Beryllium)

Copper alloys
- Copper
- Brasses

Nickel alloys
- Nickel
- Ni-Cu
- Ni-Fe
- Superalloys

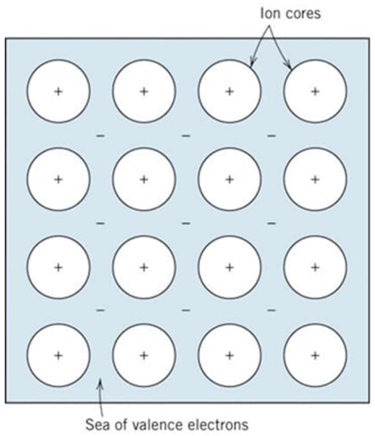
Refractory metals
- Molybdenum
- Niobium
- Tantalum
- Tungsten

Precious metals
- Gold
- Platinum
- Silver…

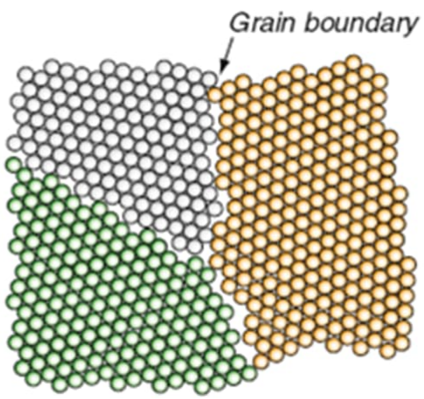
Rare earth metals
- Cerium
- Neodymium
- Yttrium…

Metal structure

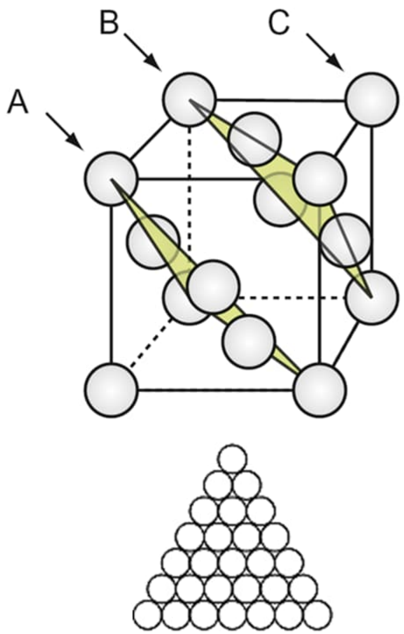
metallic bond



metal grains

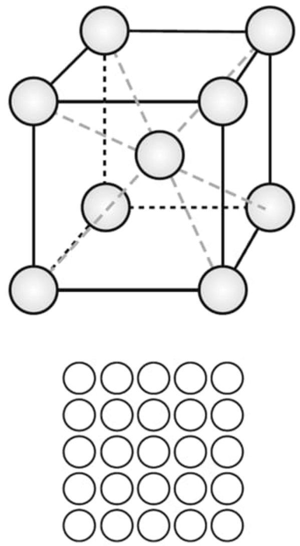


face centered cubic



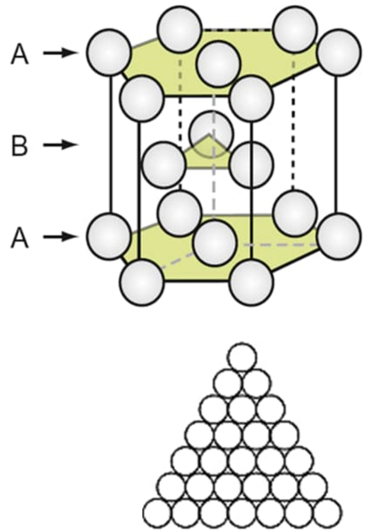
- Aluminium alloys
- Nickel alloys
- Copper and α-brass alloys
- Austenitic stainless steels
- Silver, gold, platinum, lead

body centered cubic



- Carbon steels
- Alloys steels
- β-titanium alloys
- Tungsten, chromium

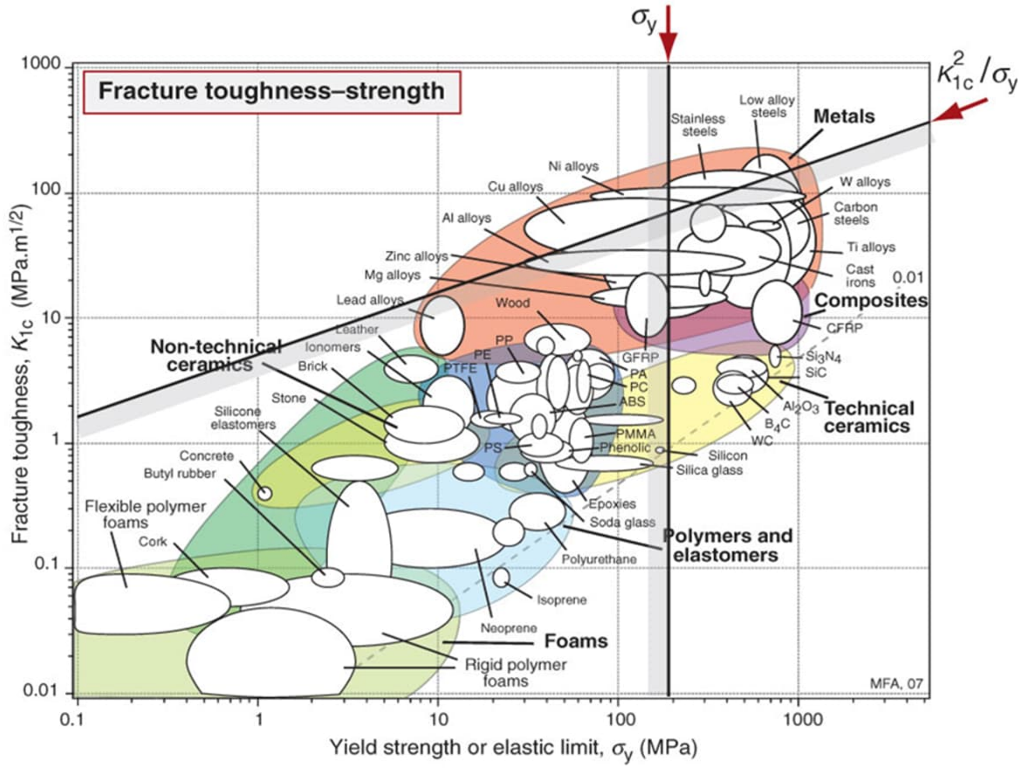
hexagonal close packed



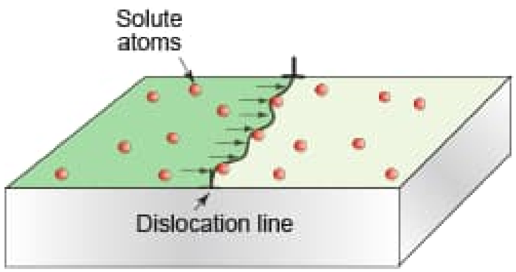
- α-titanium alloys
- Magnesium alloys
- Zinc, cobalt, beryllium

Strengthening of metals

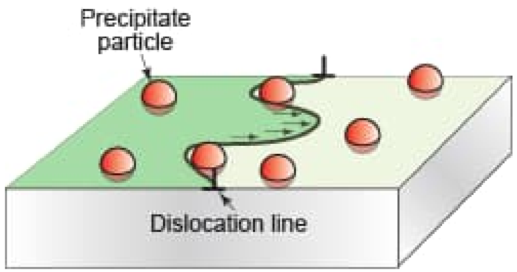
- **High strength, ductility and toughness are desirable (often exclusive)**
- **Strenghening in metals is based on reducing dislocation mobility**
- **Several ways to strengthen metals**
  - alloying
  - cold working
  - heat treatments
  - thermomechanical treatments
- **Respective strengthening mechanisms**
  - solid solution strengthening by substitutional or interstiatial atoms
  - work hardening by dislocations
  - precipitation hardening
  - refinement of grain size...
- **Certain analogy exists in heat treatments of metals but details are different**



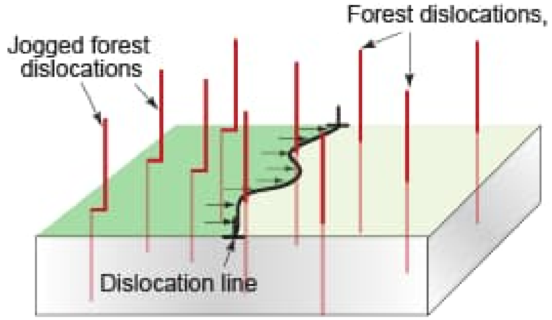
Drilling down: control of microstructure



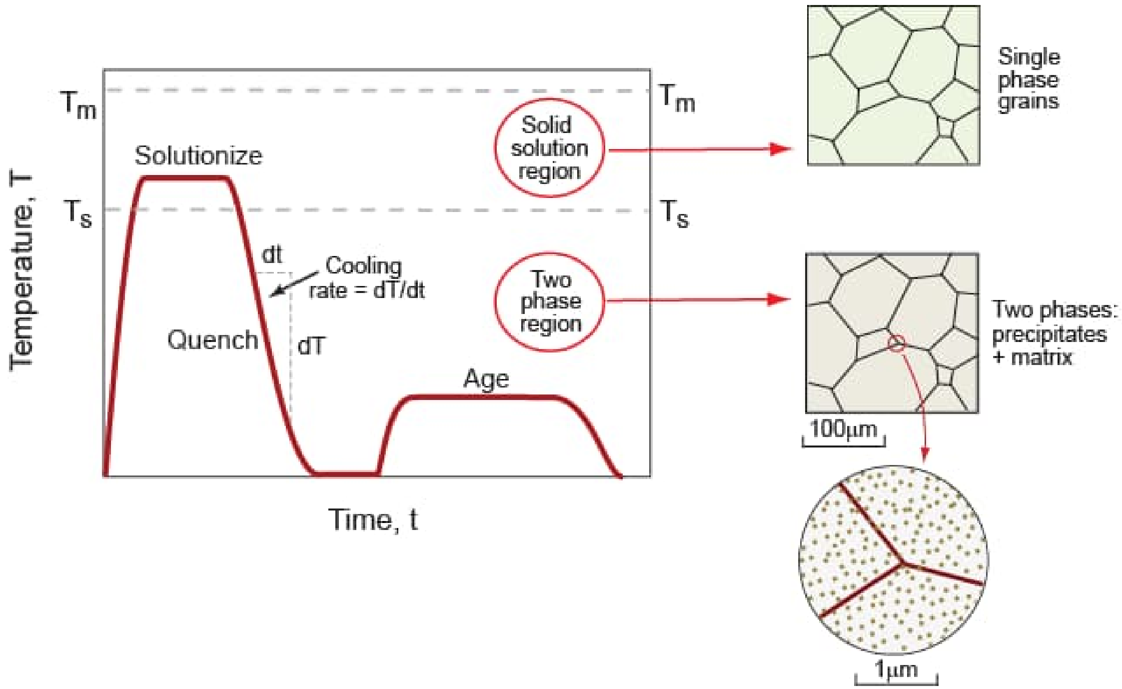
Solid solution hardening
(Composition)



Precipitation hardening
(Composition and microstructure)



Work hardening
(Microstructure)



Examples:

Heat-treatable Al alloys
(age hardening)

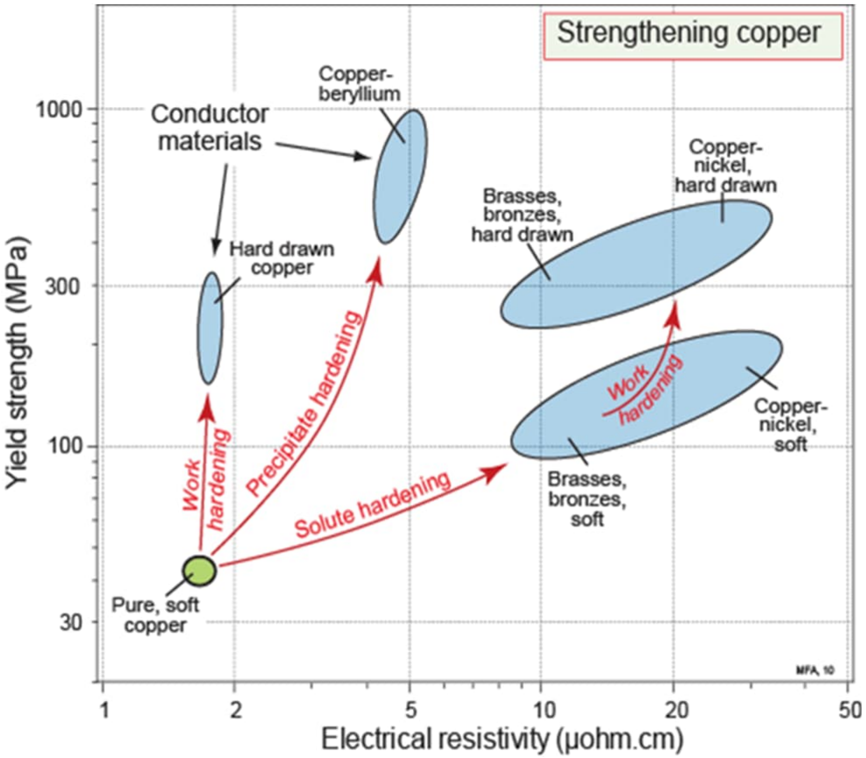
Carbon & alloy steels
(quench and temper)

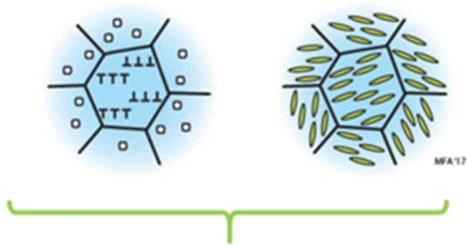
Strenghening mechanisms

- All strengthening mechanisms work together
- Contribution to yield stress for a martensitic steel

$$\sigma_{ys} = \underbrace{\sigma_i}_{\text{Peierls stress}} + \underbrace{k\sqrt{c}}_{\text{solid solution}} + \underbrace{kd^{-1/2}}_{\text{grain boundaries}} + \underbrace{\alpha G b\sqrt{\rho}}_{\text{dislocations}}$$

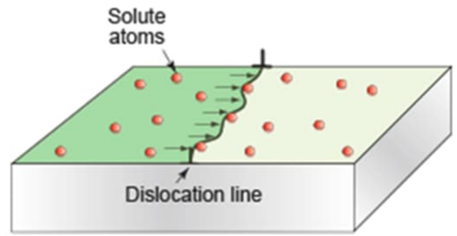
Electrical resistivity and strength of copper



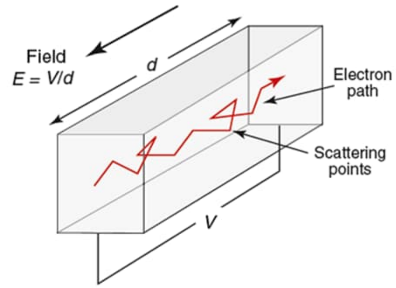


Microstructure-sensitive properties

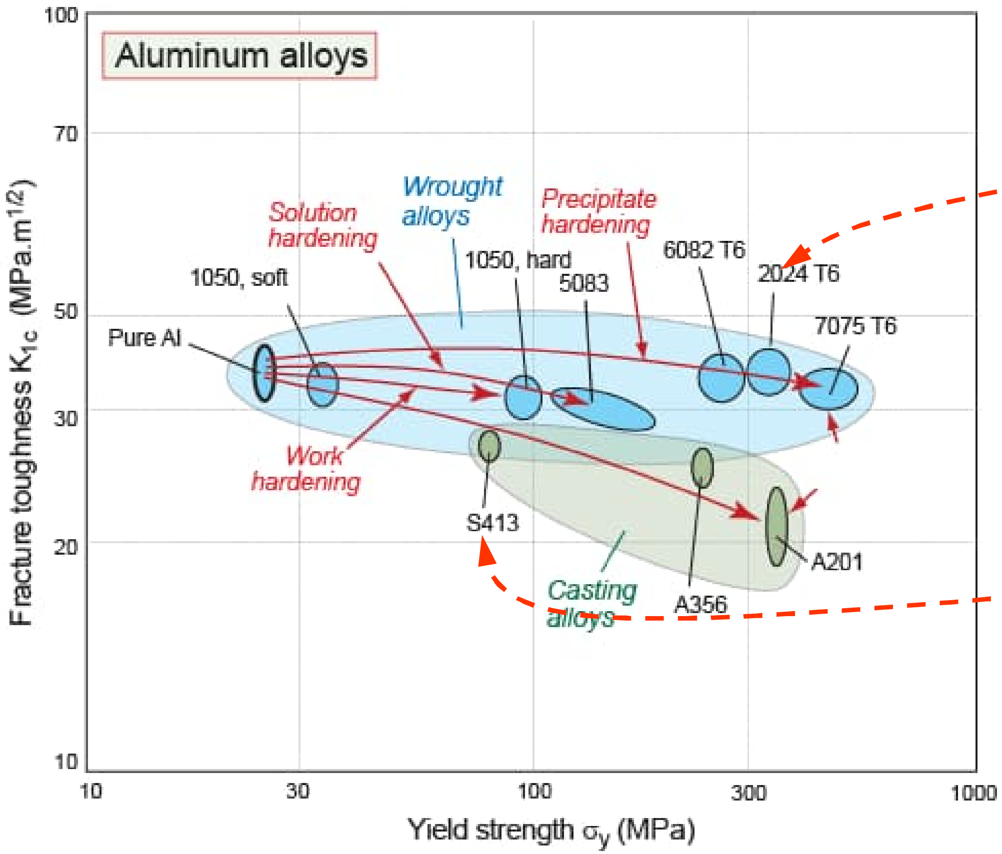
- *Strength*
- *Toughness*
- *Elongation*
- *Thermal conductivity*
- *Electrical conductivity*
- *Coercive field*
- *Energy product*

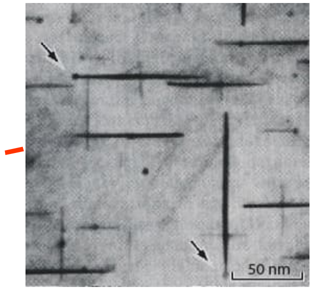


Solid solution hardening
(Composition)

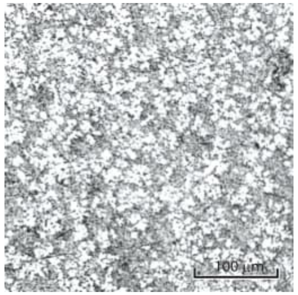


Aluminum alloys: strengthening and primary shaping



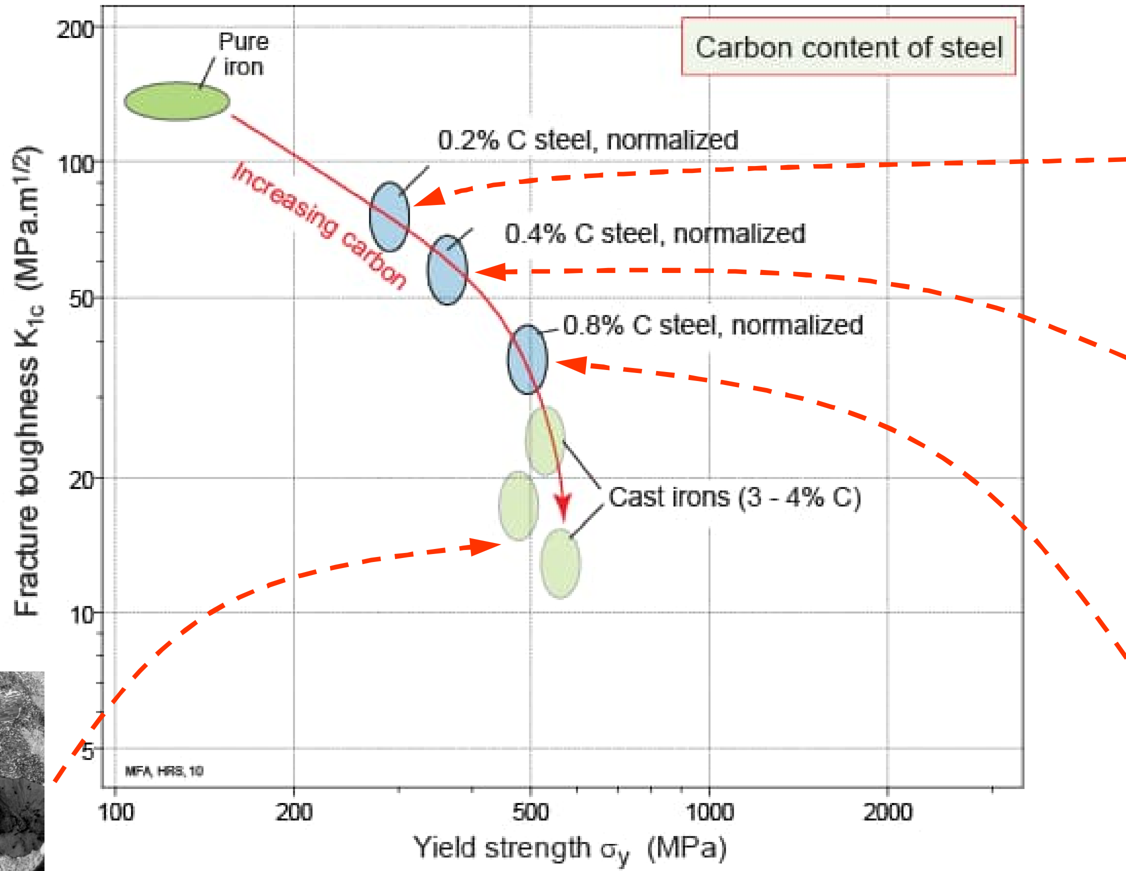


Al -Cu 2024

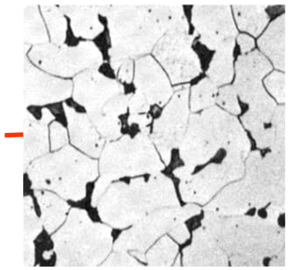


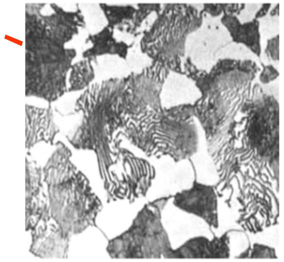
Al -Si S413

Steels: strength, toughness and carbon content

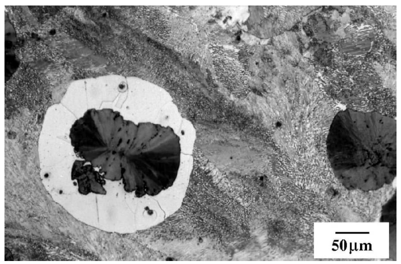


Ferrite + pearlite



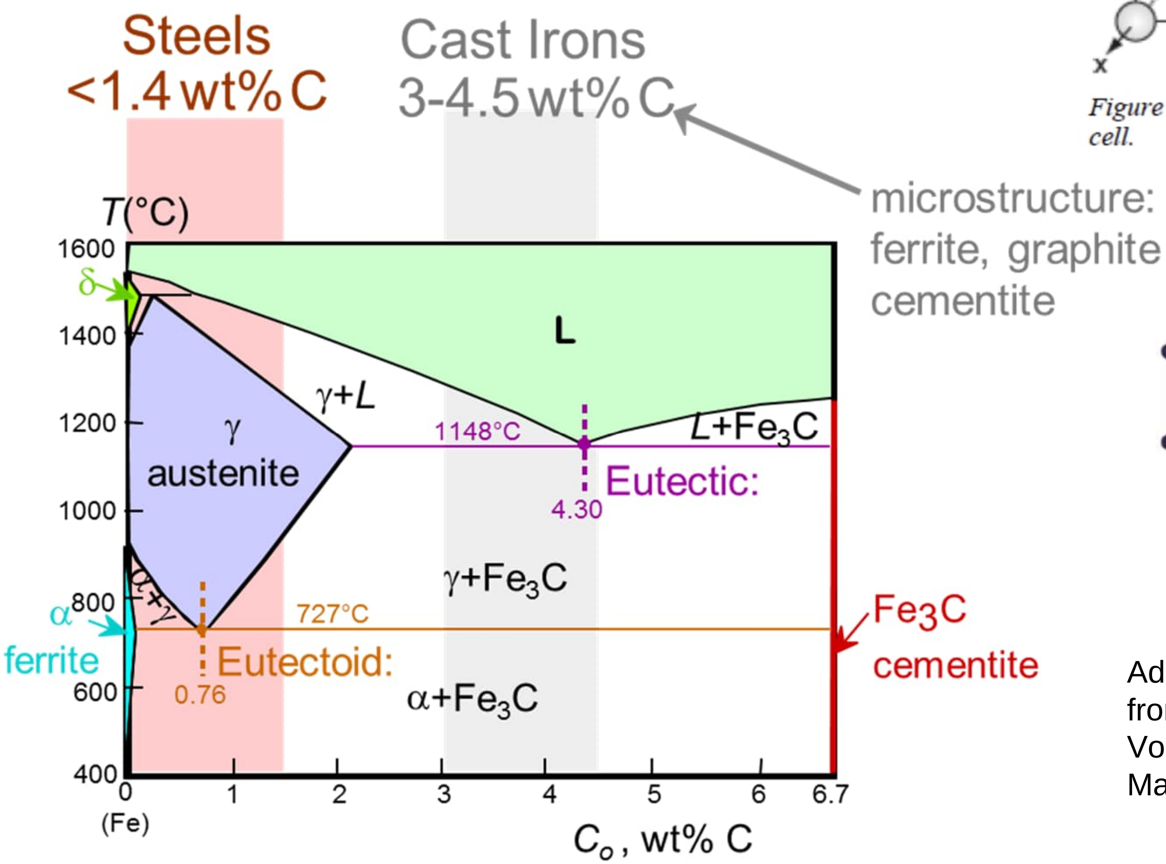


Ferrite + pearlite
+ graphite



Ferrous materials

practical limits of C



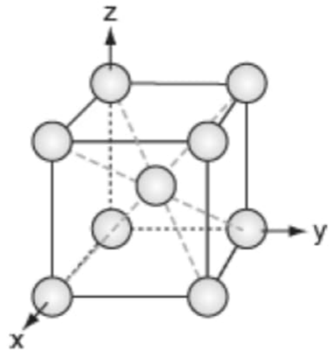


Figure C34. The BCC unit cell.

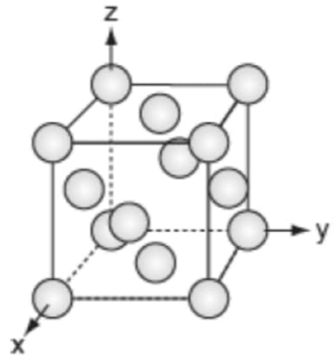
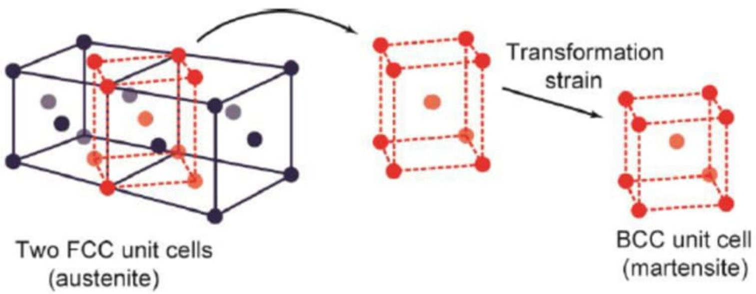
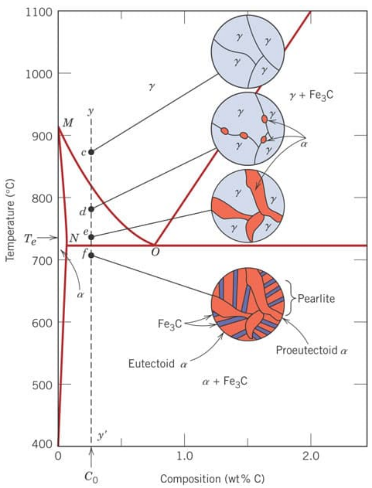


Figure C33. The FCC unit cell.

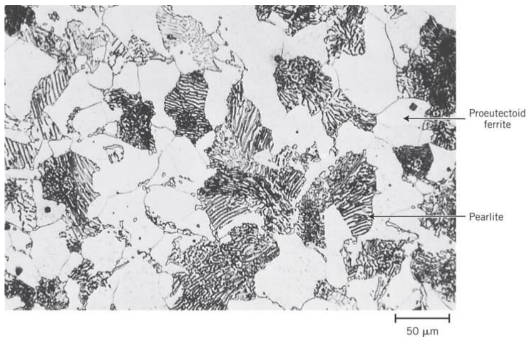


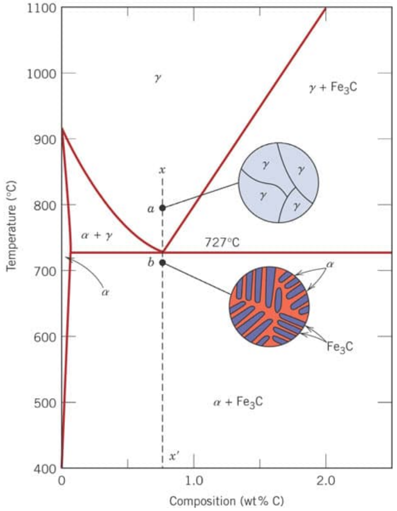
Adapted from Fig. 9.24, *Callister 7e*. (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

Austenite decomposition of carbon steel during slow cooling

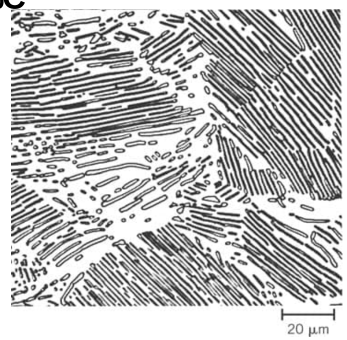


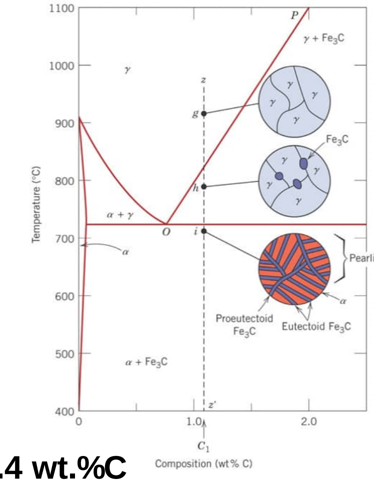
0.38 wt.%C



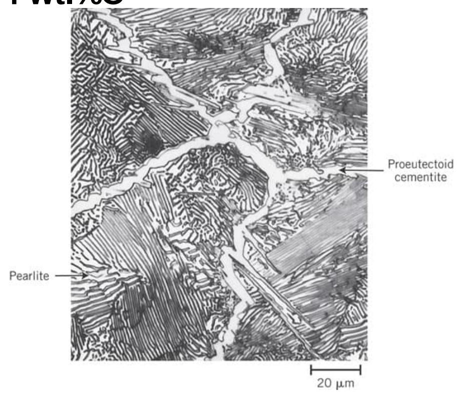


0.8 wt.%C





1.4 wt.%C



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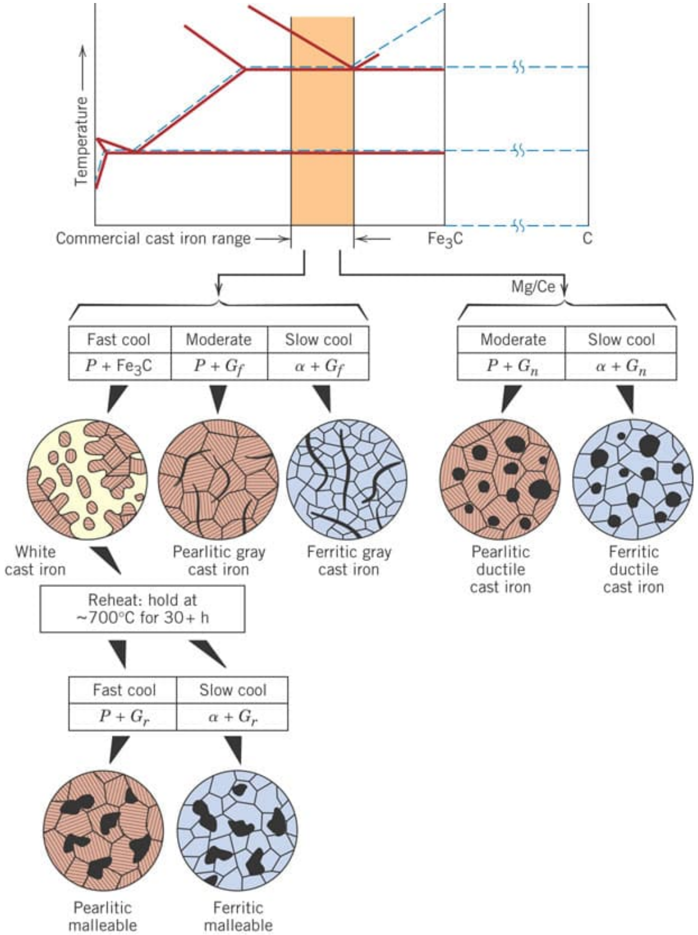
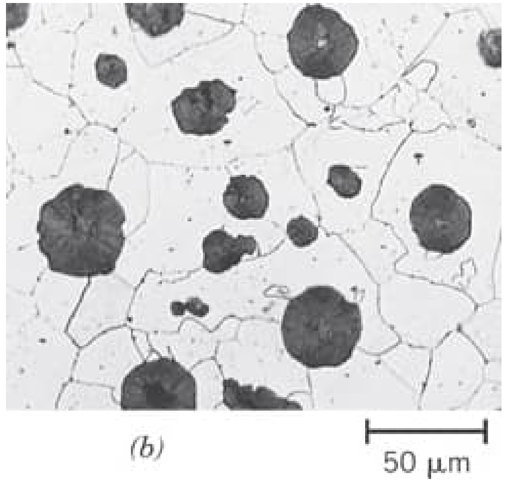
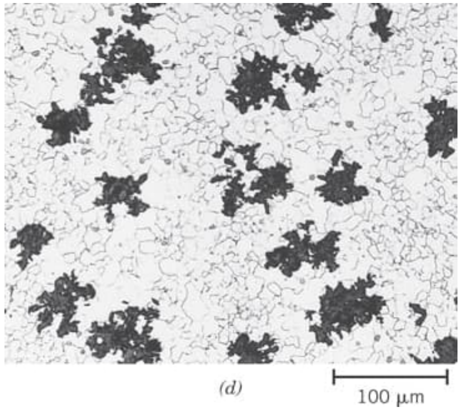
Cast irons



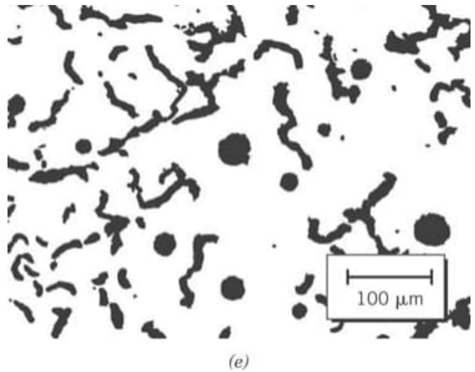
gray iron



nodular (ductile iron) graphite

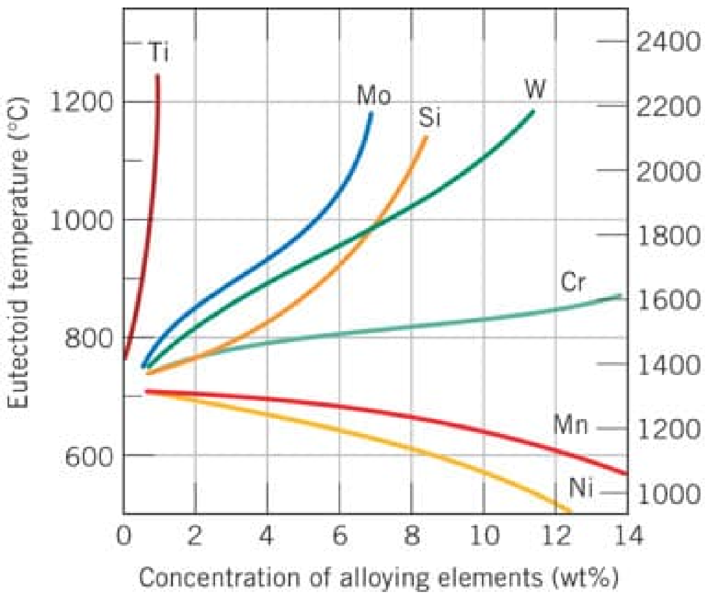


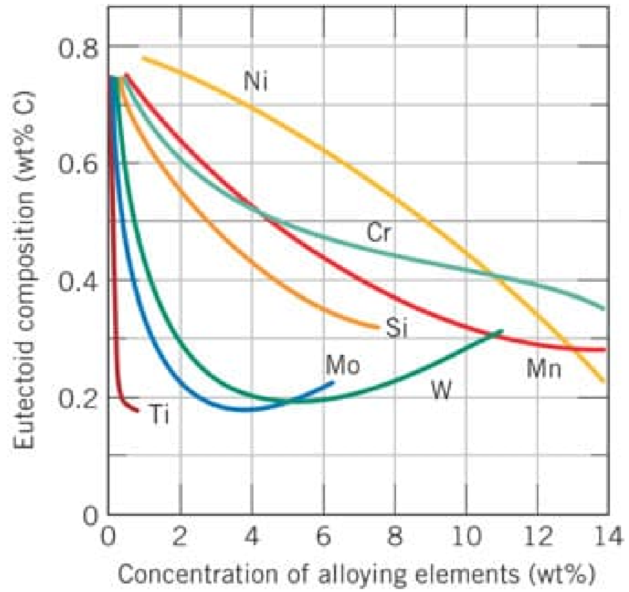
malleable iron



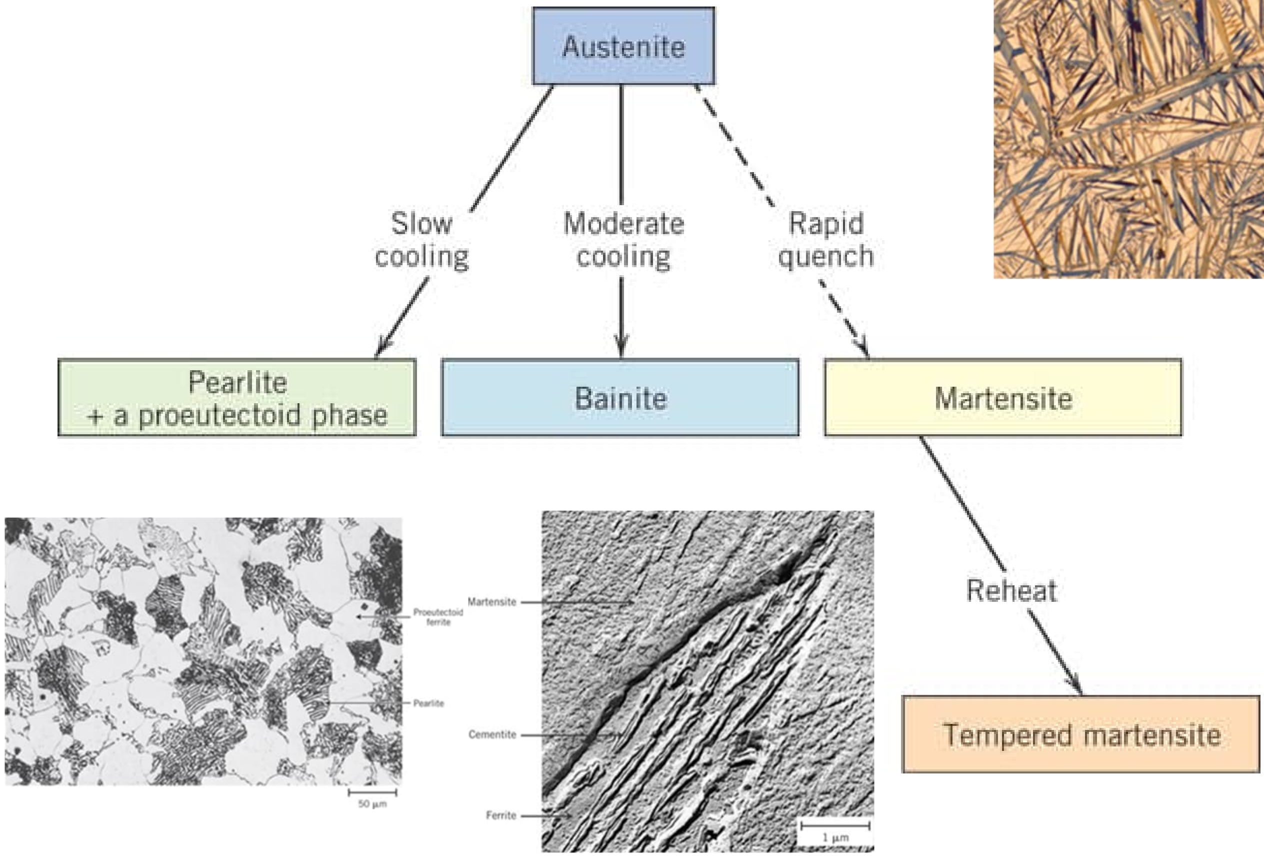
compacted graphite iron

Alloying effect on eutectoid point





Effect of cooling rate on austenite decomposition



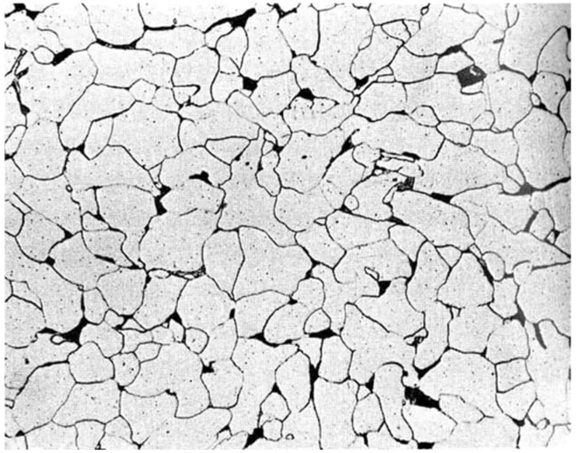
Strength

martensite
tempered martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

Basic low carbon steel

- C < 0.2 wt.%, Mn < 1.6 wt.%
- Strength (ys) 235-550 MPa, good elongation (25 %), toughness, formability and weldability
- Basic ferritic-pearlitic structural steel (e.g. S235, S355)
- Microstructure mainly ferritic with small amount of pearlite
- Steel structures, car sheet



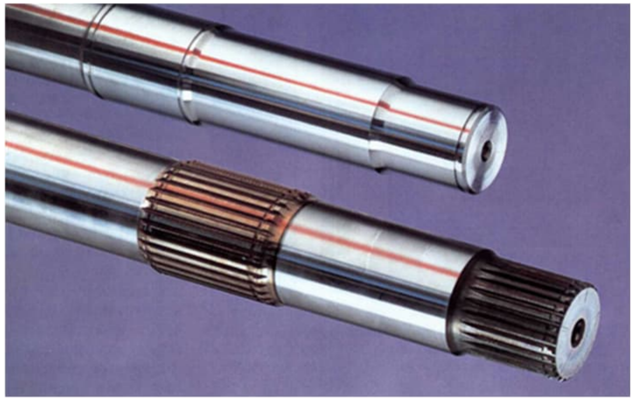
HSLA steels (high strength low alloy)

- **C 0.05…0.25 wt.%, Mn < 2.0 wt.%**
- **Microalloyed steels**
  - Small quantities of Cr, Ni, Mo, Cu, N, V, Nb, Ti, Zr in various combinations (microalloyed when < 0.15 % in total)
  - good strength, toughness, weldability and formability
- **High strength steels (HSS)**
  - Modern HSS have ys > 1000 MPa
- **Examples: weathering steels, DP (dual phase) steels, TRIP (transformation induced plasticity), TMCP (thermomechanically controlled process), CP (complex phase)**
- **Strengthened by fine grain size, heat treatment, or thermomechanical treatment**
- **Complex microstructures: fine grains, ferrite, bainite, retained austenite, martensite, dislocations**
- **Low impurity levels**
- **Examples S420N, P355NH, HSLA 350, CP 1000, Strenx 1300**
- **Bridges, cars, ships, pressure vessels, lifting booms**



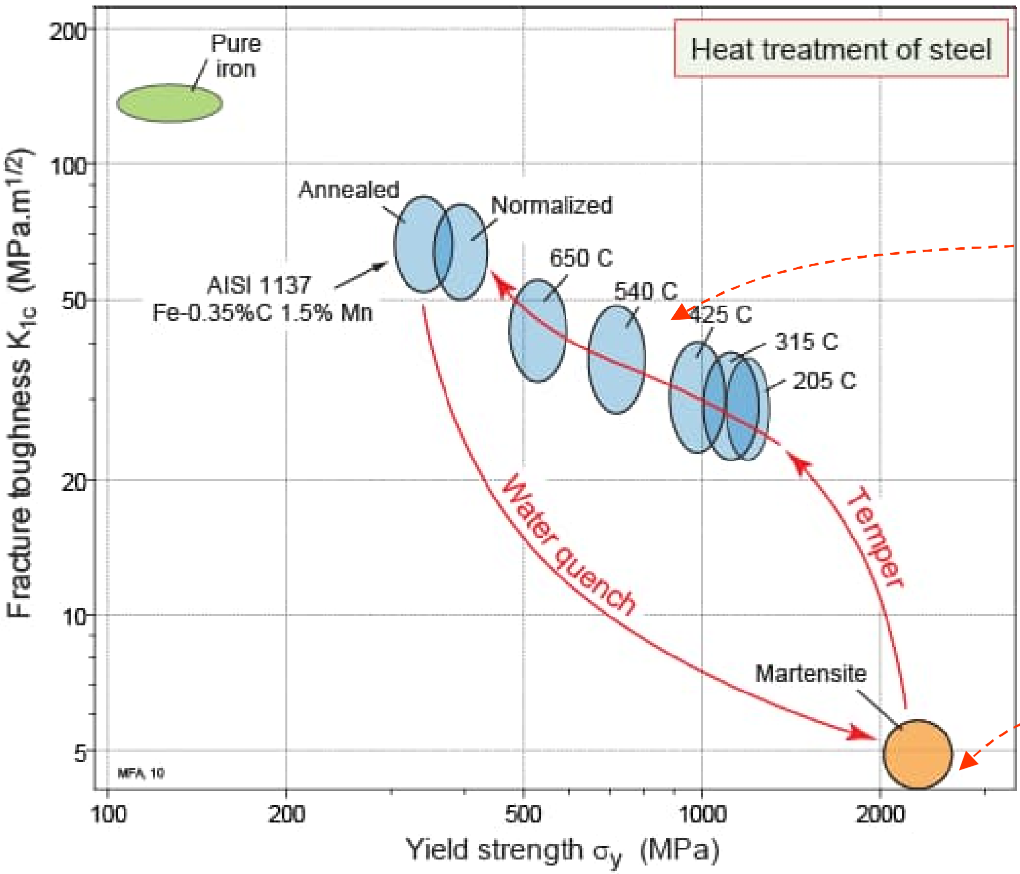

Medium carbon steels

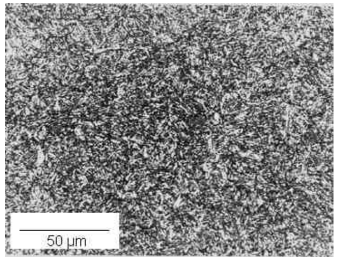
- **0.25-0.6 wt.% C**
- **Heat treated by austenizing, quenching and tempering**
- **Good combination of strength, fatigue resistance and toughness**
  - properties depend on carbon content, alloying and heat treatment
- **Typical microstructure tempered martensite**
- **Plain carbon steels**
  - low hardenability
  - e.g. C45 steel
  - simple geometries and small parts
  - ys 500-1000 MPa
- **Low alloy steels (Cr, Ni, Mn, Mo)**
  - hardenability increases with alloying
  - quenched and tempered steels, e.g. 42CrMo4
  - case hardening steels, e.g. 21CrNiMo2 (note! 0.15-0.25 %C)
  - ys 700-1900 MPa
- **Gears, shafts, springs, pistons, blades,…**



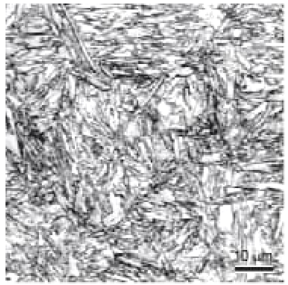
Control by microstructure: steels

Steels: Change of microstructure at constant composition





Tempered martensite



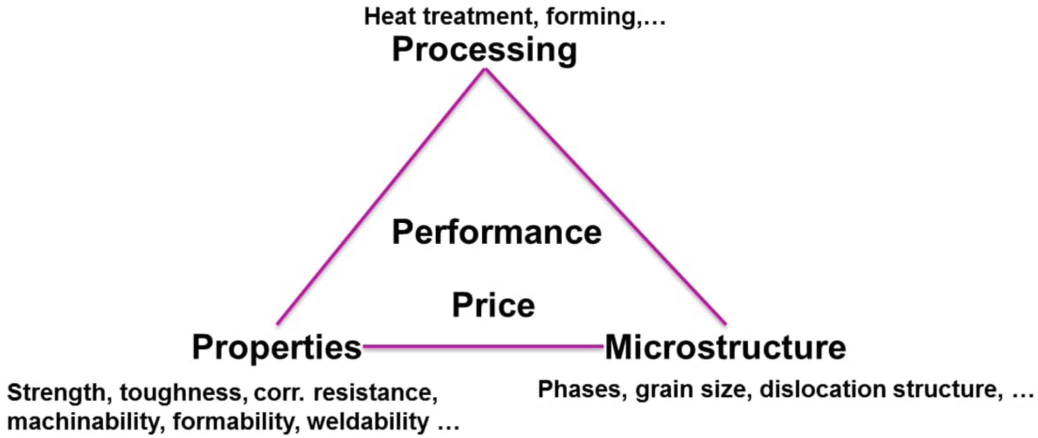
As-quenched (martensite)

High carbon steels

- **Usually quenched and tempered**
  - ys > 750 MPa
- **Plain carbon (with 0.3…0.9 % Mn)**
  - e.g. rails, tools, blades, wires, springs, wear resistant plates
  - e.g. AISI 1095
- **Alloyed high carbon tool steels**
  - Cr, V, W, Mo forms hard and wear resistant compounds (e.g. $Cr_{23}C_6$, V_4C_3, WC)
  - low and high alloy steels
  - e.g. cold work, hot work, high speed, shock resisting steels
  - e.g. AISI D2
- **Strength and hardness increase with carbon content (weldability, ductility and impact toughness reduce)**

Cutting tool

- Properties required?
- Material?
- Processing?
- Microstructure?



- High strength at elevated temperatures
- Good toughness
- Wear resistance, low cost…
- Cemented carbides (WC-Co), high speed steel (ex. AISI M2)

CES EduPack 2016 - [MaterialUniverse:\Metals and alloys\Ferrous\Tool steels\AISI MX series (Molybdenum high speed tool steels)]

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Browse

Database: Level 3 Change...

Table: MaterialUniverse

Subset: All materials

- MaterialUniverse
  - Ceramics and glasses
  - Fibers and particulates
  - Hybrids: composites, foams, honeycombs, natural materials
  - Metals and alloys
    - Ferrous
      - Alloy steels
      - Carbon steels
      - Cast irons
      - Coated steels
      - Iron, commercial purity
      - Microalloy and high strength steels
      - Stainless steels
      - Tool steels
        - AISI AX series (Air-hardening cold work tool steels)
        - AISI DX series (High-carbon, high-chromium, cold-wor
        - AISI HX series (Chromium hot work tool steels)
        - AISI HX series (Tungsten hot work tool steels)
        - AISI LX series (Special purpose tool steels)
        - AISI MX series (Molybdenum high speed tool steels)
          - AISI M1
          - AISI M10
          - AISI M2, high carbon
          - AISI M2, regular carbon
          - AISI M3, class 1
          - AISI M3, class 2
          - AISI M30
          - AISI M33
          - AISI M34
          - AISI M36
          - AISI M4
          - AISI M41
          - AISI M42
          - AISI M43
          - AISI M44
          - AISI M46
          - AISI M47
          - AISI M6
          - AISI M7
        - AISI OX series (Oil-hardening cold work tool steels)
        - AISI PX series (Low-carbon mold tool steels)
        - AISI SX series (Shock-resisting tool steels)
        - AISI TX series (Tungsten high speed tool steels)
          - AISI T1
          - AISI T15
          - AISI T2
          - AISI T4
          - AISI T5
          - AISI T6
          - AISI T8
        - AISI WX series (Water-hardening tool steels)
    - Magnetic

Home | Tool steels | Tool steel, molybdenum...

Tool steel, molybdenum alloy, AISI M2, high carbon (high speed)

Layout: All attributes | Show/Hide

Metals and alloys > Ferrous > Tool steels > AISI MX series (Molybdenum high speed tool steels) >

General information

Designation

AISI M2

Condition	Annealed; oil quenched, salt bath quenched or air cooled; tempered at 540–595°C
UNS number	T11302
US name	AISI / SAE M2
ISO name	~40CrMnNiMo8 6 4
JIS (Japanese) name	~SKH51

Typical uses

Cutting tools, Single point types, Milling cutters, Drills, Reamers, Taps, Threading dies, Form cutters
Hot forging tools and dies, Dies and inserts, Forging machine plungers and piercers (combining hot hardness with high abrasion resistance)
Hot extrusion tools and dies, Extrusion dies and mandrels, Dummy blocks, Valve extrusion tools
Cold-forming dies, bending, forming, drawing, and deep-drawing dies and punches
Shearing tools, Dies for piercing, punching, and trimming, Shear blades
Structural parts for severe service conditions

Composition overview

Compositional summary

Fe79-84 / W5.5-6.8 / Mo4.5-5.5 / Cr3.8-4.5 / V1.6-2.2 / C0.78-0.88 / Mn0.2-0.4 / Si0.2-0.4 (impurities: Ni<0.3, P<0.03, S<0.03)

Material family	Metal (ferrous)
Base material	Fe (Iron)

Composition detail (metals, ceramics and glasses)

C (carbon)	0,78	-	0,88	%
Cr (chromium)	3,75	-	4,5	%
Fe (iron)	79	-	83,5	%
Mn (manganese)	0,2	-	0,4	%
Mo (molybdenum)	4,5	-	5,5	%
Ni (nickel)	0	-	0,3	%
P (phosphorus)	0	-	0,03	%
S (sulfur)	0	-	0,03	%
Si (silicon)	0,2	-	0,4	%
V (vanadium)	1,6	-	2,2	%
W (tungsten)	5,5	-	6,75	%

Price

Price	* 6,7	-	8,39	EUR/kg

Physical properties

Density	8,08e3	-	8,25e3	kg/m^3

Mechanical properties

Risto Ilola 26.09.2022

Ready NUM

CES EduPack 2016 - [MaterialUniverse:\Metals and alloys\Ferrous\Tool steels\AISI MX series (Molybdenum high speed tool steels)]

Tool steel, molybdenum alloy, AISI M2, high carbon (high speed)

Layout: All attributes

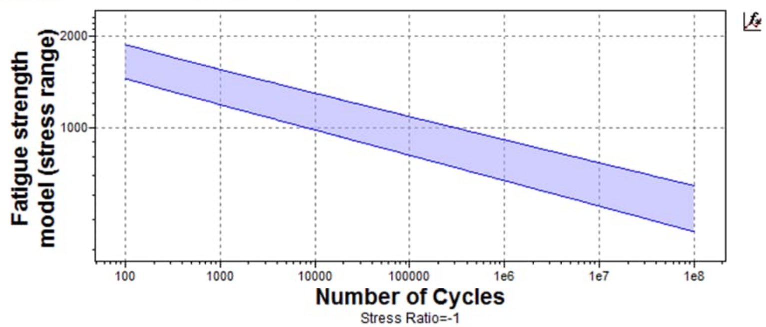
Physical properties

Density	8,08e3	-	8,25e3	kg/m^3

Mechanical properties

Young's modulus	222	-	234	GPa
Yield strength (elastic limit)	* 2e3	-	2,37e3	MPa
Tensile strength	* 2,23e3	-	2,58e3	MPa
Elongation	* 1,9	-	4,5	% strain
Compressive strength	* 2e3	-	2,37e3	MPa
Flexural modulus	* 222	-	234	GPa
Flexural strength (modulus of rupture)	* 2e3	-	2,37e3	MPa
Shear modulus	* 86	-	91	GPa
Bulk modulus	* 176	-	185	GPa
Poisson's ratio	0,285	-	0,295	
Shape factor	12			
Hardness - Vickers	700	-	840	HV
Hardness - Rockwell C	60	-	65	
Fatigue strength at 10^7 cycles	* 599	-	711	MPa
Fatigue strength model (stress range)	* 555	-	768	MPa

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta)	* 1,45e-5	-	1,94e-5	

Impact & fracture properties

Fracture toughness	* 17,8	-	20,4	MPa.m^0.5

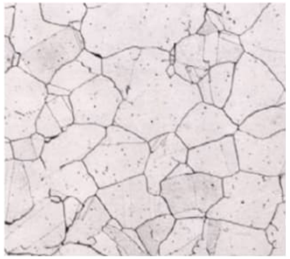
Thermal properties

Melting point	* 1,43e3	-	1,48e3	°C
Maximum service temperature	* 530	-	580	°C
Minimum service temperature	* -73	-	-53	°C
Thermal conductivity	21	-	23	W/m.°C

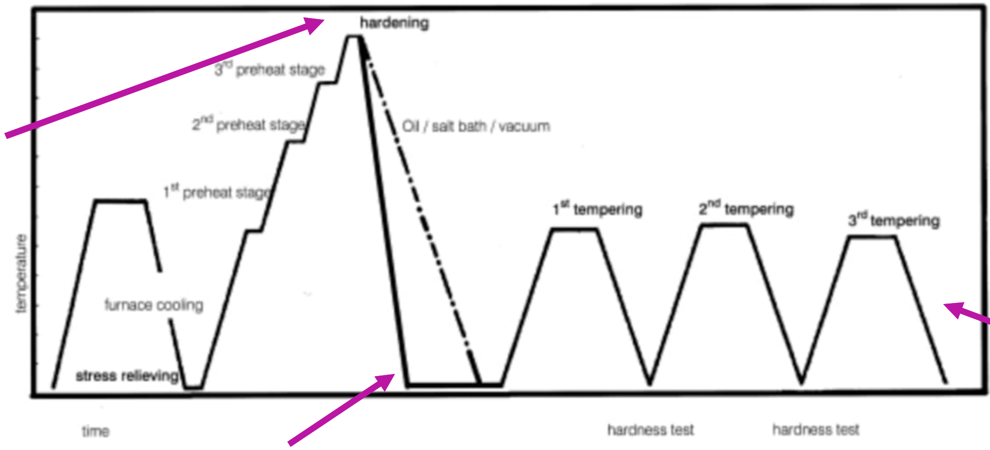
Risto Ilola 26.09.2022

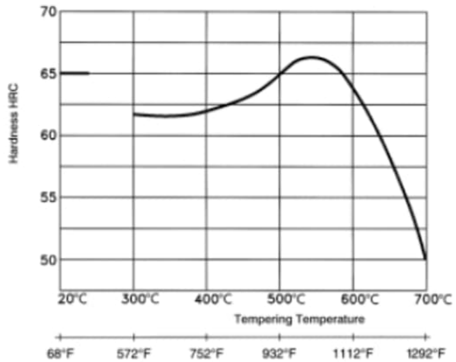
Heat treatment and microstructure of AISI M2 tool steel

Typical analysis %	C 0.85/0.90	Mn 0.25	Cr 4.10	Mo 5.00	V 1.90	W 6.40
Standard specification	~AISI M2, DIN/EN 1.3343					
Color code	Gold/Green					

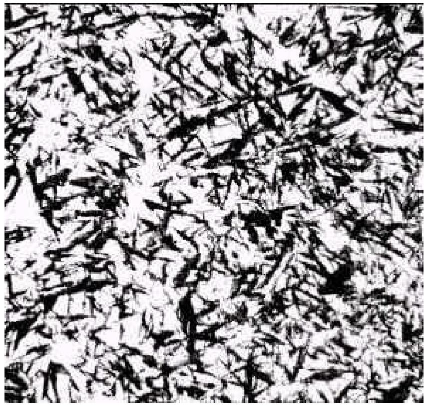


austenite

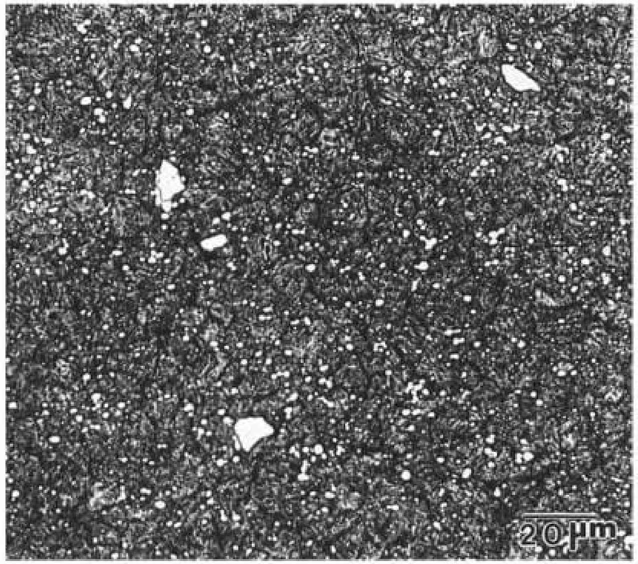




martensite and retained austenite



tempered martensite and carbides

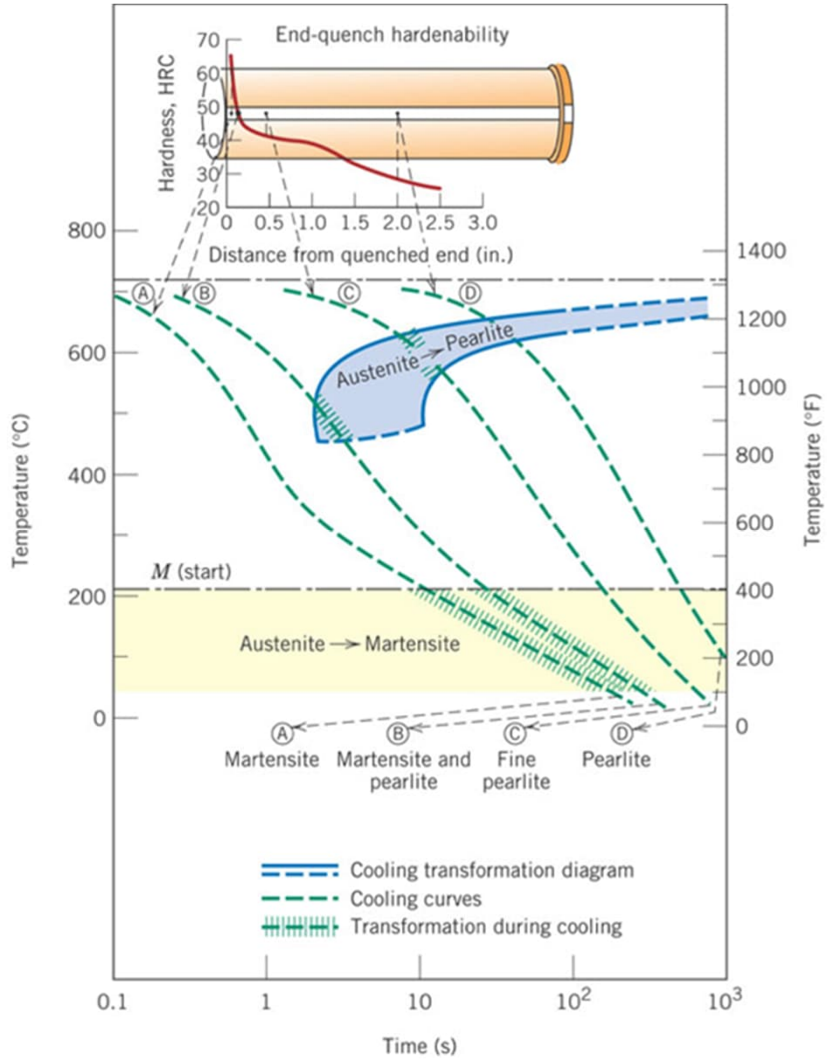


Microstructure of M-2 High-Speed Tool Steel

Aalto University
School of Engineering

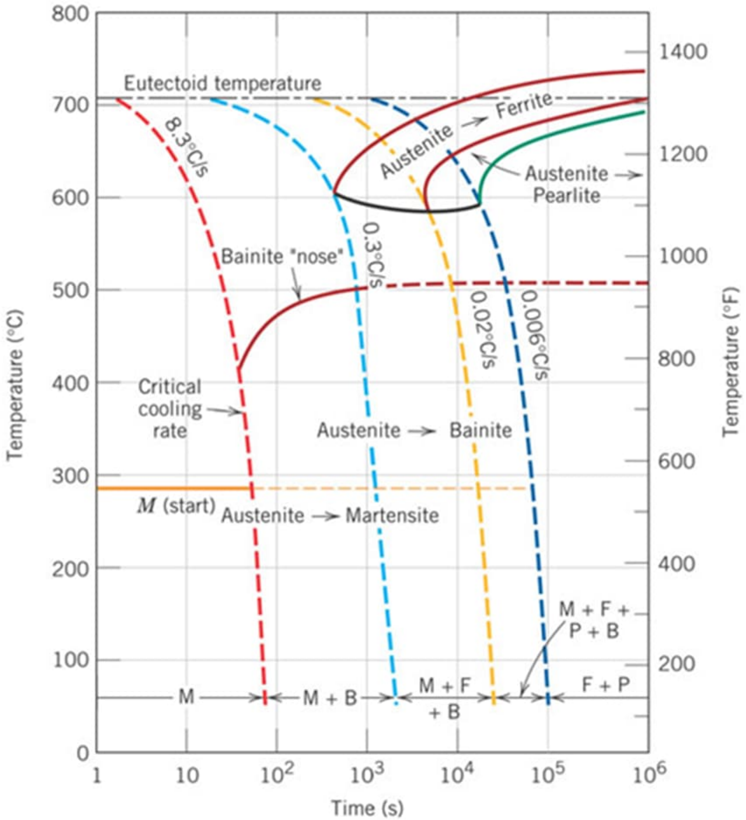
Hardenability of steels

- **Important property for steels in engineering**
- **Ability to form martensite (not the martensite strength!)**
- **Depends on chemical composition**
  - TTT and CCT diagrams
  - Critical cooling rate
- **Evaluation with jominy test**

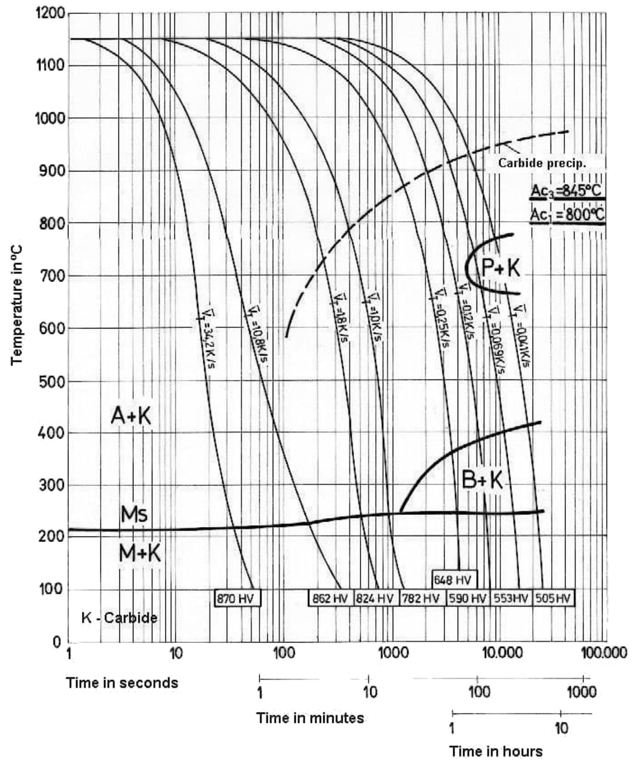


CCTs for AISI 4340 and M2

Fe-0.4C-2Ni-1Cr-0.2Mo



Fe-0.8C-4Cr-5Mo-6W-2V

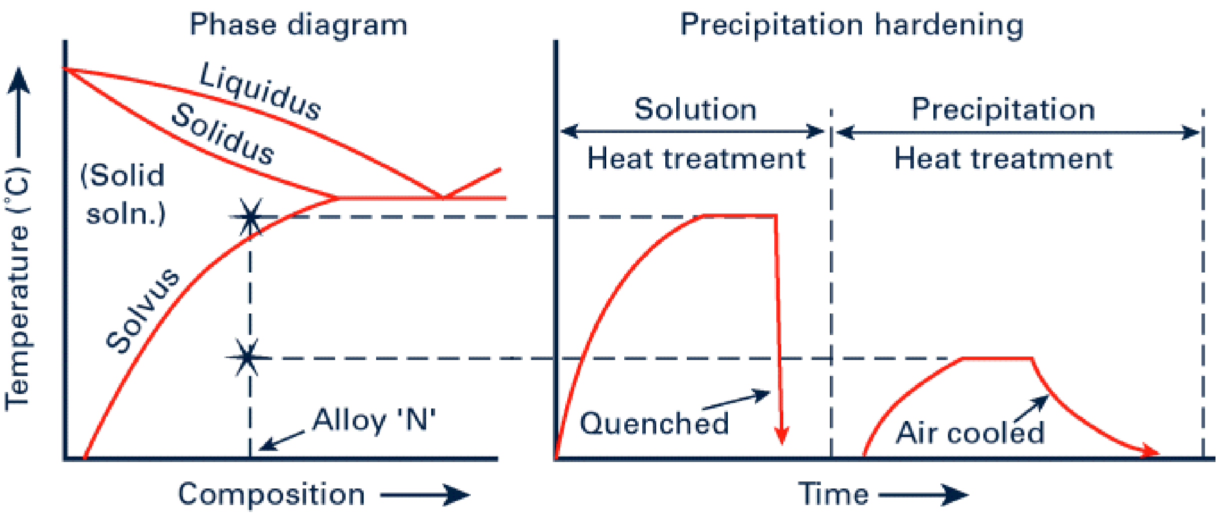


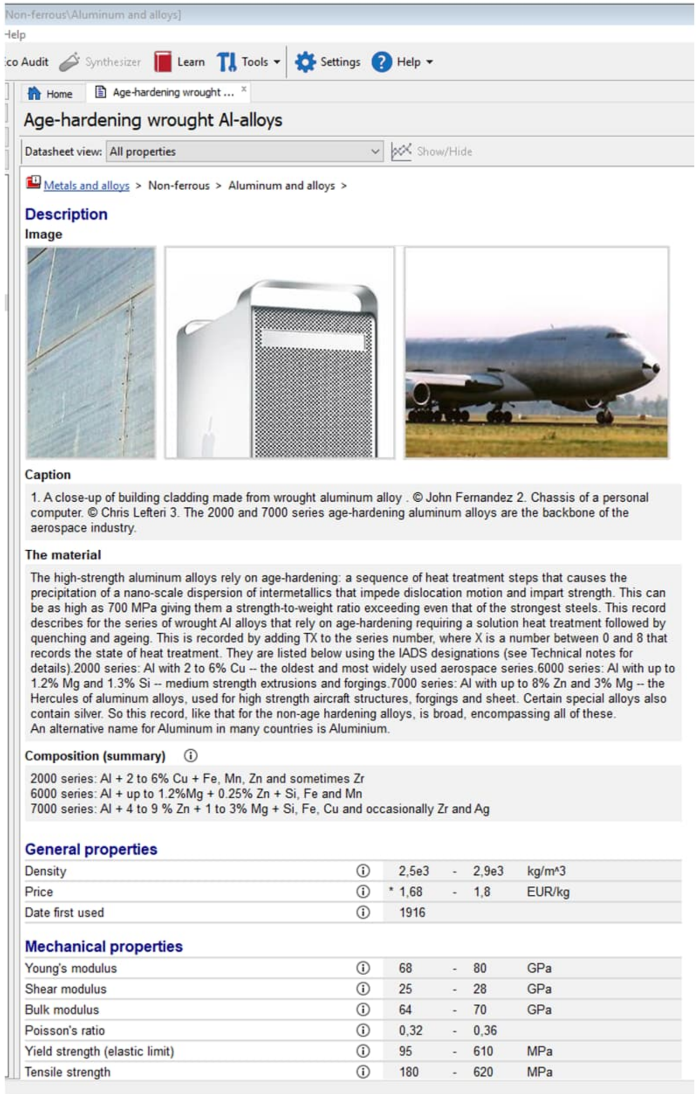
Stainless steels

- **A protective and passive oxide layer of Cr_2O_3 is formed when Cr > 11 wt.%**
- **Enhanced by Ni and Mo additions**
- **Main types**
  - Austenitic grades(e.g. 304, 316)
  - Ferritic grades (e.g. 409)
  - Martensitic grades (e.g. 410)
  - Duplex grades (e.g. 2205)
  - PH grades (e.g. 17-7PH)
- **Properties depends on alloying and microstructure**
- **Architecture, process industry, exhaust systems, flatware, tools, blades, aerospace,…**

Aluminum alloys

- **Age-hardening alloys**
  - 2000 series (Al-Cu)
  - 6000 series (Al-Mg-Si)
  - 7000 series (Al-Zn-Mg)





Non-ferrous\Aluminum and alloys]

Help

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Home | Age-hardening wrought ...

Age-hardening wrought Al-alloys

Datasheet view: All properties | Show/Hide

Metals and alloys > Non-ferrous > Aluminum and alloys >

Description

Image

Caption

1. A close-up of building cladding made from wrought aluminum alloy . © John Fernandez 2. Chassis of a personal computer. © Chris Lefteri 3. The 2000 and 7000 series age-hardening aluminum alloys are the backbone of the aerospace industry.

The material

The high-strength aluminum alloys rely on age-hardening: a sequence of heat treatment steps that causes the precipitation of a nano-scale dispersion of intermetallics that impede dislocation motion and impart strength. This can be as high as 700 MPa giving them a strength-to-weight ratio exceeding even that of the strongest steels. This record describes for the series of wrought Al alloys that rely on age-hardening requiring a solution heat treatment followed by quenching and ageing. This is recorded by adding TX to the series number, where X is a number between 0 and 8 that records the state of heat treatment. They are listed below using the IADS designations (see Technical notes for details).2000 series: Al with 2 to 6% Cu -- the oldest and most widely used aerospace series.6000 series: Al with up to 1.2% Mg and 1.3% Si -- medium strength extrusions and forgings.7000 series: Al with up to 8% Zn and 3% Mg -- the Hercules of aluminum alloys, used for high strength aircraft structures, forgings and sheet. Certain special alloys also contain silver. So this record, like that for the non-age hardening alloys, is broad, encompassing all of these.
An alternative name for Aluminum in many countries is Aluminium.

Composition (summary)

2000 series: Al + 2 to 6% Cu + Fe, Mn, Zn and sometimes Zr
6000 series: Al + up to 1.2%Mg + 0.25% Zn + Si, Fe and Mn
7000 series: Al + 4 to 9 % Zn + 1 to 3% Mg + Si, Fe, Cu and occasionally Zr and Ag

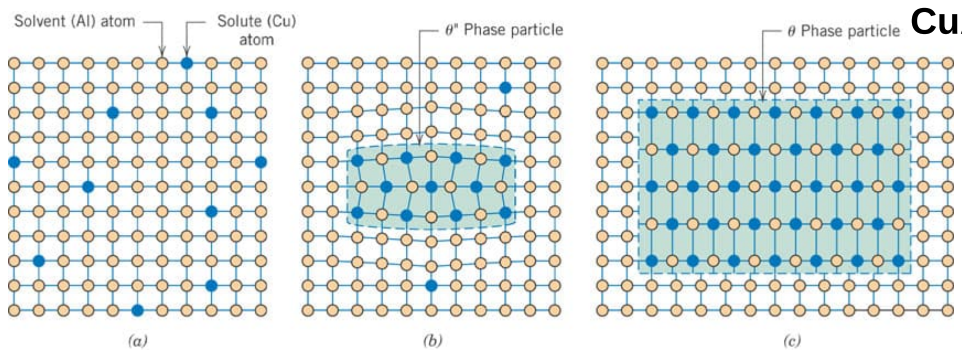
General properties

Density	2,5e3	-	2,9e3	kg/m^3
Price	* 1,68	-	1,8	EUR/kg
Date first used	1916			

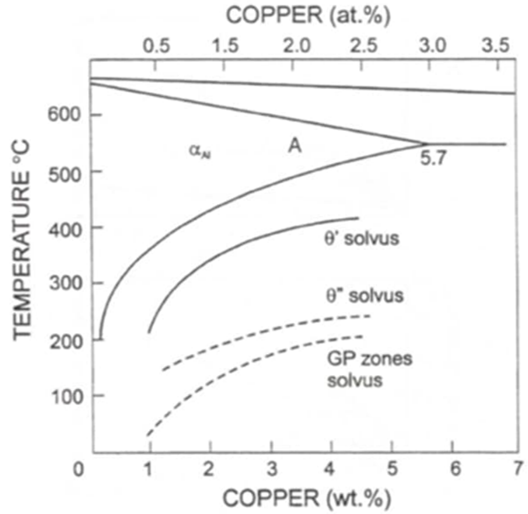
Mechanical properties

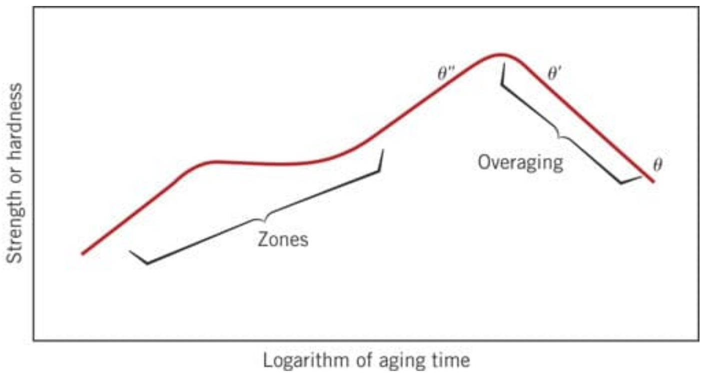
Young's modulus	68	-	80	GPa
Shear modulus	25	-	28	GPa
Bulk modulus	64	-	70	GPa
Poisson's ratio	0,32	-	0,36	
Yield strength (elastic limit)	95	-	610	MPa
Tensile strength	180	-	620	MPa

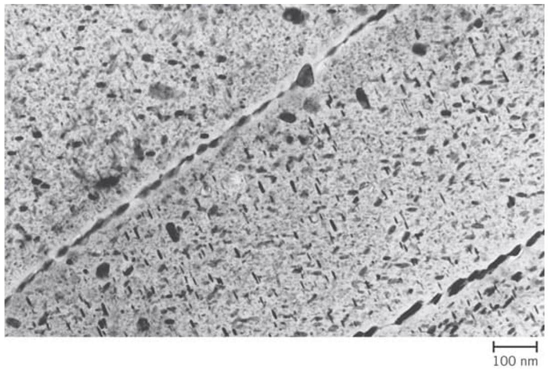
Strengthening mechanisms in precipitation hardening

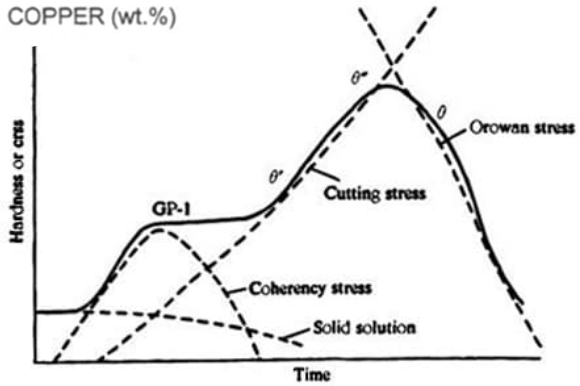


CuAl$_2$





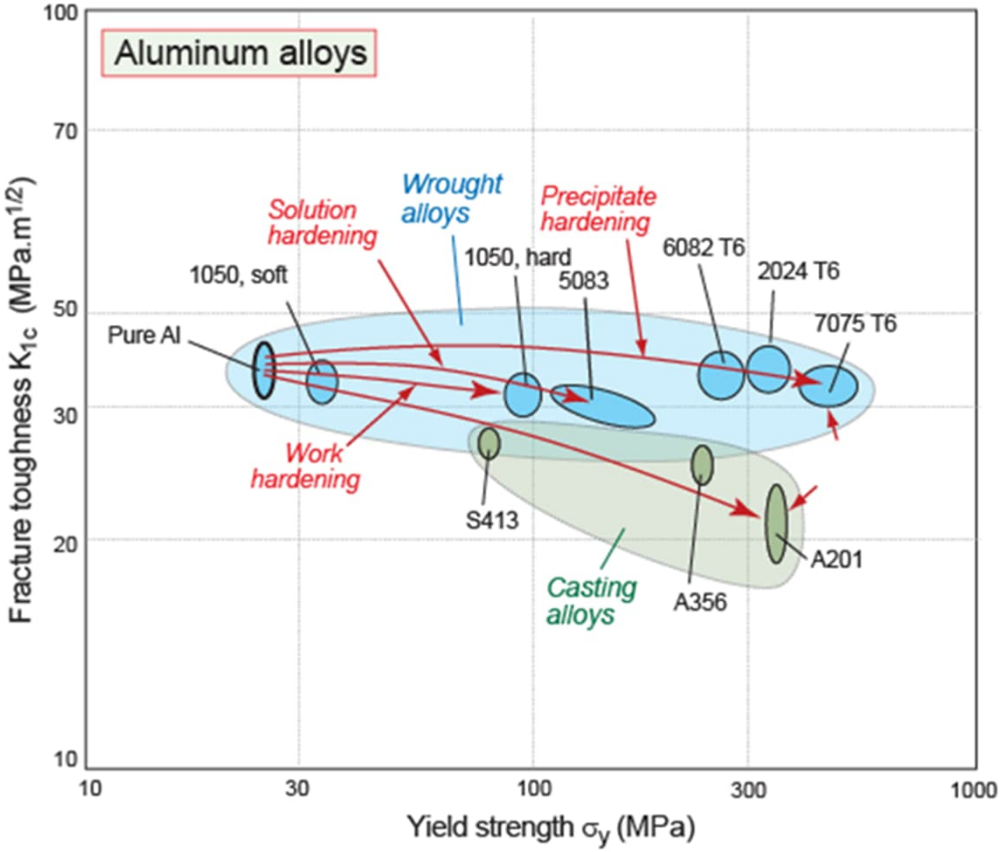




Again: all strengthening mechanisms work together

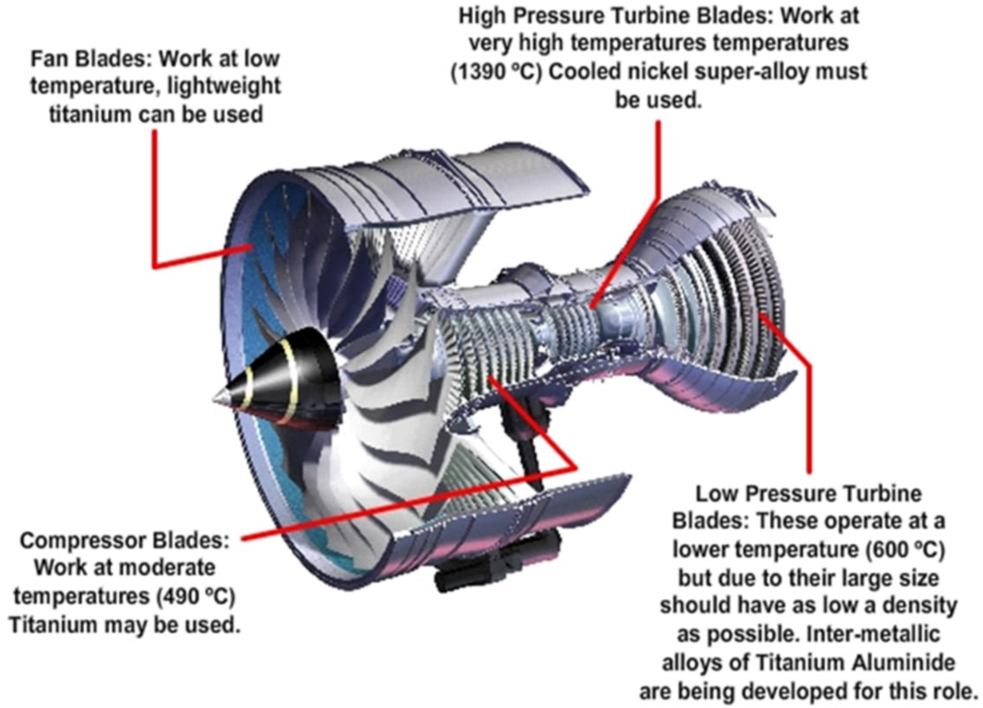
Aluminum alloys

- **Non age-hardening Al alloys**
  - 1000 series (> 99% Al)
  - 3000 series (Al-Mn)
  - 5000 series (Al-Mg)



High-performance materials

- **For example gas turbine materials**
- **Ni-base superalloys**
  - Creep
  - Oxidation
  - Fatigue
  - High-temperature corrosion resistance
- **Titanium alloys**
  - High strength-to-weight ratio



Specific strength

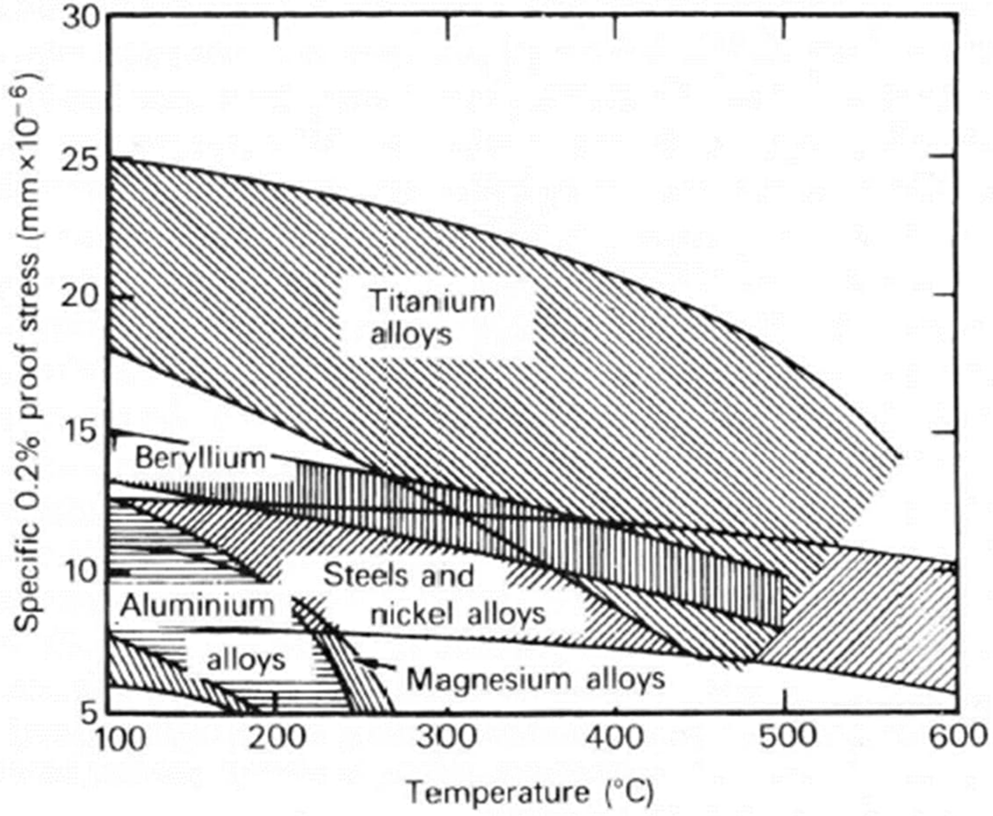
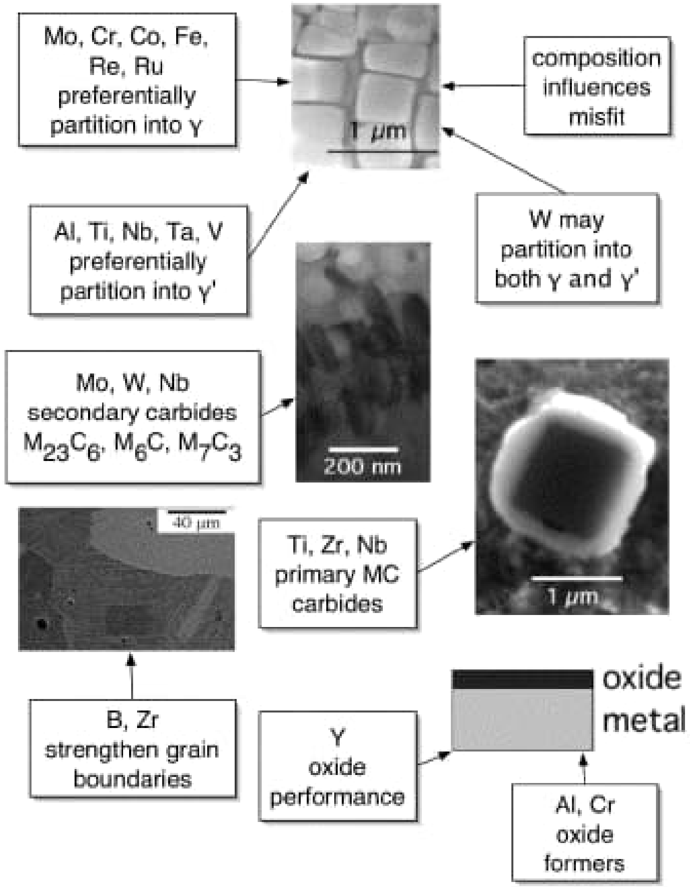
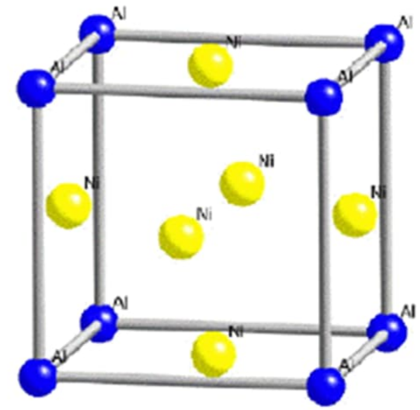


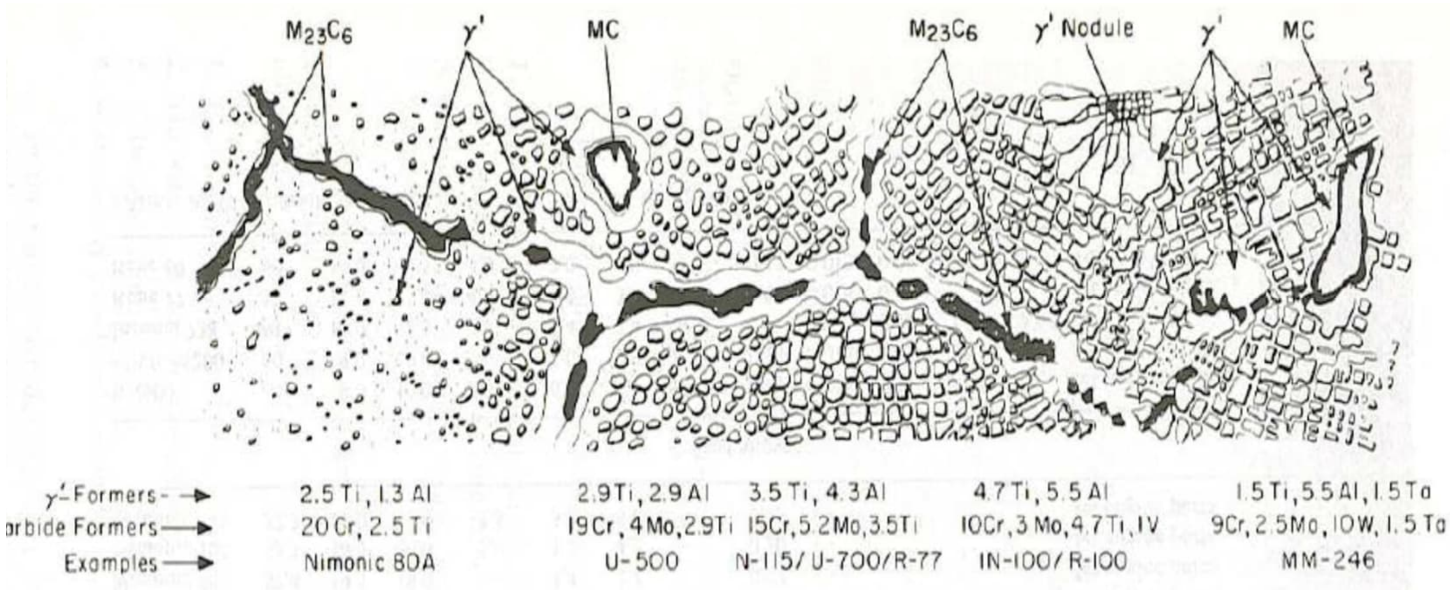
Fig. 1.6 Relationship of specific 0.2% proof stress (ratio of proof stress to relative density) with temperature for light alloys, steels and nickel alloys

Microstructure of precipitation hardened Ni-based superalloys



Ni_3Al





Car frame material

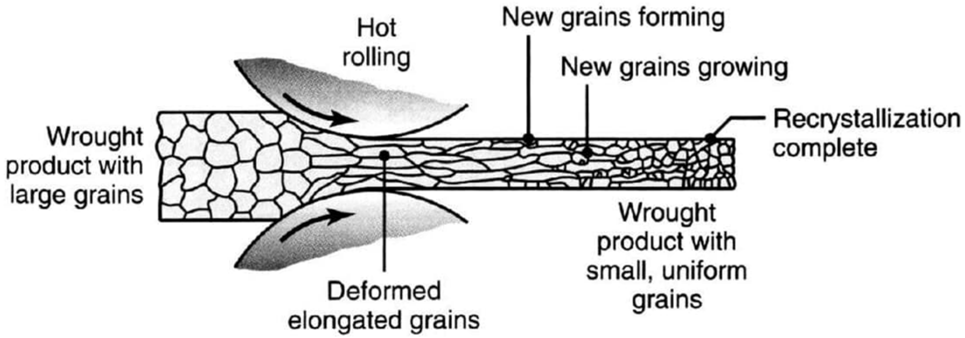
- **Which one is the best material?**
  - Low-carbon steel?
  - Aluminum alloy?
  - Stainless steel?
  - (CFRP)
- **Desired properties?**
  - Safety
  - Lifetime
  - Weight
  - Technological properties (formability, weldability, ...)
  - Price (life cycle costs and environmental effects)

Car frame and panel materials

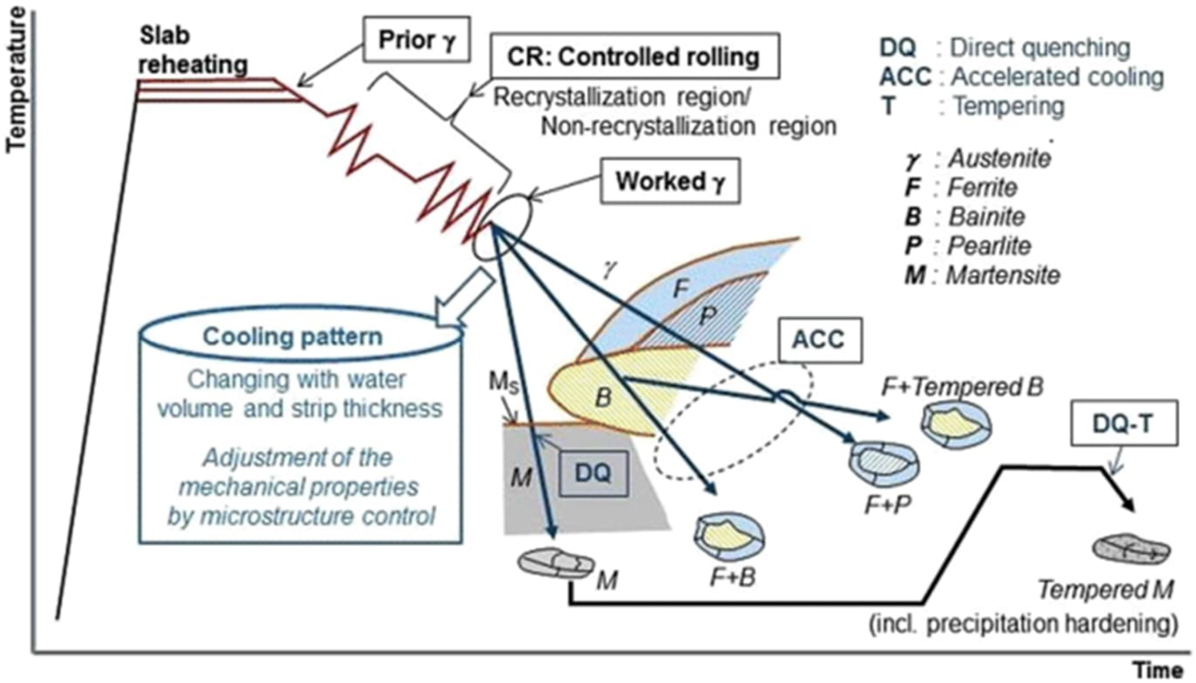
- **Aluminum**
  - Audi A8, Tesla, Jaguar XE, ...
  - light but expensive, difficult to repair
  - 5xxx (strain hardening), 2xxx, 6xxx and 7xxx (precipitation hardening) alloys are used
- **Stainless steel**
  - corrosion resistant, high strength-to-toughness ratio (safety),
  - applications in car frames under investigation, used in buses
  - exhaust systems
  - expensive, but has a long lifetime
- **Carbon steel**
  - majority of cars
  - heavy, less expensive, good technological properties
  - advanced high strength structural steels (AHSS)

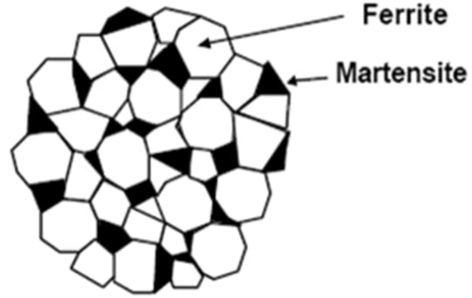
Thermomechanical treatments

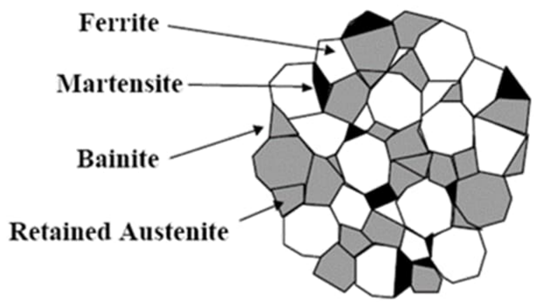
- **Simultaneous heat treatment and processing**
  - purpose to improve strength, toughness and ductility
- **Traditional hot working is a thermomechanical treatment**
  - shaping and repeated dynamic recrystallisation in austenite field
  - fine grain size, breaking of non-metallic inclusions
- **Controlled rolling is a more sophistigated method**
  - precisely defined rolling parameters (temperature, strain, number of passes, finishing temperature, cooling,...)
  - e.g. HSLA, TMCP, AHSS, UHSS, DP, TRIP,...



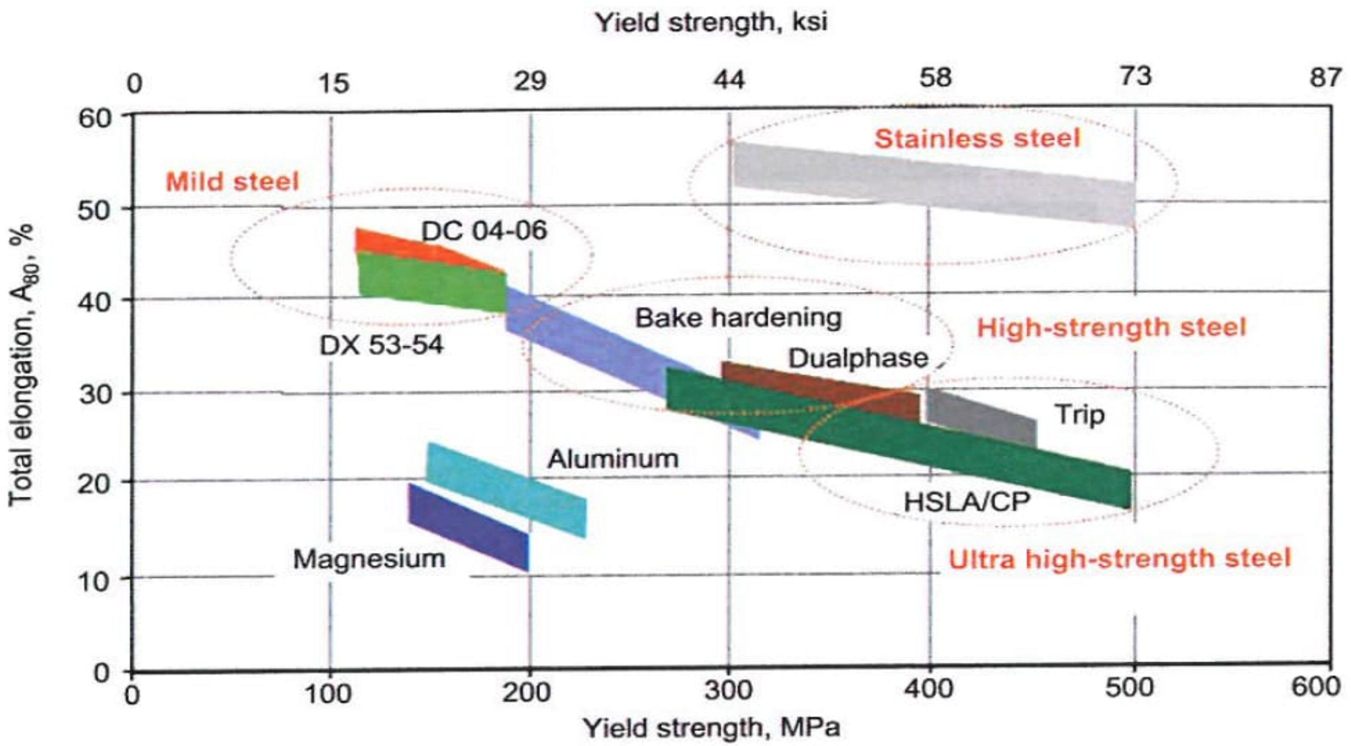
HSLA steels (high strength low alloy)







Development of HSLA steels

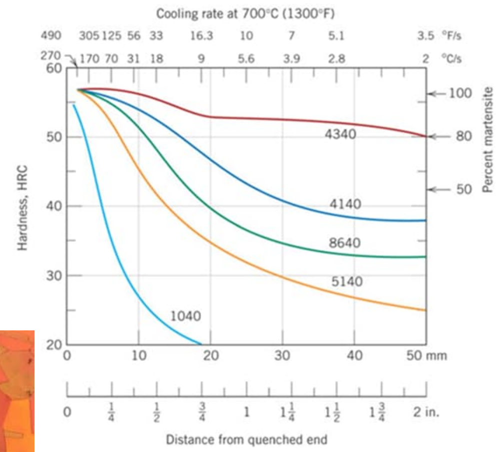


Yield strength and ductility of various alloys

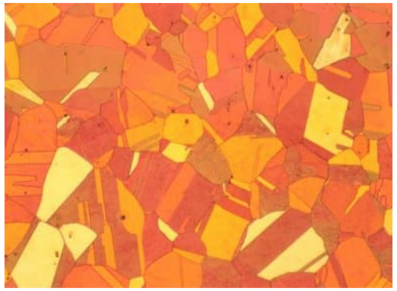
Laboratory course structure MEC-E6006

Lecture → Work in laboratory → Homework

Assignments



- **Metallography basics**
  - sample preparation
  - optical microscopy and micrographing
  - hardness measurement
- **Hardenability of steels**
  - hardenability test
  - microstructures and mechanisms in austenite decomposition and tempering of martensite
- **Stainless steels**
  - advanced sample preparation and microscopy
  - properties of stainless steels
- **Failure analysis**
  - examination of fracture surfaces
  - SEM and EDS



Steam diffuser made of X35CrMo17 martensitic stainless steel, operated at 540C/147 bar

origin of fracture