Phase-Transformations
and the driving Mechanisms behind it

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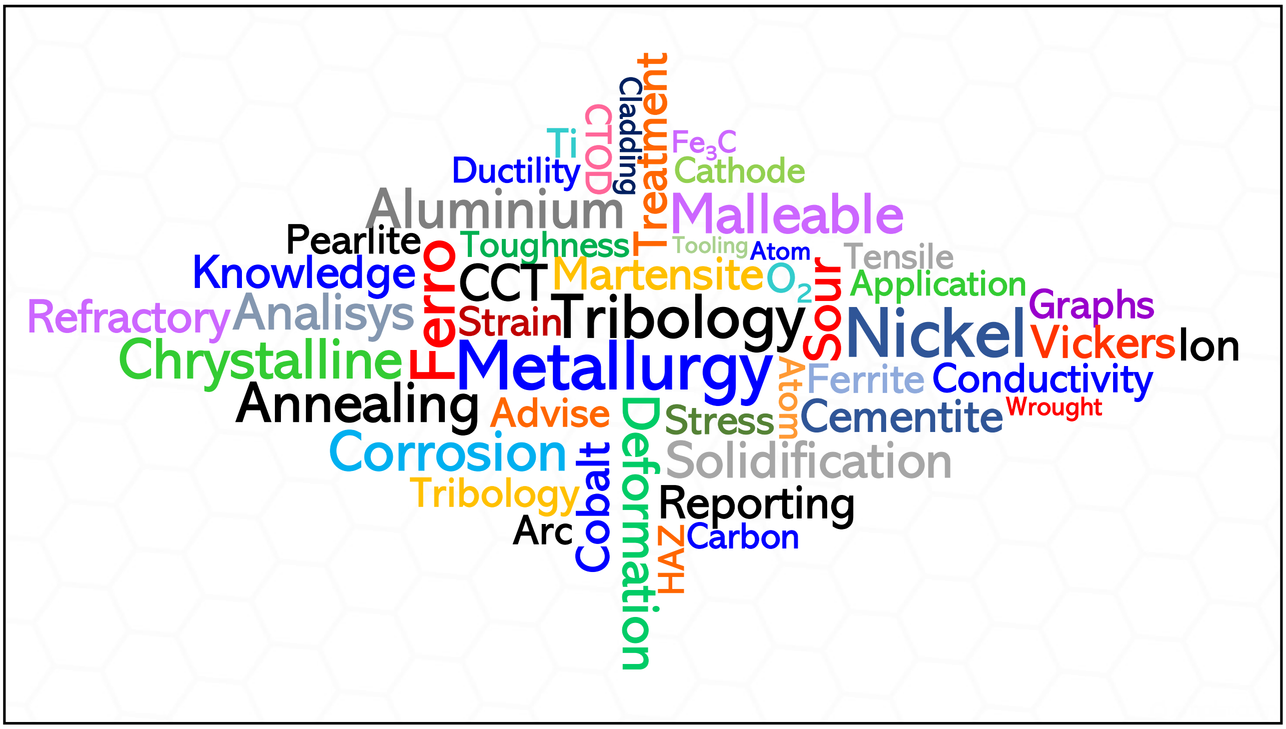

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Topics

1. Categorizing Phase Transformations
2. In-depth look at the mechanism(s) and their effect on material properties

Heat Treatment

Material crystal lattice configuration in steel and their effect:

Soft Annealing →	Better Formability
Coarse Grain Annealing →	Better Machinability
Solution Annealing →	Homogenization of alloying elements
Stress Relief Annealing →	Reduction of residual Stress
Hardening →	Increasing Hardness and strength
Tempering →	Controlling of strength & toughness

Fe/Fe_3C Phase Diagramm

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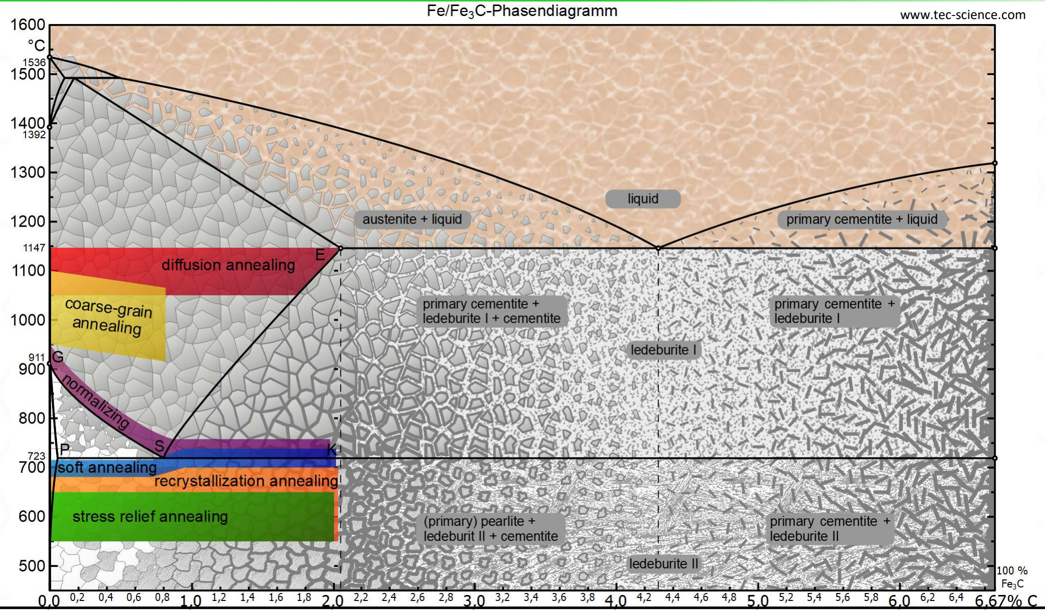
In metallurgy, welding & fabrication.



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Phase Transformations

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(Common knowledge)
Formation of Lattice structures (Phases) is determined by:

- Carbon percentage
- Soaking temperature
- Soaking time
- **Cooling rate**

Can this formation (of lattice structures) be categorized?
Yes, in 2 categories: **Diffusional** (or **Reconstructural**) and **Displacive**

NL:
Diffusie gestuurde fase transformatie en **Diffusieloze fase transformatie**

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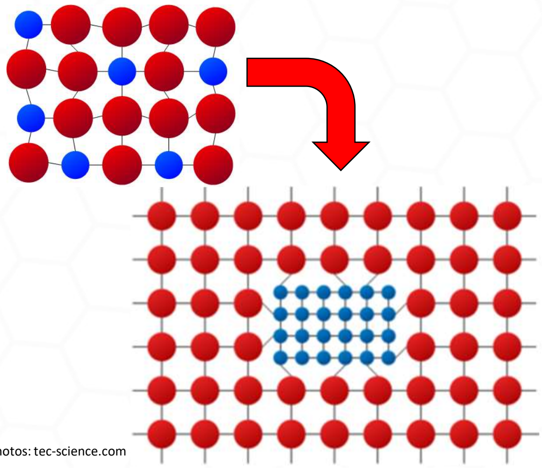
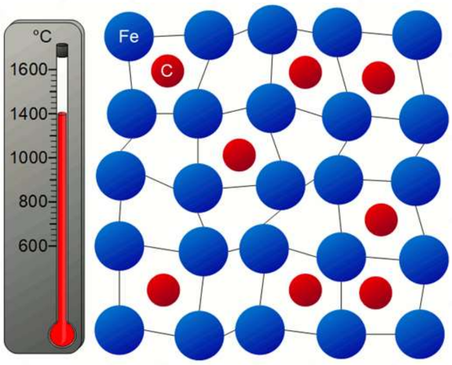
Phase Transformations: Chemistry

Diffusional
Chemical composition is altered



Displacive
Chemical composition is not altered, only the chrystal structure



Photos: tec-science.com

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Phase Transformations: Speed

Diffusional
takes time and can therefore be slowed by Quenching, slowing the movement of atoms

Displacive
Phase transition (in some cases) almost at the speed of sound

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Phase Transformations: Temperature

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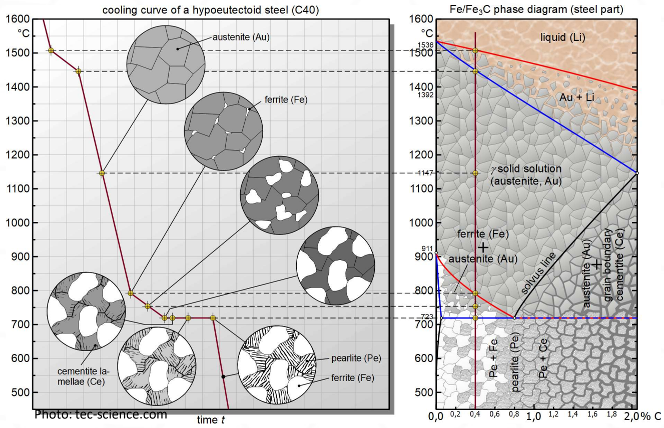
Diffusional	Displacive
isothermal process	*a-thermal* process
continues at constant temperature	requires temperature reduction



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Phase Transformations

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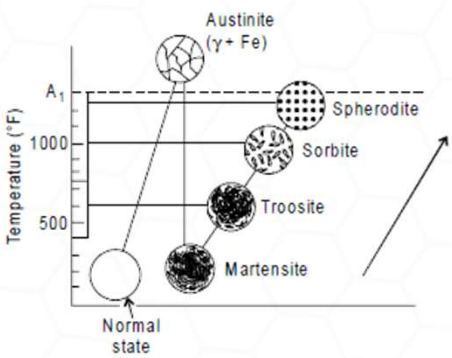
Diffusional	Displacive
Cementite	Ferrite
Pearlite	Martensite
Ledeburite	Bainite
Troostite	
Sorbite	
Spheroidite	



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Sidestep

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Origins of various lattice structure names:

Ferrite	“**Ferrum**” (Latin name for pure iron)
Cementite	“**Cement**” (something that binds or glues)
Pearlite	“**Pearl-like**” luster under microscope
Austenite	W.C. Roberts-**Austen** (UK) (1843–1902)
Ledeburite	A. **Ledebur** (D) (1837 - 1916)
Martensite	A. **Martens** (1850 - 1914)
Bainite	E.C. **Bain** (1891 - 1971)
Troostite	L. J. **Troost** (1825 - 1911)
Sorbite	H. C. **Sorby** (1826 - 1908)
Widmannstätten	A. von Beckh-**Widmanstätten** (1754-1849)

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Phase Transformations

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(Common knowledge ⇨)

Transformation of:
Austenite ⇨ Pearlite = **2** steps

1. Displacive (FCC ⇨ BCC)
2. Diffusional (C ⇨ Fe_3C)

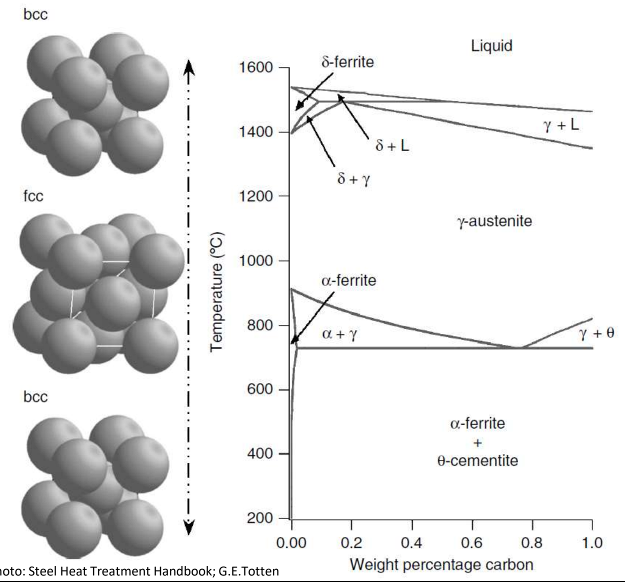

Photo: Steel Heat Treatment Handbook; G.E.Totten

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Phase Transformation

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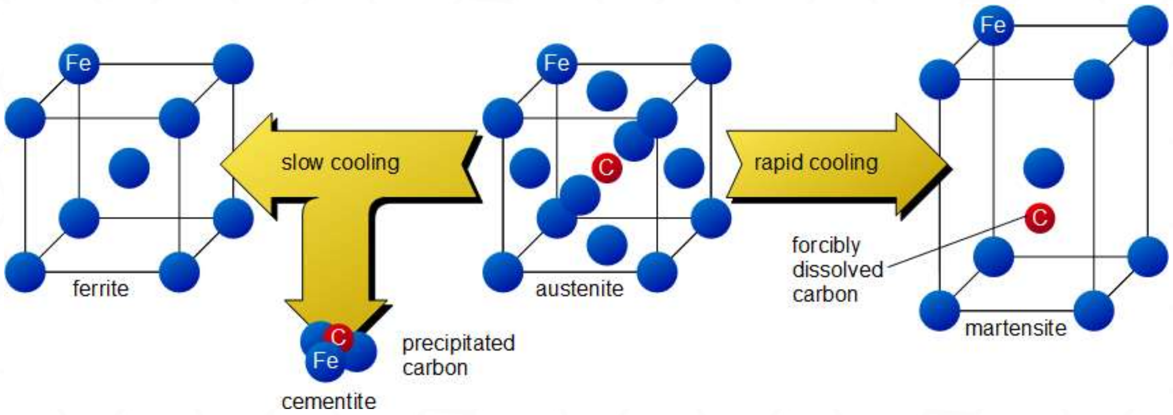

Diffusion of C-atoms to form Fe_3C.
Elements that will 'aid' the diffusion-rate are **Mn** and (although less influential) **Si**.

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Pearlite

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Diffusion of C-atoms from Ferrite to form Fe_3C.
Cooling rate detemines size of lathes

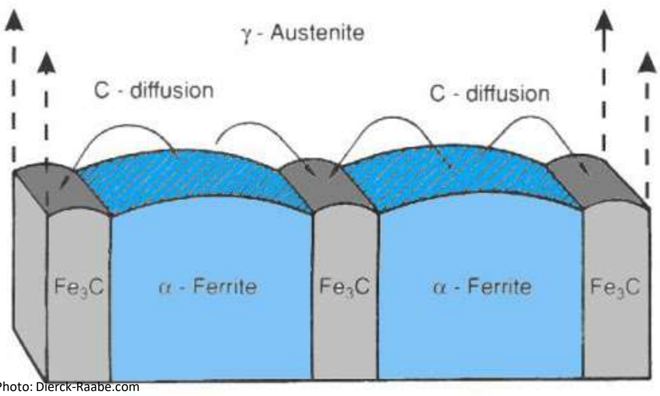

Photo: Dierck-Raabe.com

Fe_3C molecular structure:

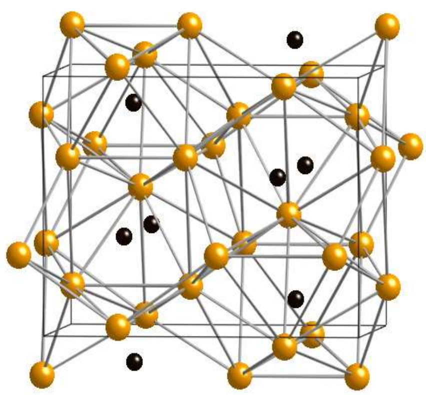

Photo: som.web.cmu.edu

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Pearlite: growth of cementite lathes

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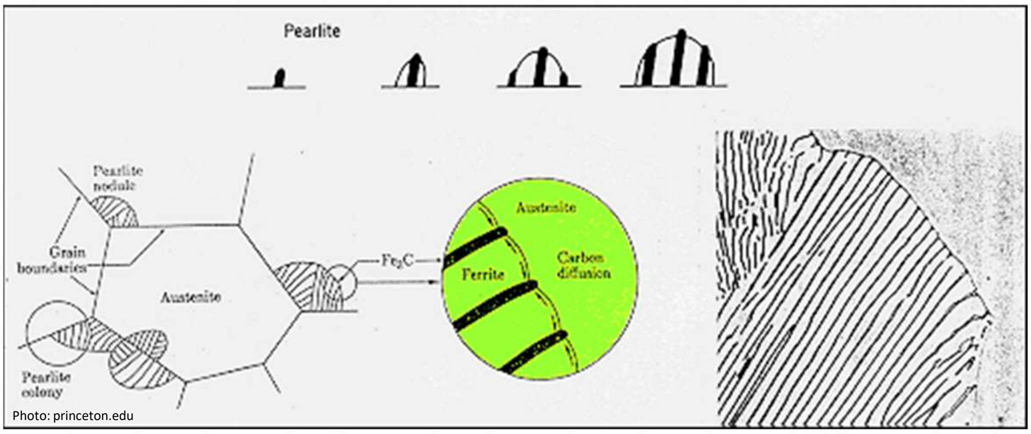

Note: formation of Pearlite starts at the **edge** of a grain and **grows inwards** in various directions.

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Pearlite under a microscope

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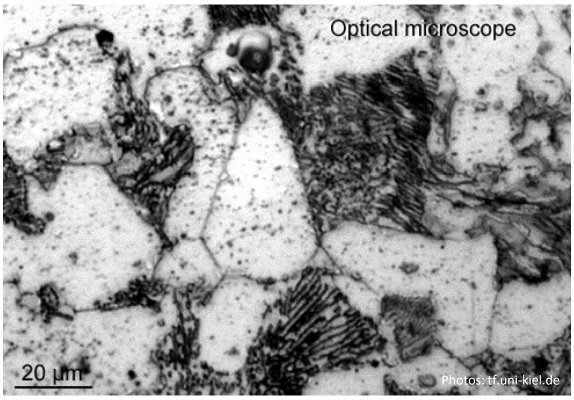
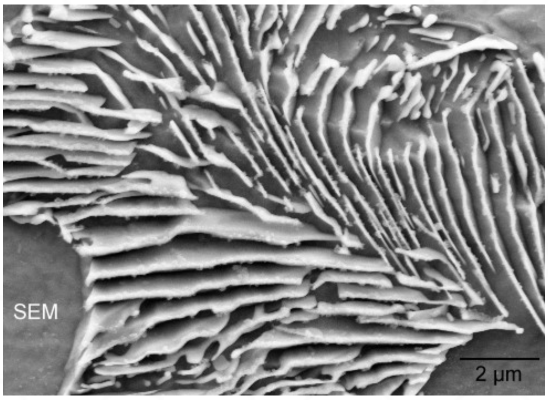
Optical Microscope



SEM



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Pearlite

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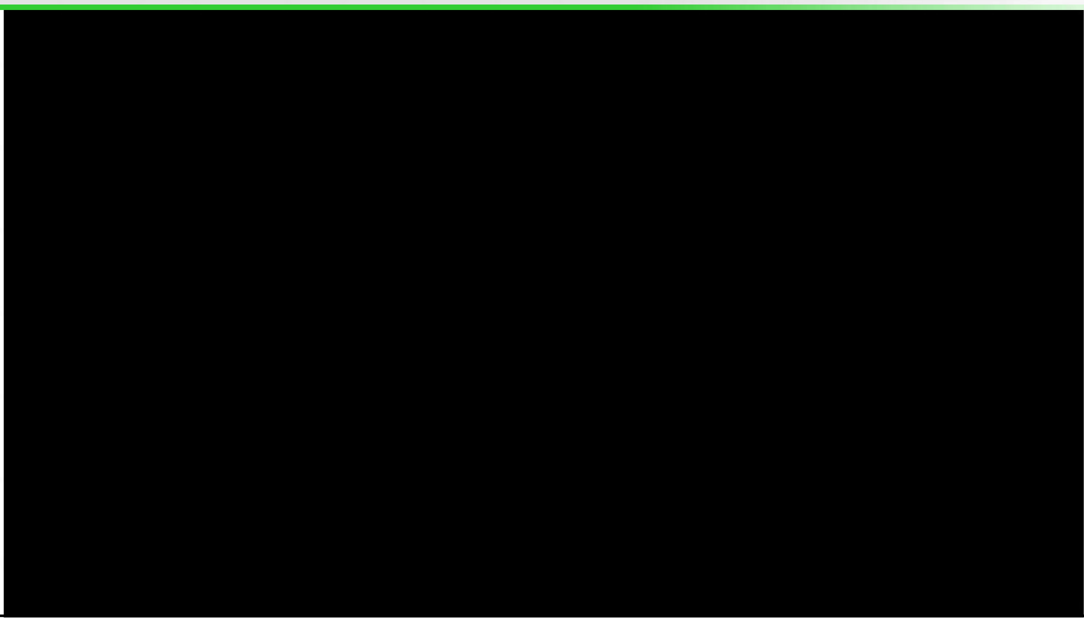

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Pearlite; lathe size

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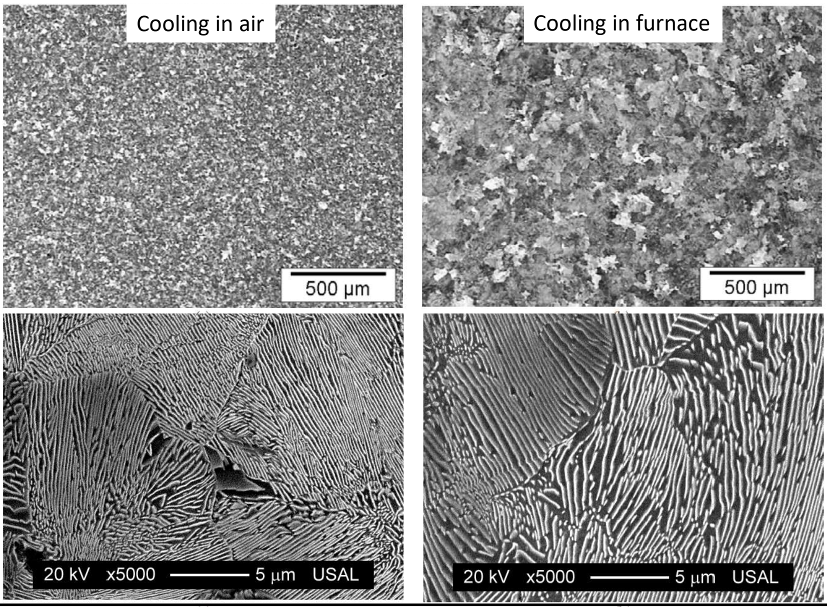
Eutectoidic steel

Composition:

C :	0,789%
Mn:	0,681%
Si:	0,210%
Cr:	0,218%
V:	0,061%



Source:
"Role of the microstructure on the mechanical properties of fully pearlitic eutectoid steels" DOI: 10,3221

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Pearlite; lathe size & mechanical properties

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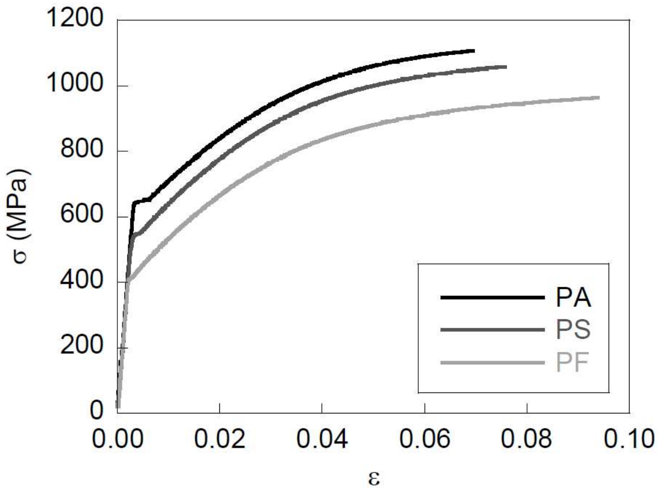
Steel	E (GPa)	σ_Y (MPa)	σ_R (MPa)	ε_R	RA (%)
PA	202	650	1105	0.067	33
PS	200	560	1055	0.072	20
PF	203	441	965	0.092	14



PA = cooling in air (= rapid cooling)
PS = cooling in partially opened furnace
PF = cooling in frunace

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Pearlite in TTT diagram

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This *generic* TTT diagram shows:

- continued growth of pearlite after placement in furnace
- Forced cooling in molten Pb could result in upper-bainite
- Rapid (forced) cooling will result in Martensite

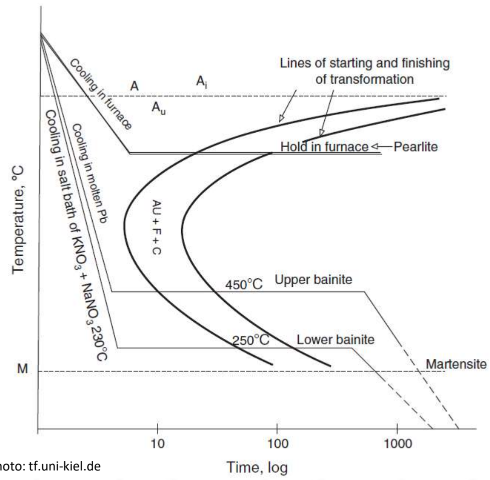

Photo: tf.uni-kiel.de

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Pearlite; Chrystalline carbide structures

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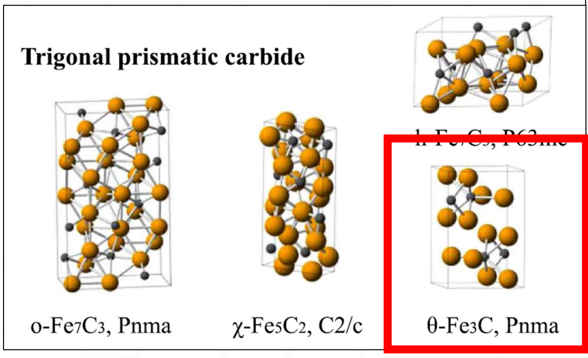
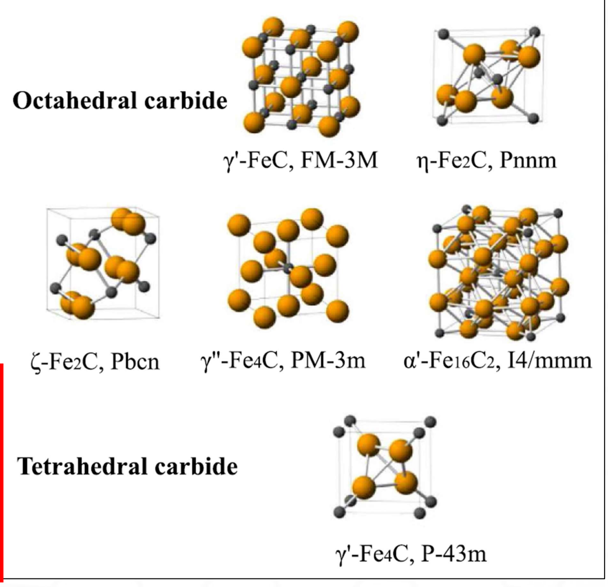
Cementite = **Fe_3C**.
Or is it?

Partially true:
Ferro-Carbide can be found in various configurations:





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Sidestep: Slip systems in BCC and FCC

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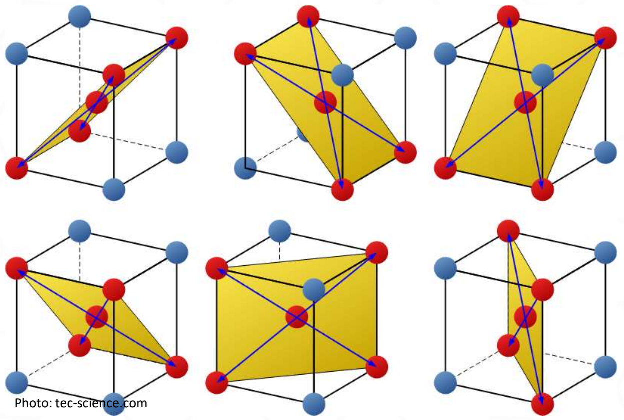
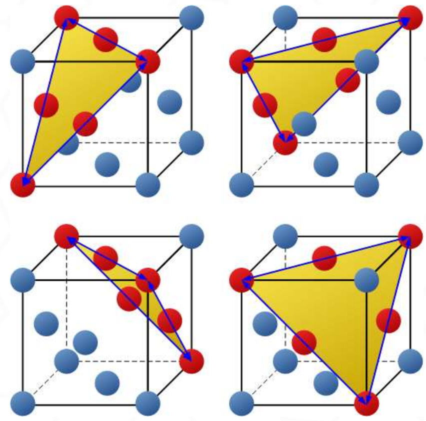
Slip-planes in **BCC** (Ferrite):
2x 6 directions = 12 slip directions



Slip-planes in **FCC** (Austenite):
3x 4 directions = 12 slip directions



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Sidestep: Slip systems in BCC and FCC

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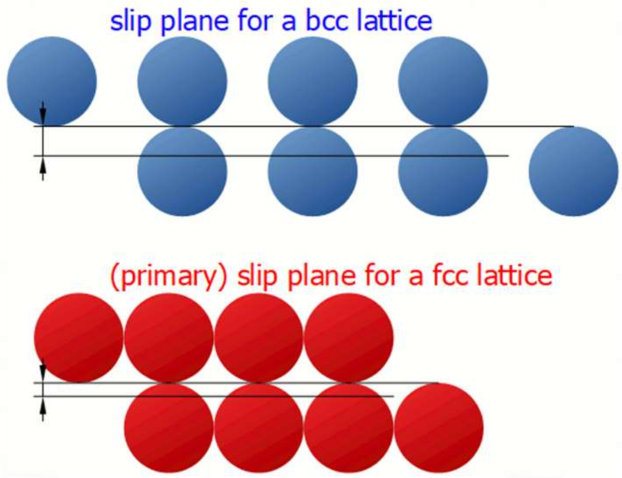
'Slipping' of atoms relative to their lattice structure:



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Slip Planes

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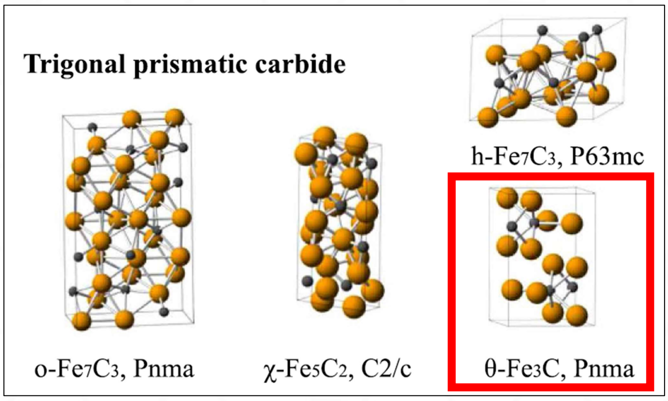
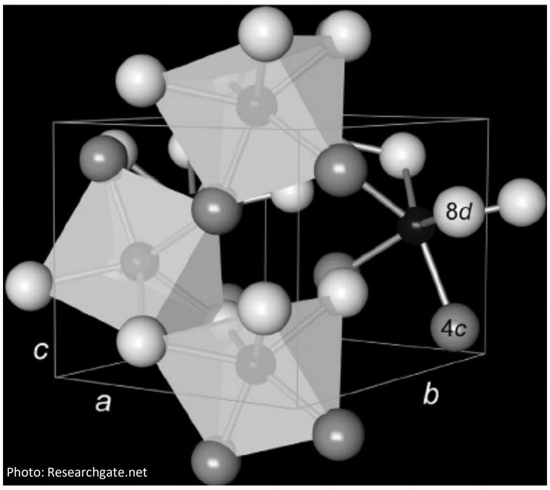
Slip-planes in
orthorhombic lattice (Cementite):

Not present!





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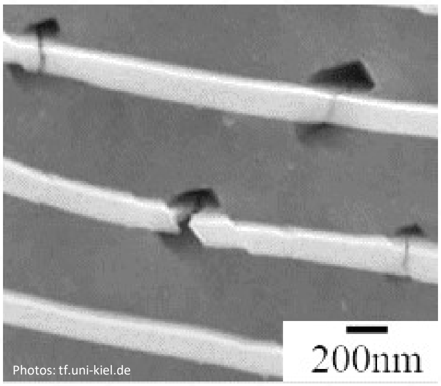
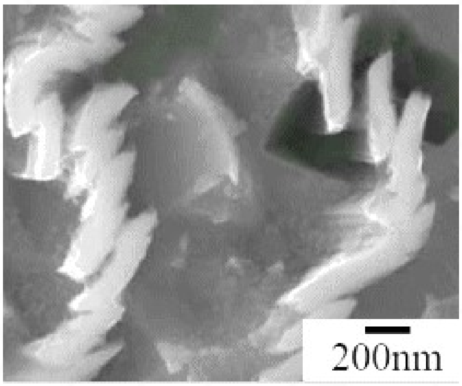
Pearlite

Cold deformation of Pearlite lattice will result in breaking of Cementite into 'Platelets'





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Pearlite: mixed blessings?

Strong 'braces' and elastic filling: Comparable to Ferrite / Cementite structure in Pearlite.

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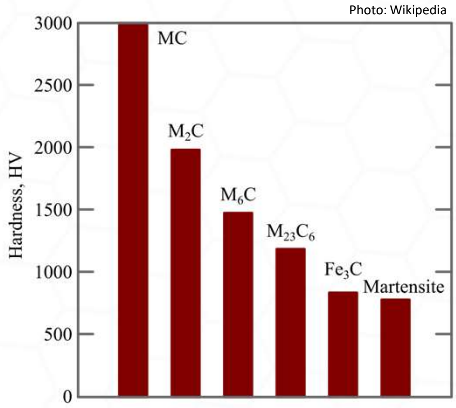
Pearlite…. some final thoughts

- Pearlite may be considered a dual-phase chrystal; Ferrite and Cementite in one
- Fine cementite structure will increase Yield and deformation, coarse structure will reduce these mechanical properties.
- Cementite is the hardest structure in Fe/Fe_3C diagram: approx. 600 HB or 600 HV_{10}
- Cooling rate is the determining factor in formation of Pearlite size and resulting strength

Photo: Wikipedia



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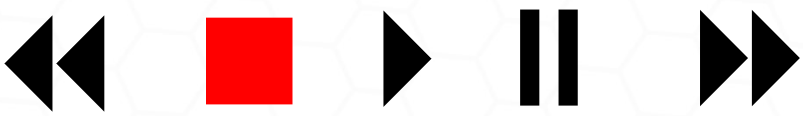

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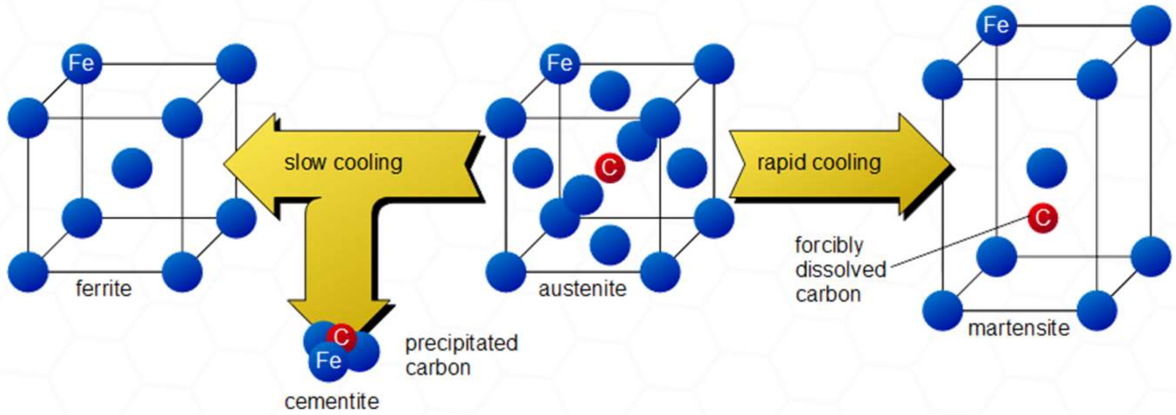
Phase Transformation



Rapid cooling will result in a forcibly dissolved carbon atom in a Body Centered Tetragonal (BCT) structure.

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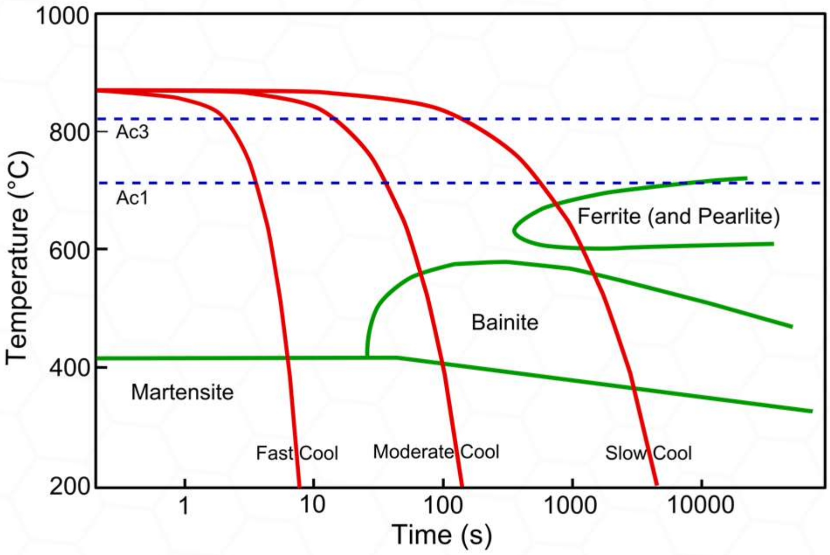
Phase Transformation



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Phase Transformations: Chemistry

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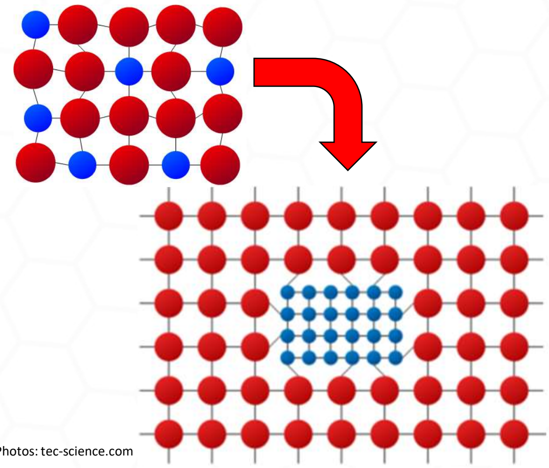
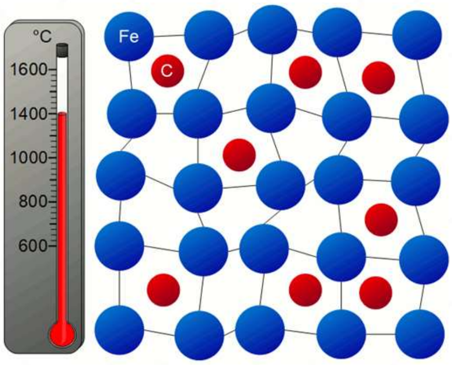
Diffusional
Chemical composition is altered



Photos: tec-science.com

Displacive
Chemical composition is not altered, only the chrystal structure



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Phase Transformations: Speed

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Diffusional
takes time and can therefore be slowed by Quenching, slowing the movement of atoms

Displacive
Phase transition (in some cases) almost at the speed of sound

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Phase Transformations: Temperature

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Diffusional
isothermal process
continues at constant temperature

Displacive
a-thermal process
requires temperature reduction

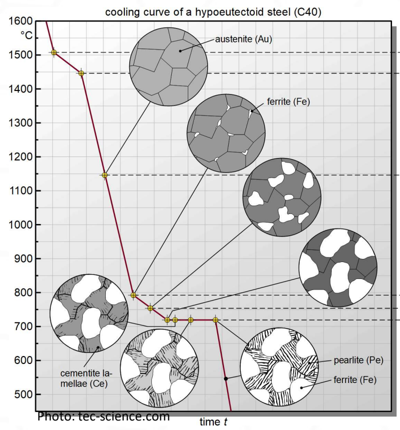
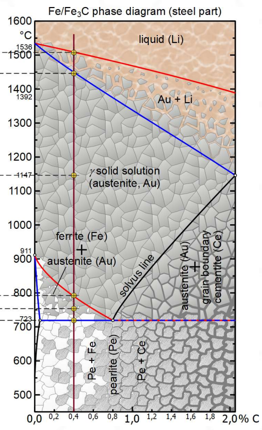


Photo: tec-science.com



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Phase Transformations: Temperature

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Diffusional
isothermal process
continues at constant temperature

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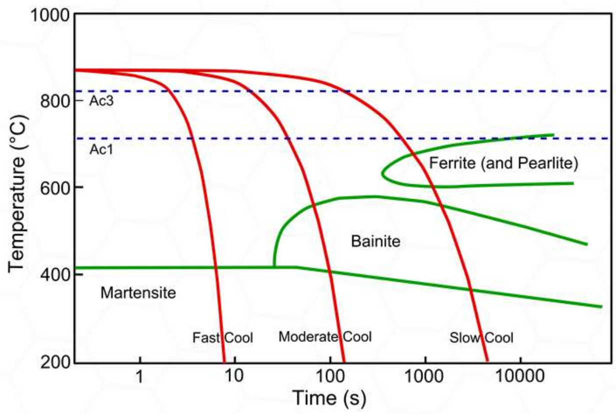

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Martensite

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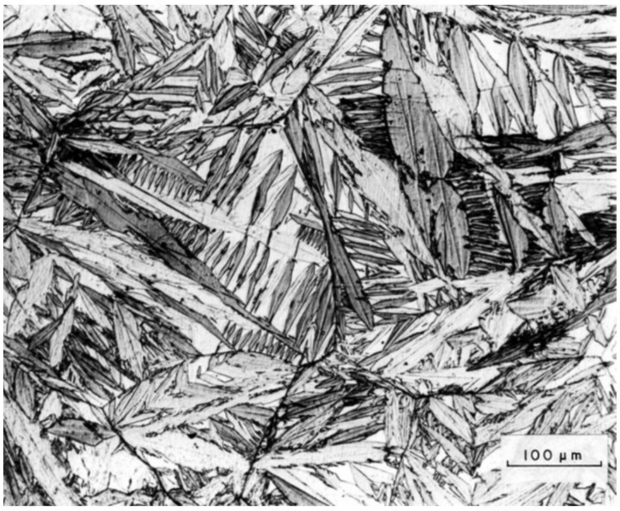

A 'typical' picture of Martensite **in steel** we all can recognize.

But is this typical structure always the case?
(asking the question is answering it…)

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Martensite: hardness & Yield

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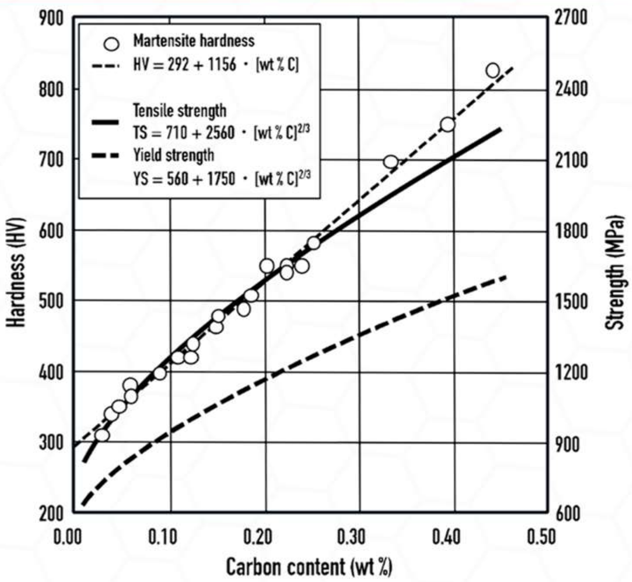
The influence of % Carbon on hardness, Tensile- and Yield strenght of an unalloyed C-Mn steel

Hardness:	> 800 Hv10
Tensile:	> 2000 N/mm^2
Yield:	> 1500 N/mm^2

But what makes Martensite so hard and strong….



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BCC ⟶ FCC and back

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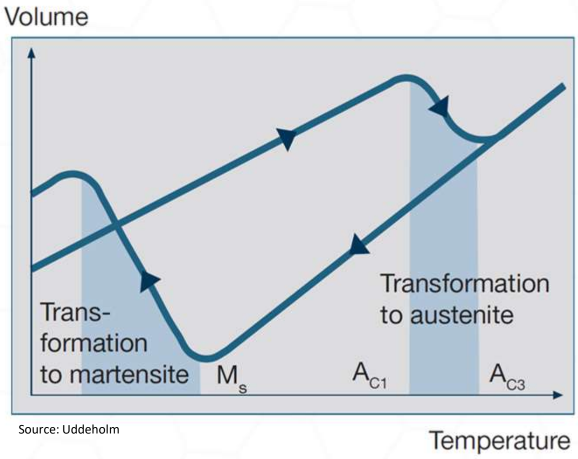

Source: Uddeholm

Formation of Martensite is mainly influenced by the following factors:

- Cooling rate + 'under-cooling'
- Carbon percentile

⟵ Generic graph by a Dilatometer

volume change:
transformation BCC ⟶ FCC and vice versa

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Interstitiële ruimte in BCC en FCC

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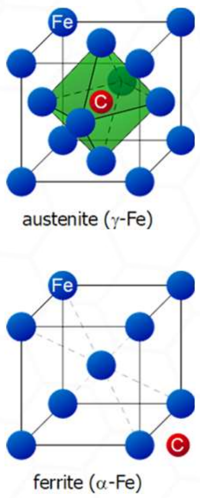

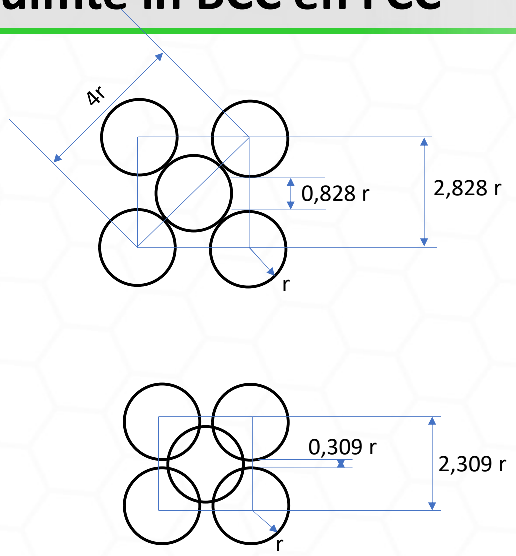

FCC:
hogere pakkings-graad dan BCC.

Interstitieel opgelost atoom max grootte: 0,828*r

BCC:
Interstitieel opgelost atoom max grootte: 0,309*r

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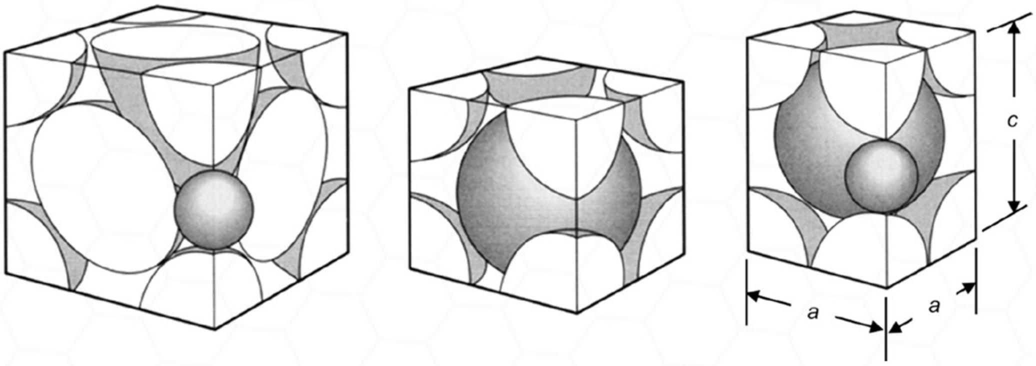
Transformation FCC to BCT

Carbon can be dissolved in FCC structure, but not BCC.
BCC spaces in the structure do not allow this, resulting in a *deformed* BCC structure, called **Body Centered Tetragonal** or BCT.



BCT is inherent metastabile: meaning C will diffuse from the Octahedral space, when heated.

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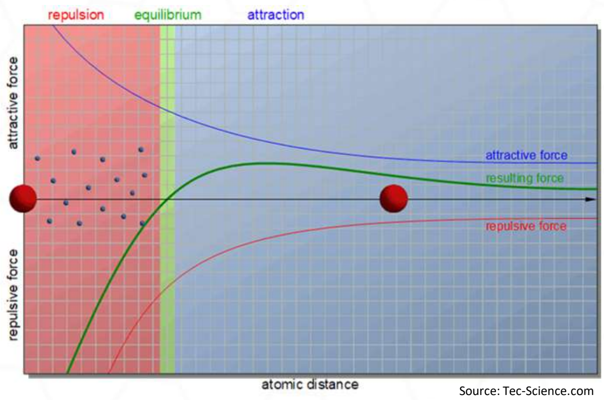
Transformation FCC to BCT . . .

- … does not involve diffusion
- … does require constant reduction of temperature
- … can be considered a chain reaction, speed of transition will approach speed of sound in metal
- … results in a super-saturated solid solution
- … results in a volumetric increase (FCC is more efficient, takes in less space)



Source: Tec-Science.com

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Martensite types

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Packets with laths

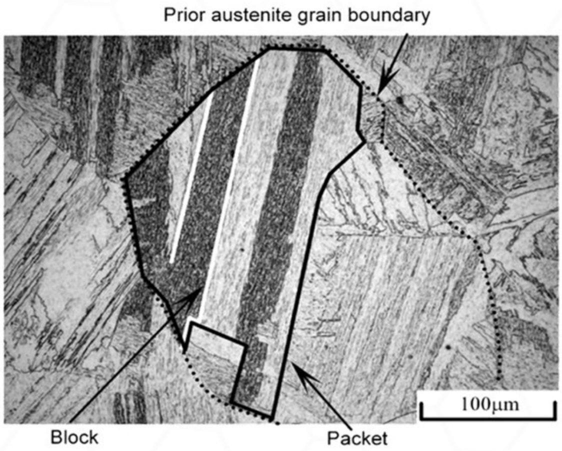
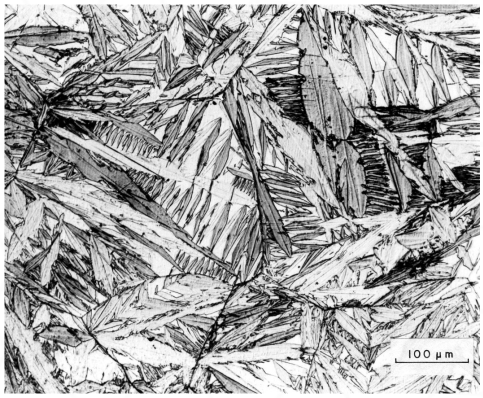


Plate- or Lenticular discs (lens-shape)



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Martensite types

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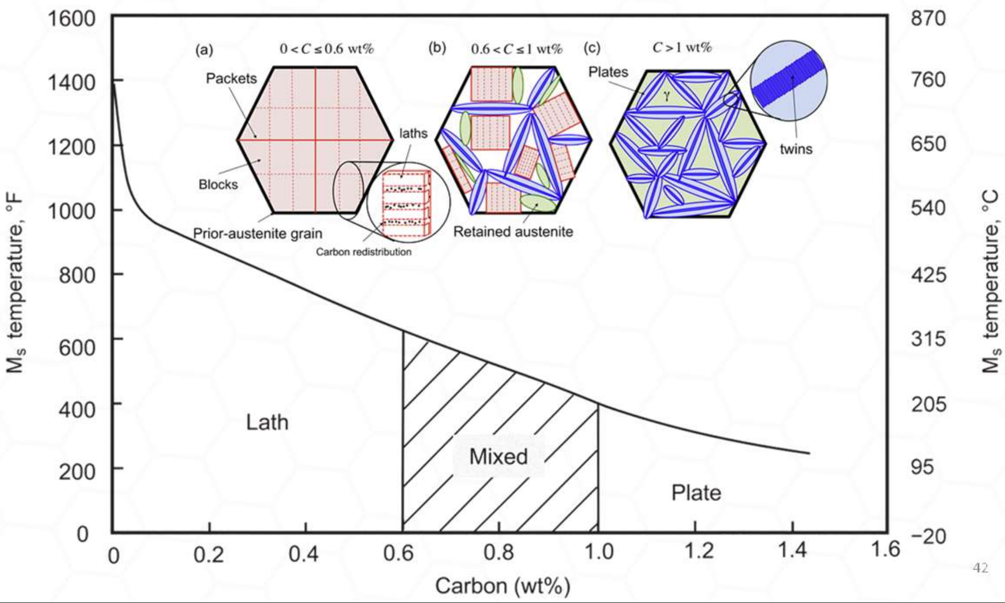
< 0,6% Carbon, martensite will form as laths.

Between 0,6% and 1,0% Carbon a **mixed structure** of lath- and lenticular martensite can be found.



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Lath Martensite

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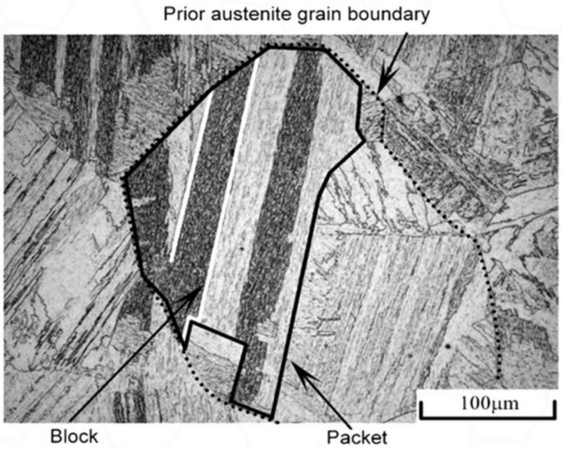

When %C is lower than approx. 0,6%, Martensite will form in the shape of **laths**.

In a ‘former’ Austenite grain, Martensite will form in the shape of:

- packets , which consist of
- various parallel blocks, which consist of
- laths

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Lath Martensite

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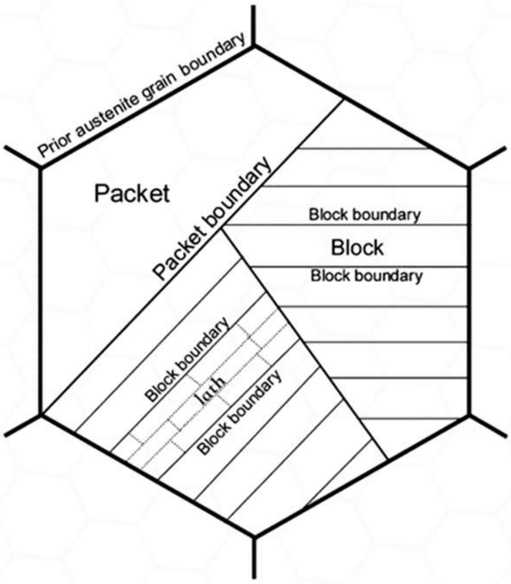
When %C is lower than approx. 0,6%, Martensite will form in the shape of **laths**.

In a ‘former’ Austenite grain, Martensite will form in the shape of:

- packets , which consist of
- various parallel blocks, which consist of
- laths

Blocks and Laths will increase in size when austenitizing temperature is increased.

Austenite grains <10μm tend to form single blocks, without sub-structure.



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Lath Martensite

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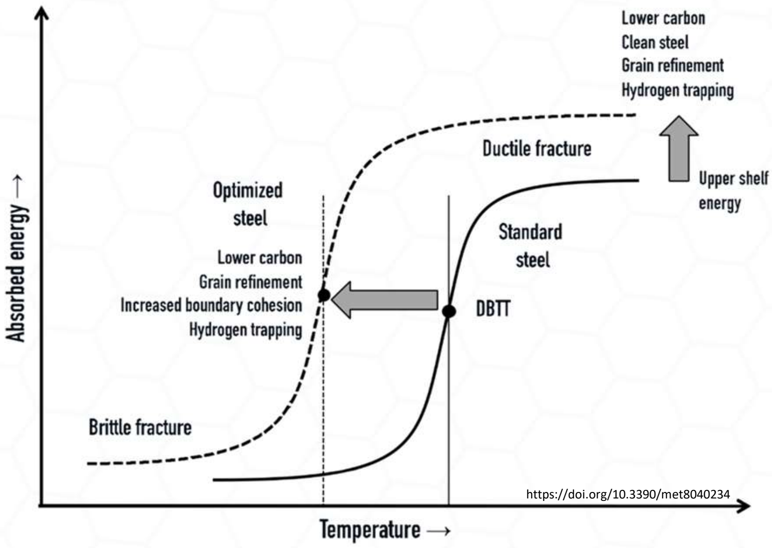

Size of (prior) Austenite grain is determining for the size of Blocks.

But: **yield** and **hardness** of Martensite are **not affected** by prior Austenite grain size.

However, **Hall-Petch relation** shows smaller austenite grains increase ductility and impact toughness at lower temperature.

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Martensite: hardness & Yield

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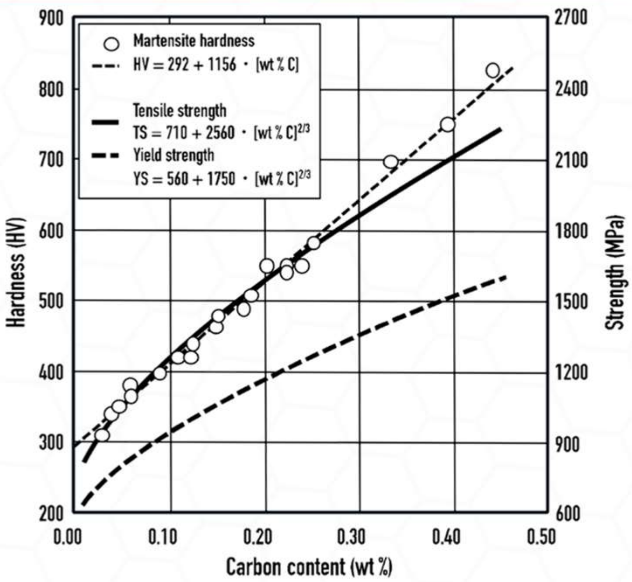
The influence of % Carbon on hardness, Tensile- and Yield strenght of an **unalloyed C-Mn steel** →

The **inherent hardness** and effective depth into the material is only a few milimeters.

After several milimeters of depth, cooling rate is longer; Carbon is diffusing from FCC and forms Cementite.



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Martensite: Alloying elements

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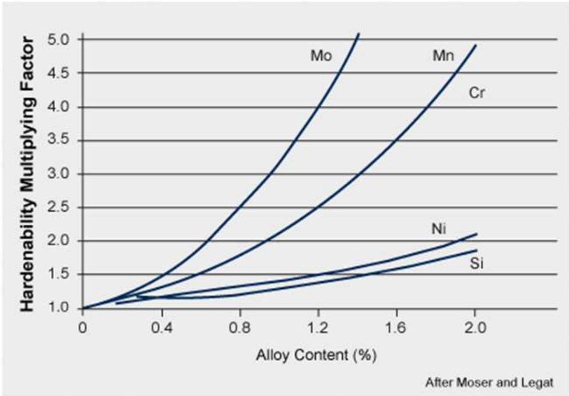
- Hardenability effect caused by reduced diffusity of carbon will therefore hinder formation of Ferrite and Pearlite.
- **Molybdenum** has the strongest effect of these 3 elements.



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Martensite: Alloying elements

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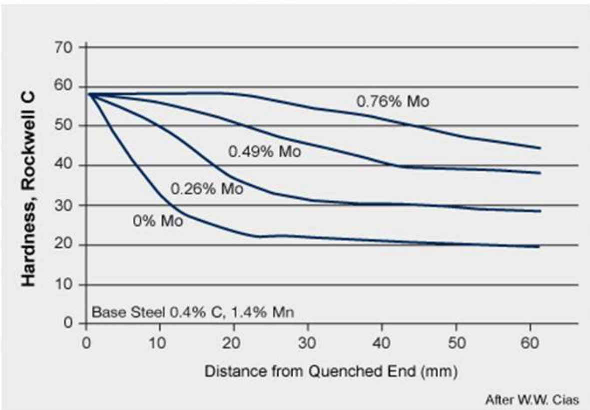
- Mo amounts of 0,2 – 0,5 % are sufficient for through hardening when quenching.
- Mo increases parent austenite grain boundary cohesion: higher resistance against intergranular fracture



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Martensite: Alloying elements

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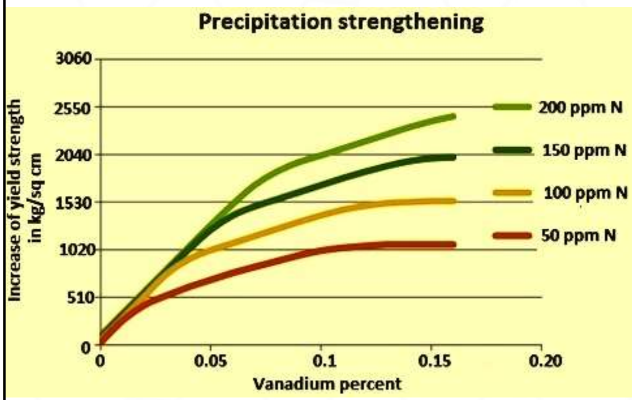

Vanadium:

- Good solubility in Austenite
- Precipitation strengthening during tempering treatment only (!), meaning: no influence during initial quenching
- Also provides grain size control and limiting grain growth
- Effective amounts between 0,01 – 0,15%

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Martensite: Alloying elements

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Boron is added in very small quantities (0,0010 – 0,0050% or: 10-50 ppm) as the effect on hardenability is significant:

- Solute Boron segregates to Austenite grain boundary at lower temperatures . . .
- . . . obstructs nucleation of Ferrite below equilibrium transformation temperature
- . . . thus preserving metastabile Austenite down to (and below) M_S

Source: ThyssenKrupp

Boron in high concentrations (>1%) in steel mainly used in cold formed applications, e.g. car industry

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Austenite size & M_S / M_F

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C:	0,1%
Si:	0,3%
Mn:	0,9%
Cr:	0,7%
Mo:	0,5%
Nb:	0,005%
Ti:	0,02%
V:	0,04%
P:	0,02%
S:	0,003%

Note:
no steel designation could be found that fits this composition

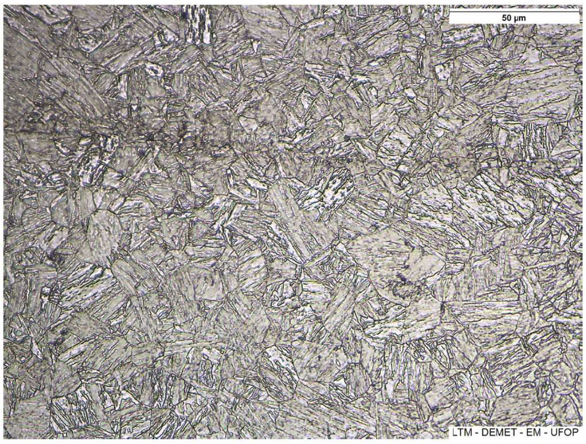

Figure 1. Optical micrograph of the studied steel in the initial state. Nital 2%. 500x.

Source: https://doi.org/10.1590/1980-5373-MR-2019-0570

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Austenite size & M_S / M_F

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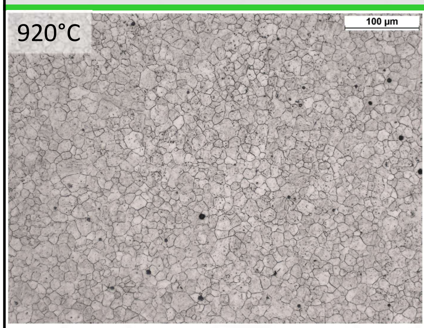

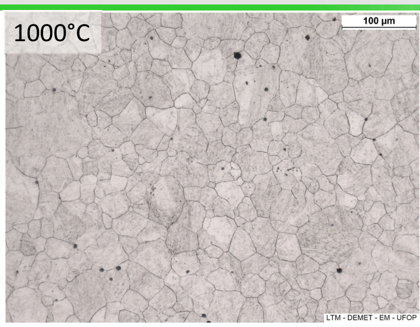

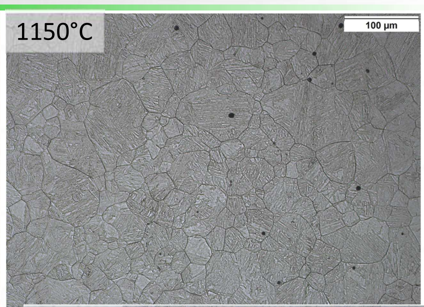

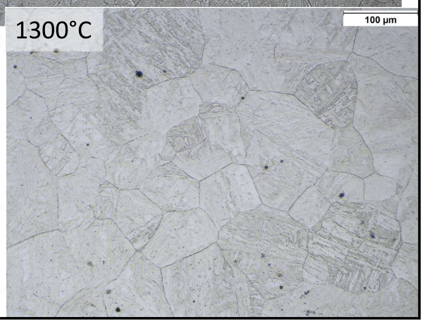

For determining the relation between Prior Austenite Grain Size (PAGS) and $\mathbf{M_S}$ and $\mathbf{M_F}$, the steel was transformed to Austenite for 180 sec and cooled.

Critical cooling rate for Martensite formation: **>25°C/sec**

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Austenite size & M_S / M_F

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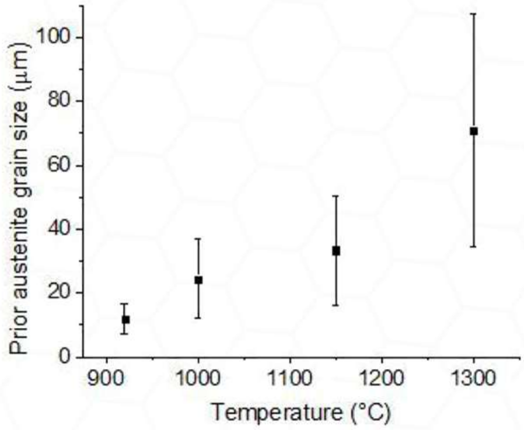

Cooling rate (°C/s)							
25°C/s		50°C/s		75°C/s		100°C/s	
M_S	M_f	M_S	M_f	M_S	M_f	M_S	M_f
484	333	457	311	446	304	436	293

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Austenizing temperature

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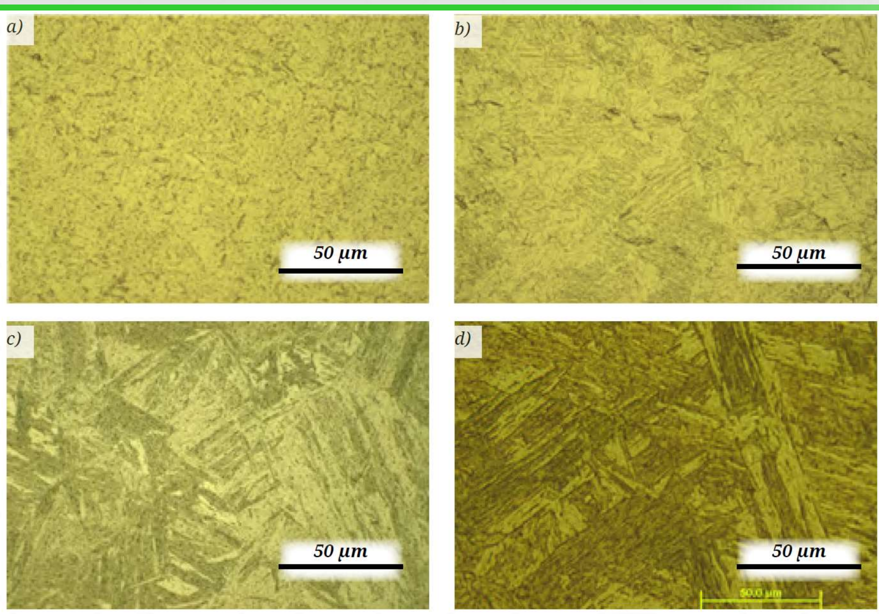

C = 0.15%,
Mn = 1.43%
Si = 0.29%

a. T_{aus} = 900°C
b. T_{aus} = 1000°C
c. T_{aus} = 1100°C
d. T_{aus} = 1200°C

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Source: https://doi.org/10.2478/amt-2018-0008

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Tempered Martensite

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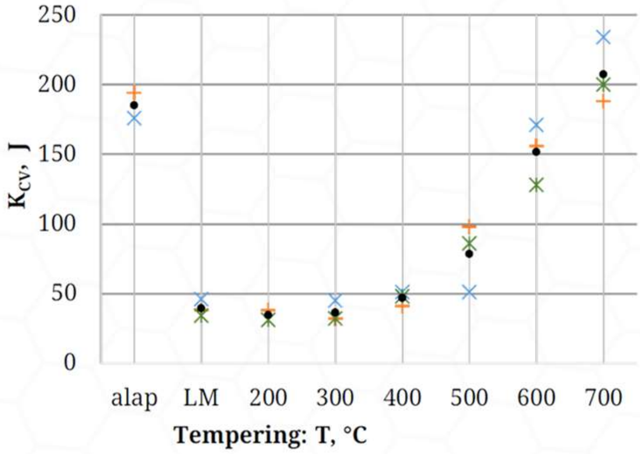
Austenizing for 20 minutes and quenching in agitated ice water, tempering at

- 200°C
- 300°C
- 400°C
- 500°C
- 600°C
- 700°C

for 20 minutes will result in:

- Reduction of brittleness
- Increase in impact toughness
- Slight lowering of tensile strength



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Tempered Martensite

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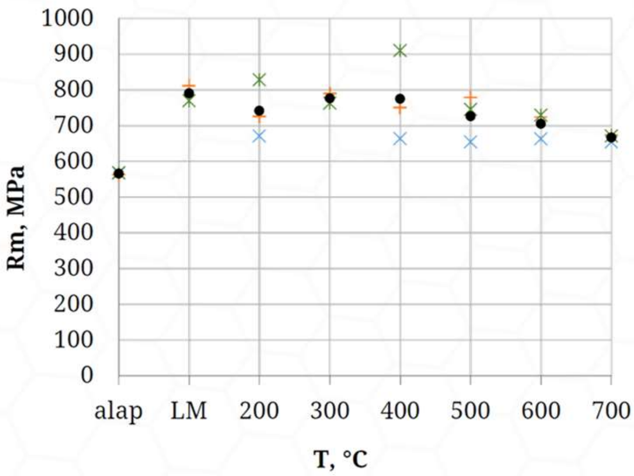

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Tempered Martensite

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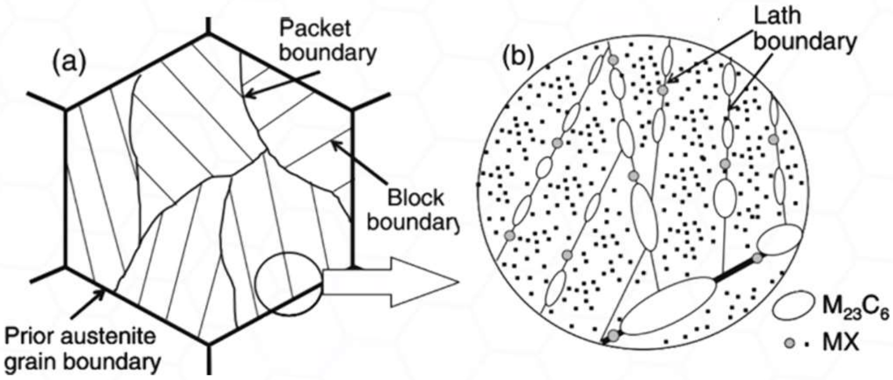
Heat treatment will:

- Diffusion of Carbon from BCT
- Carbon will form Cementite on Block- and Packet boundaries
- Depleted BCT will morph back to BCC



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Martensite types

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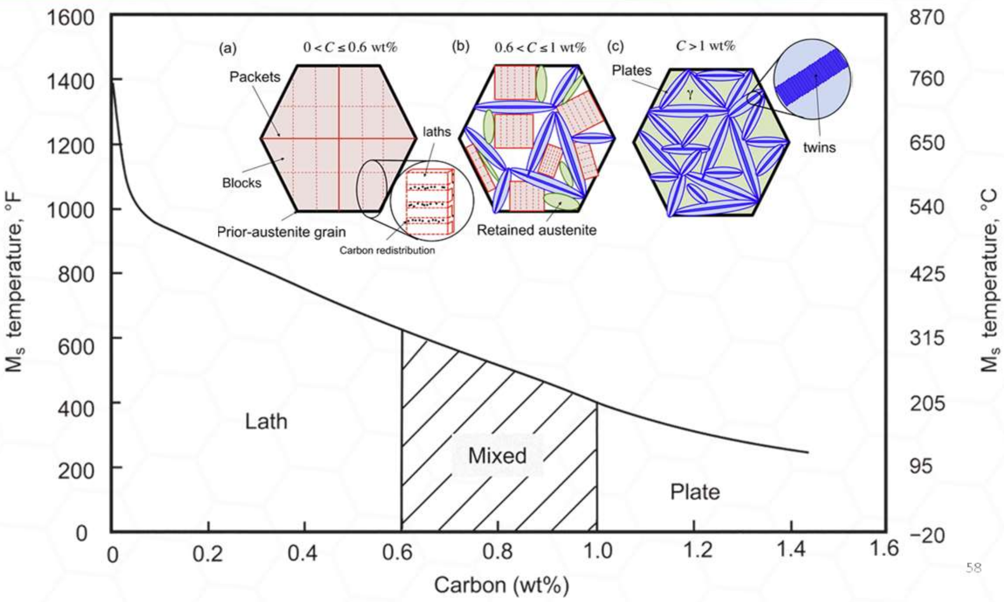
> 1,0% Carbon: lenticular martensite will be formed, also called 'Plate' or 'Lens' shape.



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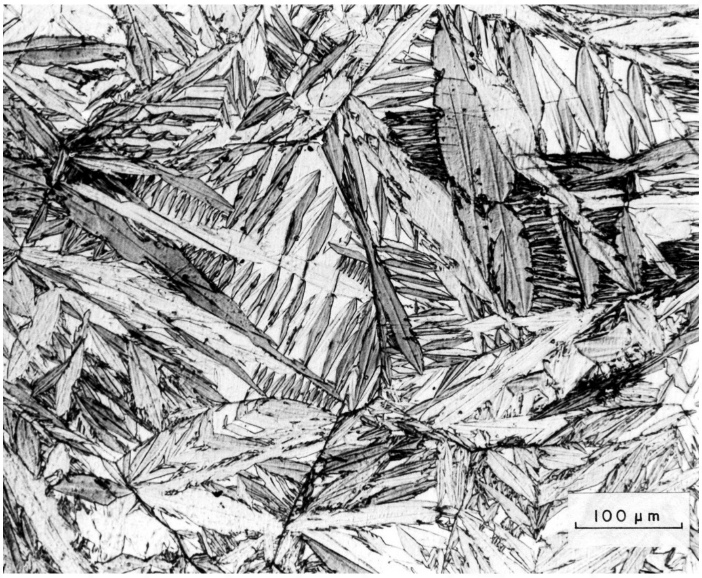
Martensite - Lenticular



When >1,0% Carbon, Martensite will be shaped in Lenticular discs, the 'classic' needle shaped structure we (most likely) all recognize.

As this high percentage of Carbon is highly unusual in construction steel, application is limited to tool-steel and niche markets, i.e. rails.

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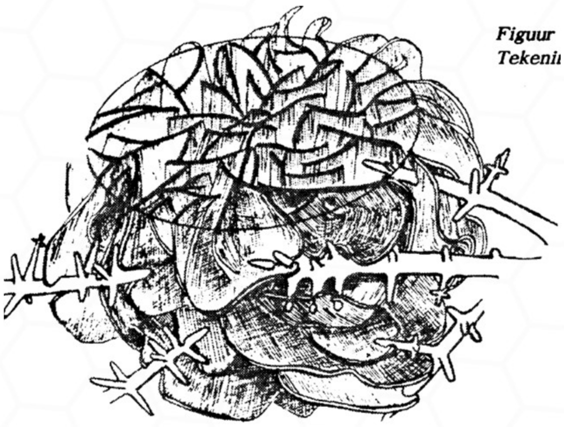
Martensite - Lenticular

The Lenticular disc structure is also called 'needle-like' structure, due to the shape 'on the screen or photo'.

In reality, what is shown on a photo is a slice or: cross-section of the structure.

This is comparable to the lamellair 'rozet' structure of **high-carbon cast iron** →



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Tempered Martensite

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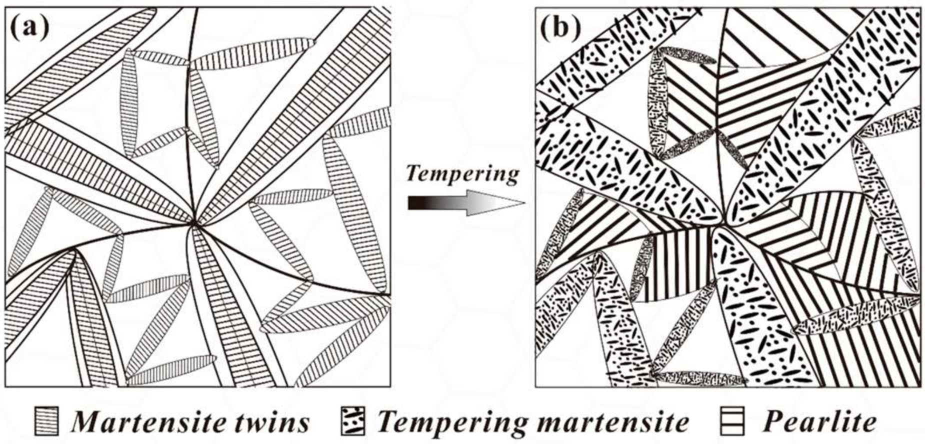
Tempering of lenticular Martensite will allow Carbon to diffuse into Pearlite platelets



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Martensite; Some final thoughts…

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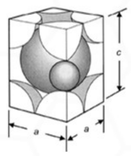
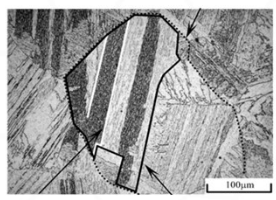
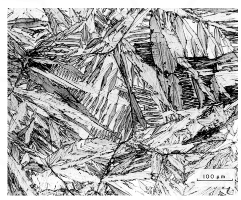
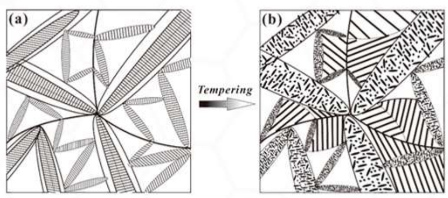
- Rapid cooling from Austenite and the consecutive undercooling will retard FCC transformation into BCC.
- Carbon in the Ferrite matrix will shape BCC into BCT, including high internal stresses.
- Amount of Carbon determins the structure type the Martensite will take on:
  < 0,6% C: Lath
  > 1% C: Lenticular
- Elements **Mo**, Cr, Mn, V and B will positively influence hardenability by postponing FCC transformation.
- Tempering will not remove the martensite structure, but is will reduce hardness and increase toughness.









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End of presentation

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University of Delft: https://www.tudelft.nl/
University of Eindhoven: https://www.tue.nl/en/

Video's
Slide 09: https://www.youtube.com/watch?v=OQ5lVjYssko
Slide 18: https://www.youtube.com/watch?v=qyEsuBpII2k

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