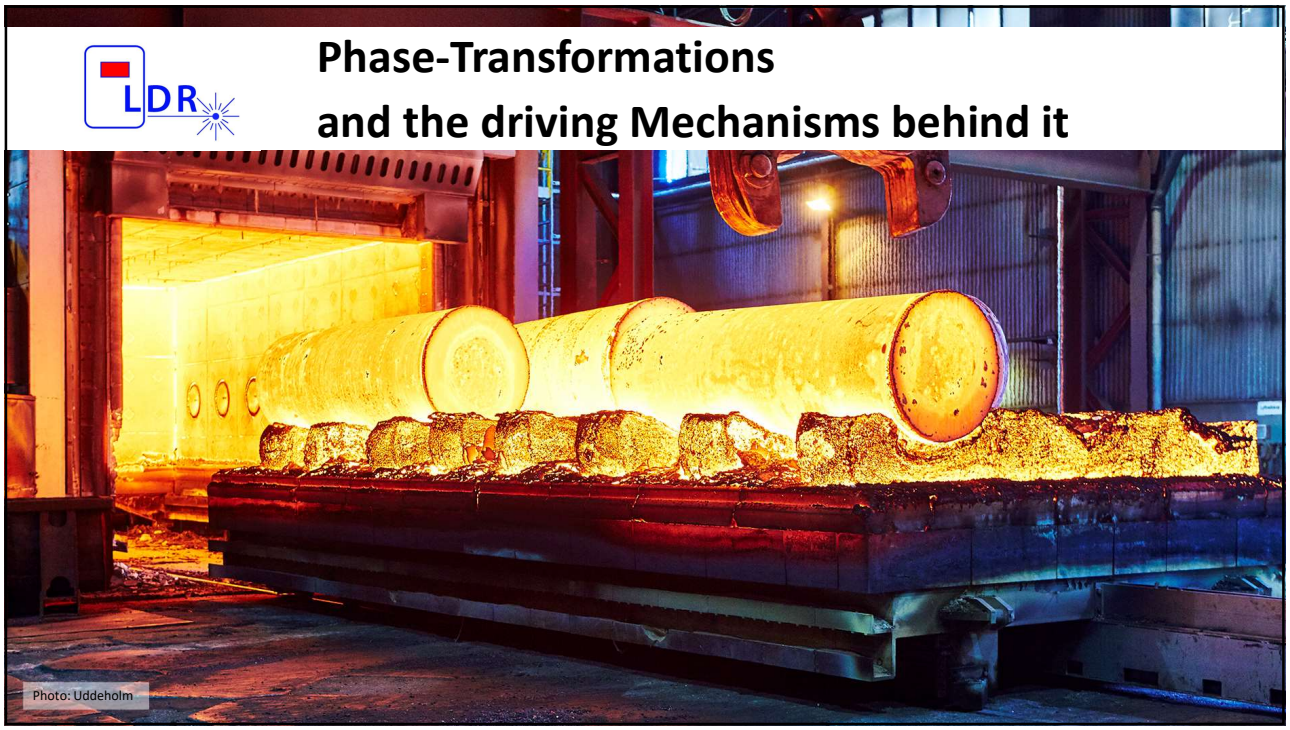
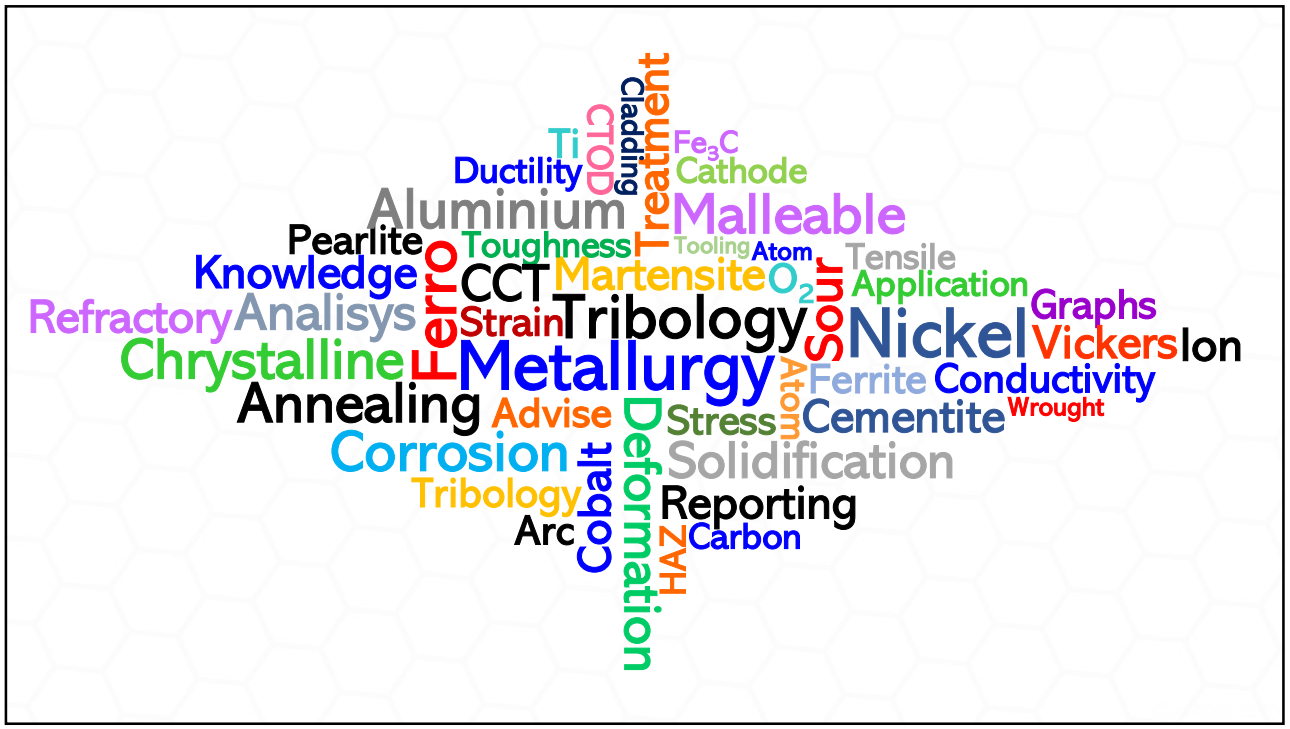

LDR
Phase-Transformations
and the driving Mechanisms behind it
Photo: Uddeholm

1


Ti
CTOD
Cladding
Treatment
Fe3C
Ductility
Cathode
Aluminium
Malleable
Pearlite
Toughness
Tooling
Atom
Tensile
Knowledge
Ferro
CCT
Martensite
O2
Sour
Application
Refractory
Analisys
Strain
Tribology
Nickel
Graphs
Chrystalline
Metallurgy
Vickers
Ion
Annealing
Advise
Deformation
Stress
Ferrite
Conductivity
Cementite
Wrought
Corrosion
Solidification
Tribology
Cobalt
Reporting
Arc
HAZ
Carbon

2

Topics

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In metallurgy, welding & fabrication.

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

3

3

Heat Treatment

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Material crystal lattice configuration in steel and their effect:

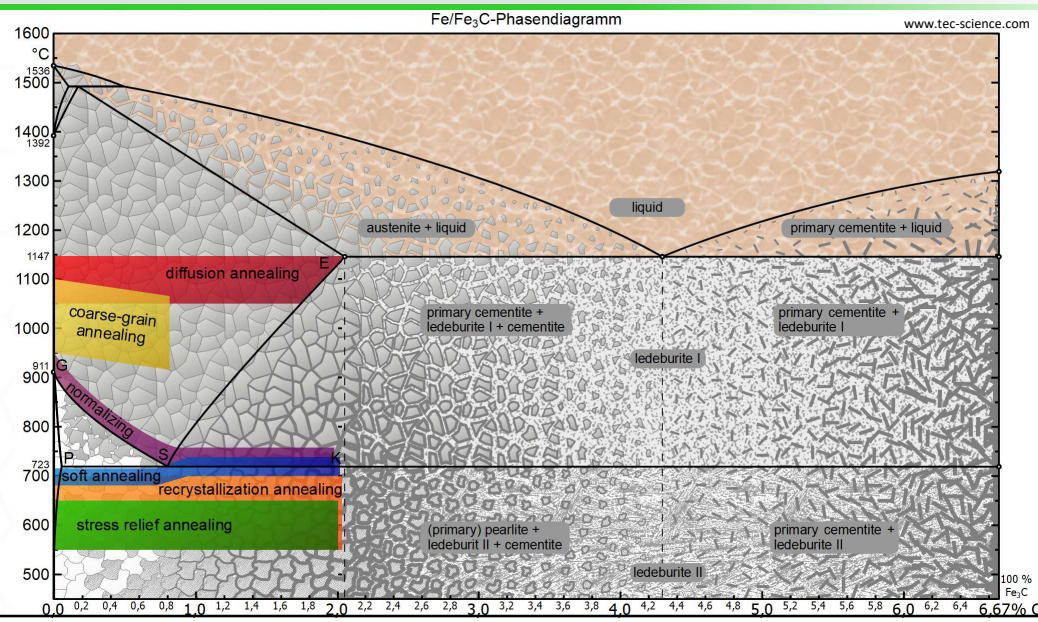
Soft Annealing	⇨	Better Formability
Coarse Grain Annealing	⇨	Better Machinability
Solution Annealing	⇨	Homogenization of alloying elements
Stress Relief Annealing	⇨	Reduction of residual Stress
Hardening	⇨	Increasing Hardness and strength
Tempering	⇨	Controlling of strength & toughness

4

4

Fe/Fe_3C Phase Diagramm

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5

5

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**

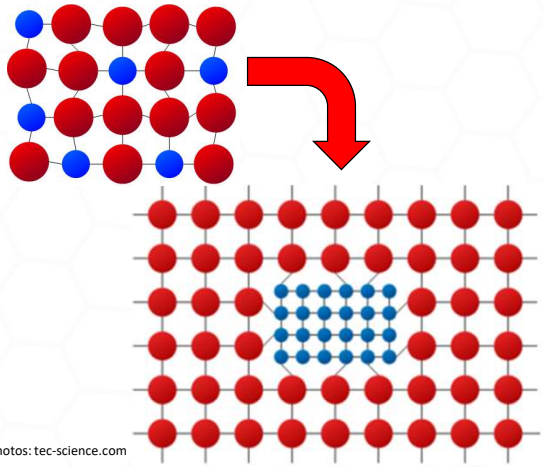
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Phase Transformations: Chemistry

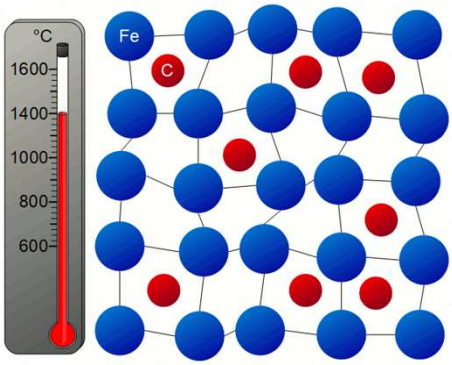
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Diffusional
Chemical composition is altered



Photos: tec-science.com

Displacive
Chemical composition is not altered, only the chrystal structure



7

7

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



8

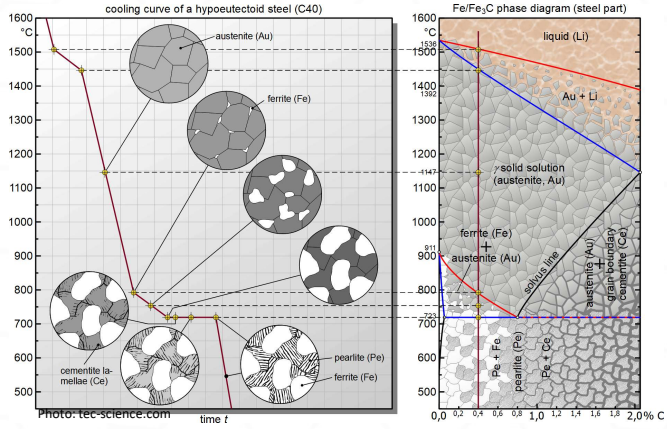
8

Phase Transformations: Temperature

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Diffusional
isothermal process
continues at constant temperature

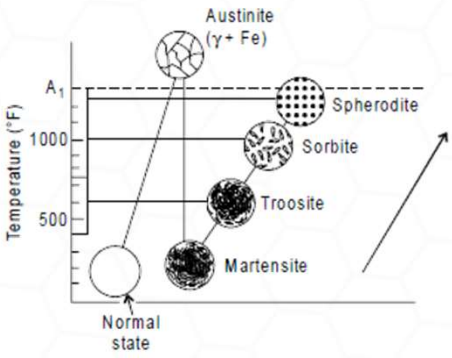
Displacive
a-thermal process
requires temperature reduction



Phase Transformations

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Diffusional	**Displacive**
Cementite	Ferrite
Pearlite	Martensite
Ledeburite	Bainite
Troostite	
Sorbite	
Spheroidite	



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)

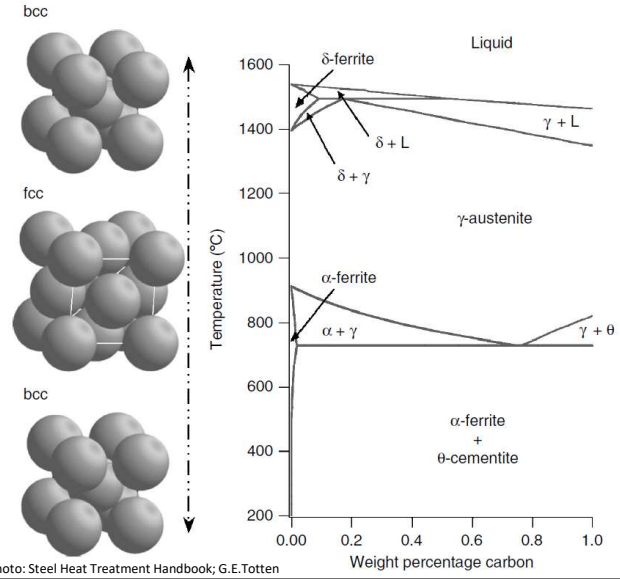


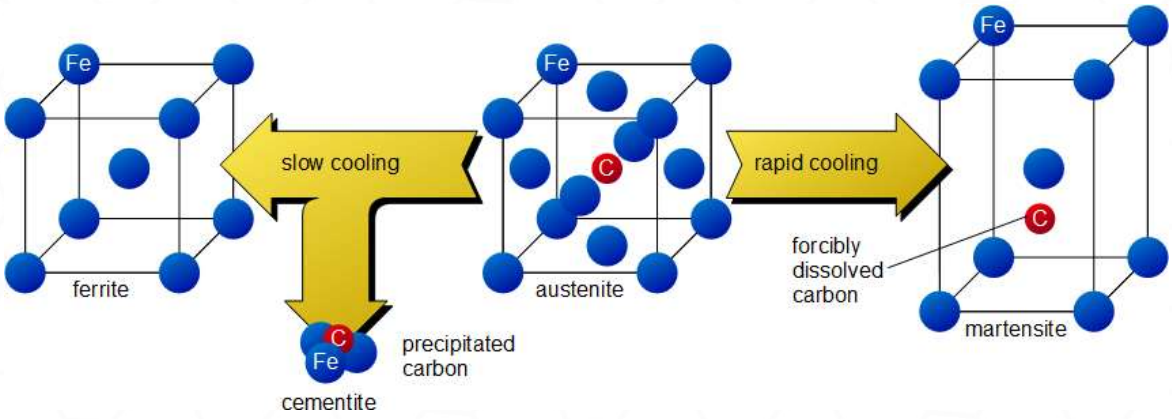
Photo: Steel Heat Treatment Handbook; G.E.Totten

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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

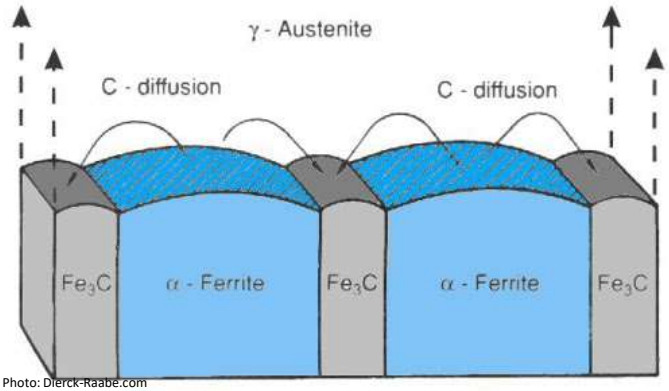


Photo: Dierck-Raabe.com

Fe_3C molecular structure:

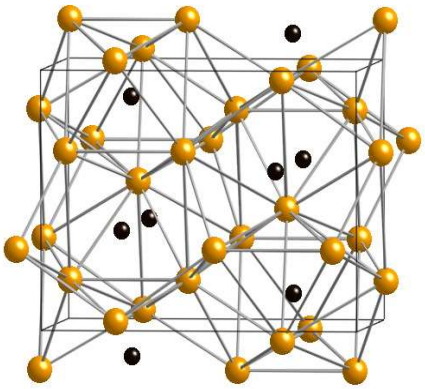


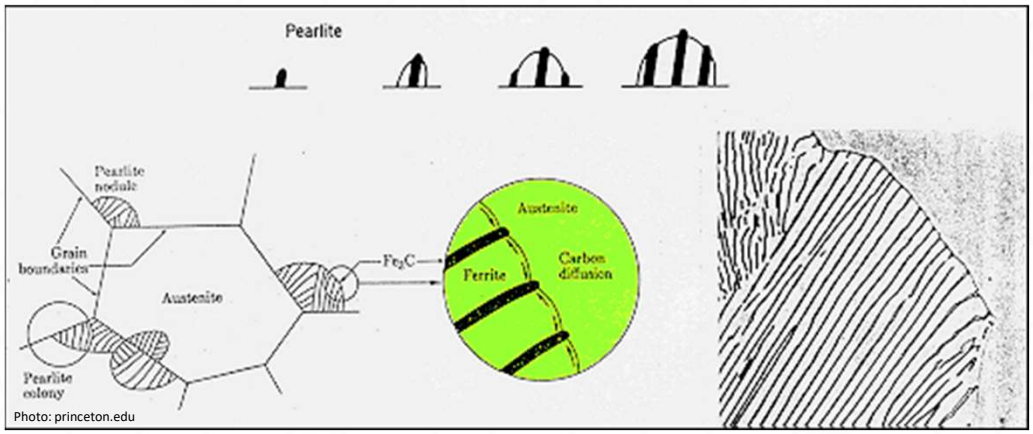
Photo: som.web.cmu.edu

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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.

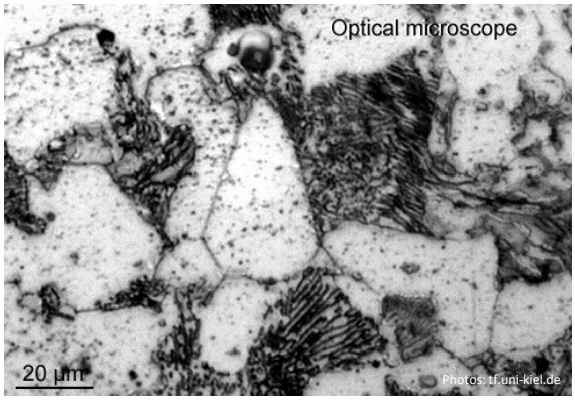
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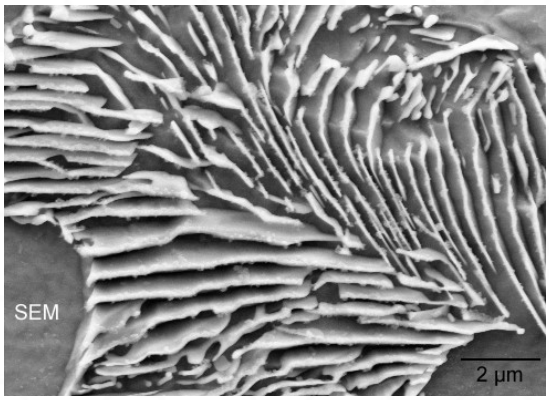
Pearlite under a microscope

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Optical Microscope



SEM

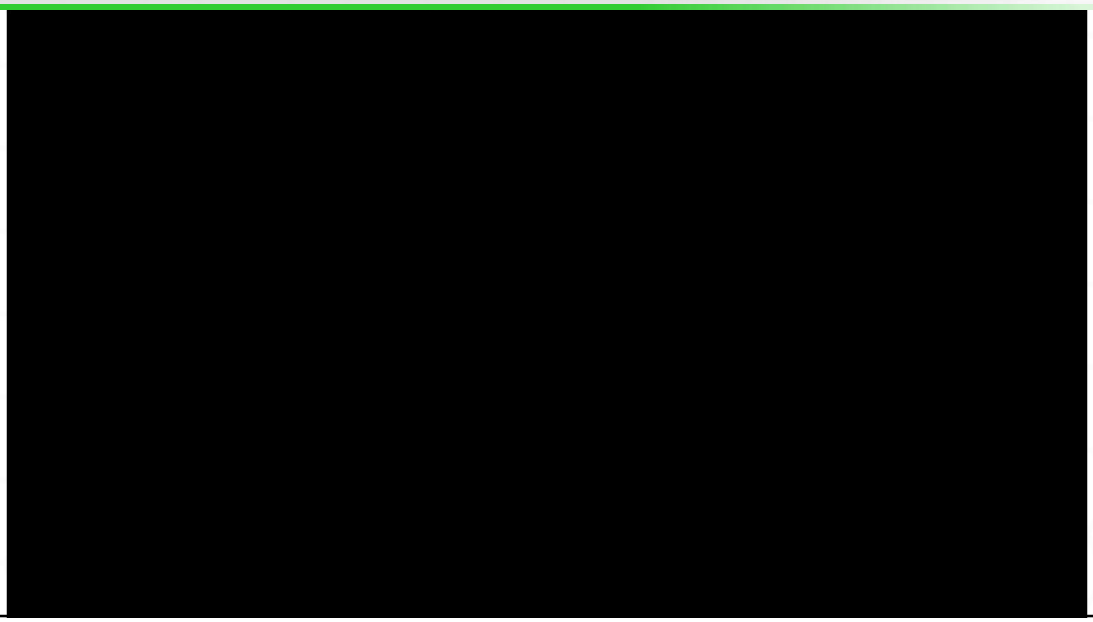


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16

Pearlite

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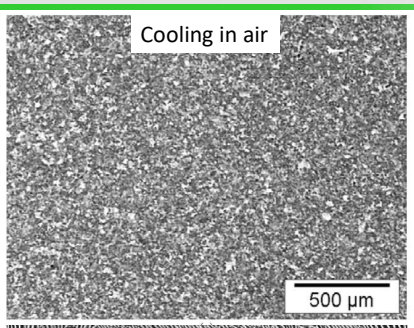
Pearlite; lathe size

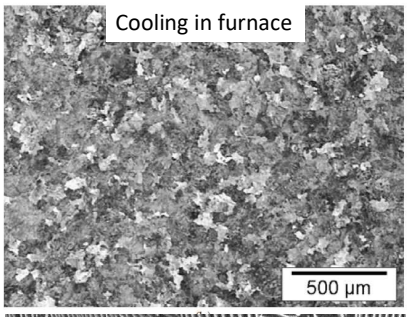
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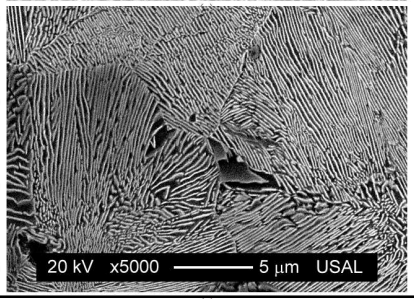
Eutectoidic steel

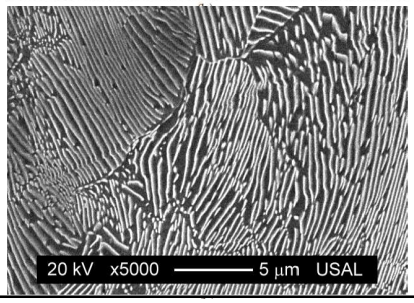
Composition:

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









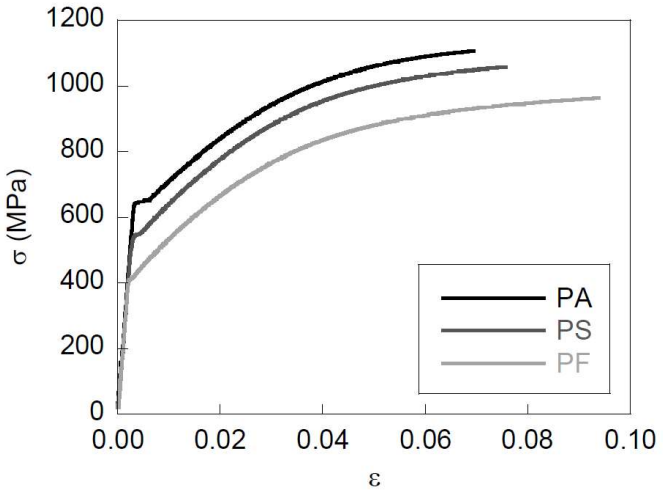
Source:
"Role of the microstructure on the mechanical properties of fully pearlitic eutectoid steels" DOI: 10,3221

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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

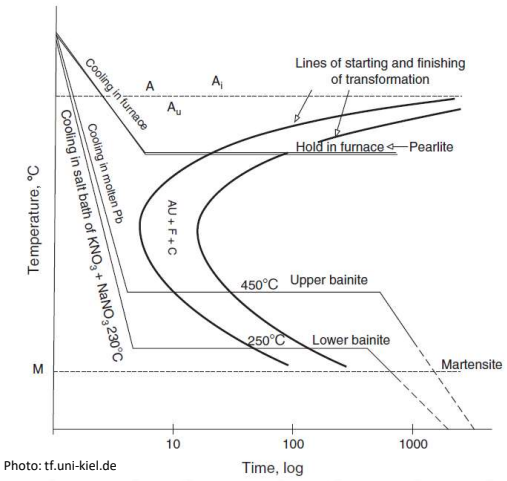


Photo: tf.uni-kiel.de

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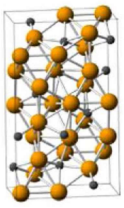
Pearlite; Carbide chrystalline structures

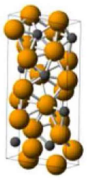
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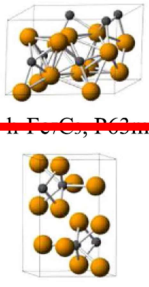
Cementite = **Fe_3C**.
Or is it?

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

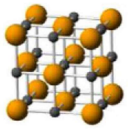
Trigonal prismatic carbide

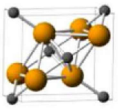

o-Fe_7C_3, Pnma

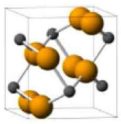

χ-Fe_5C_2, C2/c

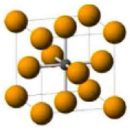

h-Fe_7C_3, P63mc
θ-Fe_3C, Pnma

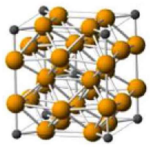
Octahedral carbide


γ'-FeC, FM-3M

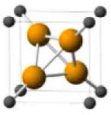

η-Fe_2C, Pnnm


ζ-Fe_2C, Pbcn


γ''-Fe_4C, PM-3m


α'-$Fe_{16}C_2$, I4/mmm

Tetrahedral carbide


γ'-Fe_4C, P-43m

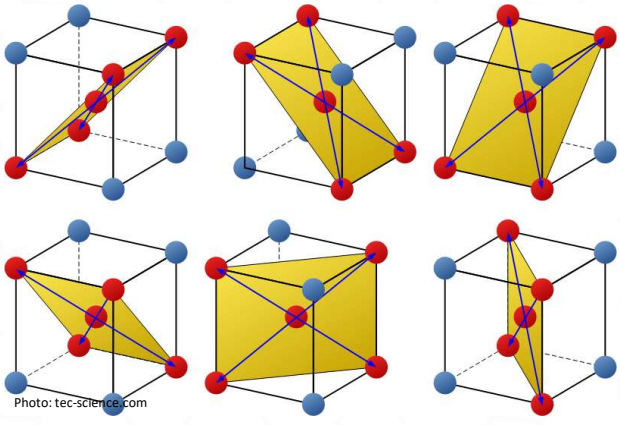
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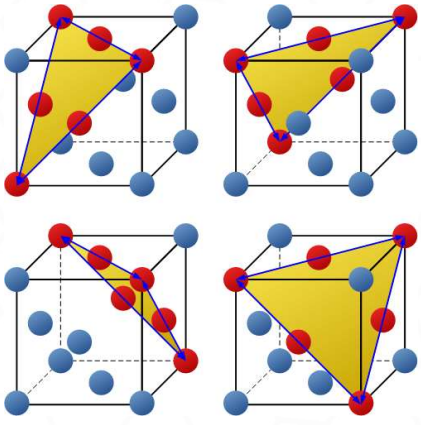
Sidestep: Slip systems in BCC and FCC

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


Photo: tec-science.com

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



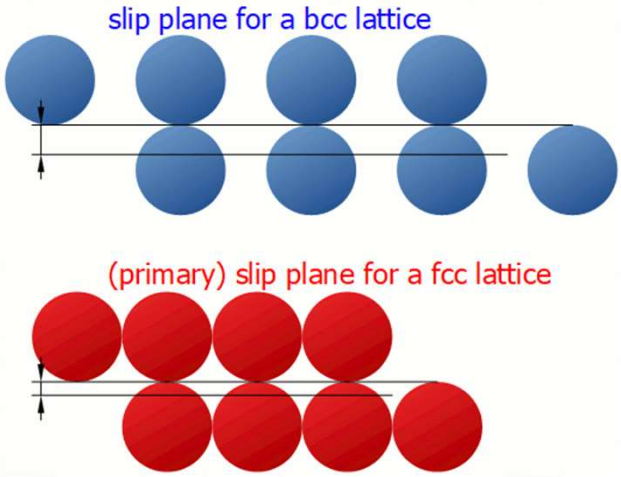
22

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Sidestep: Slip systems in BCC and FCC

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'Slipping' of atoms relative to their lattice structure:



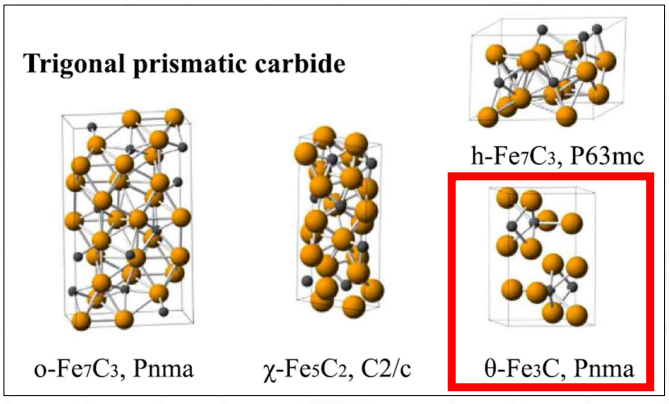
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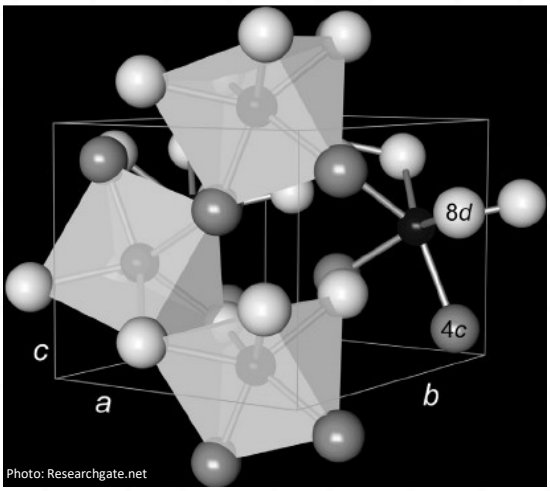
23

Slip Planes

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Slip-planes in
orthorhombic lattice (Cementite):
Not present!





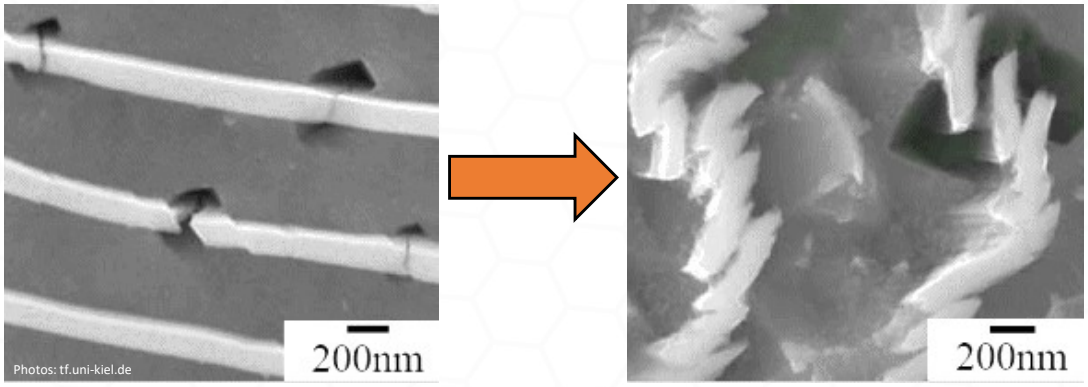
24

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Pearlite

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



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Pearlite: mixed blessings?

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

26

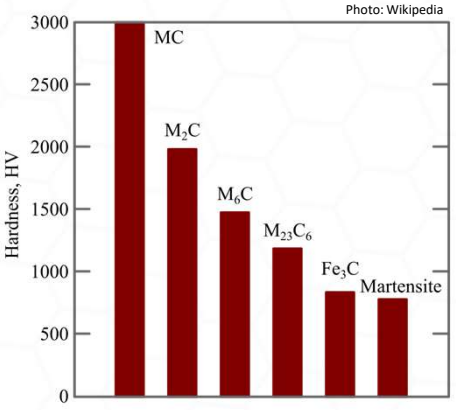
26

Pearlite…. some final thoughts

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In metallurgy, welding & fabrication.

- 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

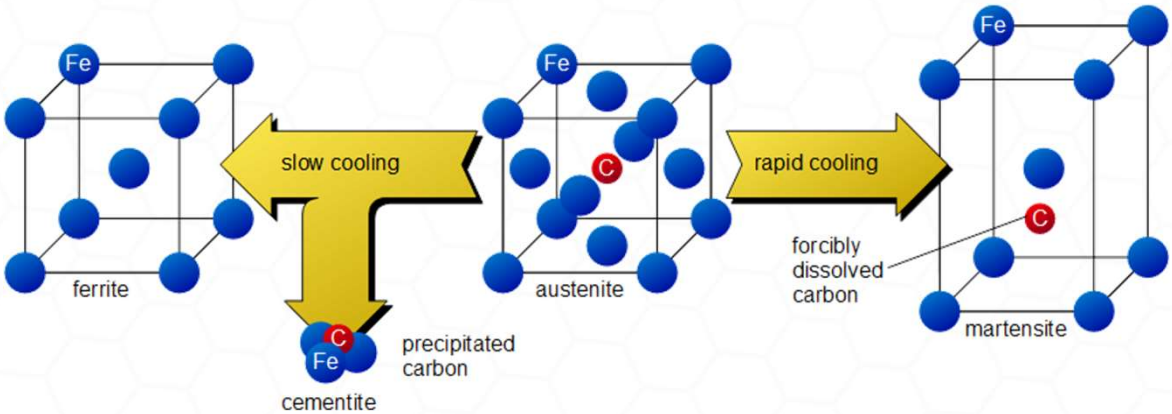


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Phase Transformation

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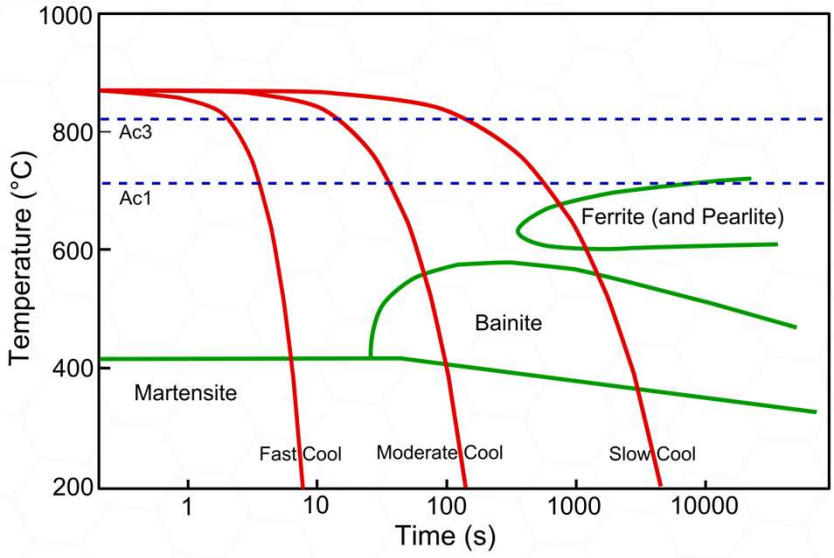
Rapid cooling will result in a forcibly dissolved carbon atom in a Body Centered Tetragonal (BCT) structure.

28

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Phase Transformation

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29

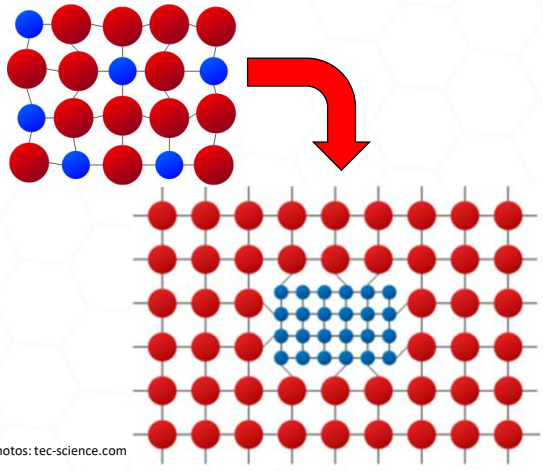
29

Phase Transformations: Chemistry

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In metallurgy, welding & fabrication.

Diffusional

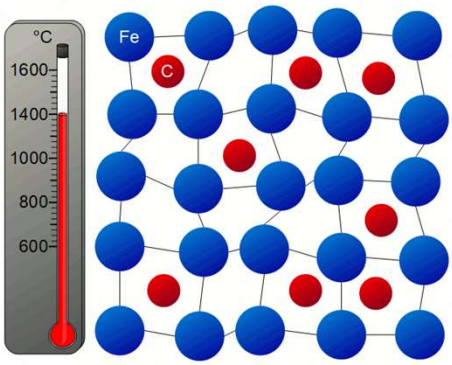
Chemical composition is altered



Photos: tec-science.com

Displacive

Chemical composition is not altered, only the chrystal structure



30

30

Phase Transformations: Speed

GROEN TRAINING & CONSULTANCY
In metallurgy, welding & fabrication.

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



31

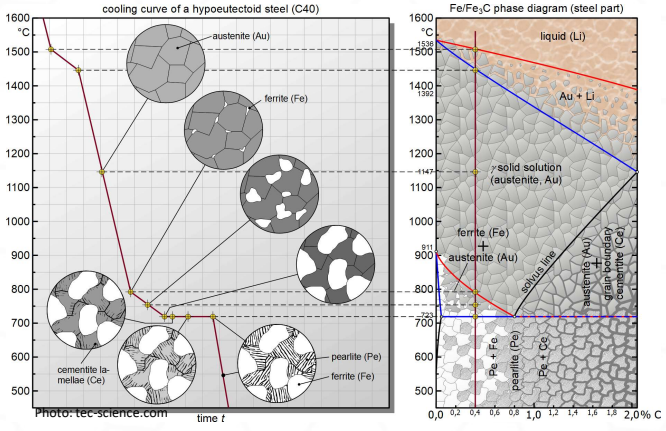
31

Phase Transformations: Temperature

GROEN TRAINING & CONSULTANCY
In metallurgy, welding & fabrication.

Diffusional
isothermal process
continues at constant temperature

Displacive
a-thermal process
requires temperature reduction



32

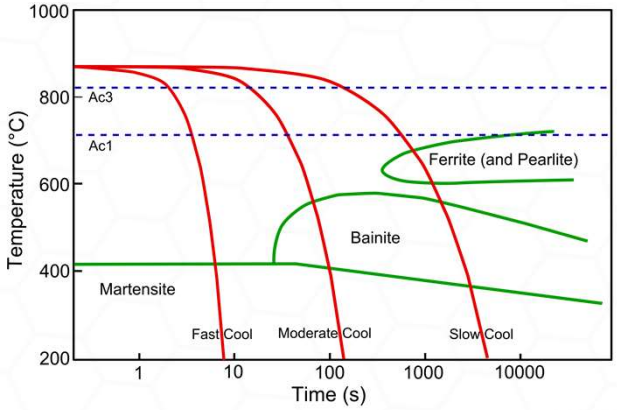
32

Phase Transformations: Temperature

GROEN TRAINING & CONSULTANCY
In metallurgy, welding & fabrication.

Diffusional
isothermal process
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Displacive
a-thermal process
requires temperature reduction

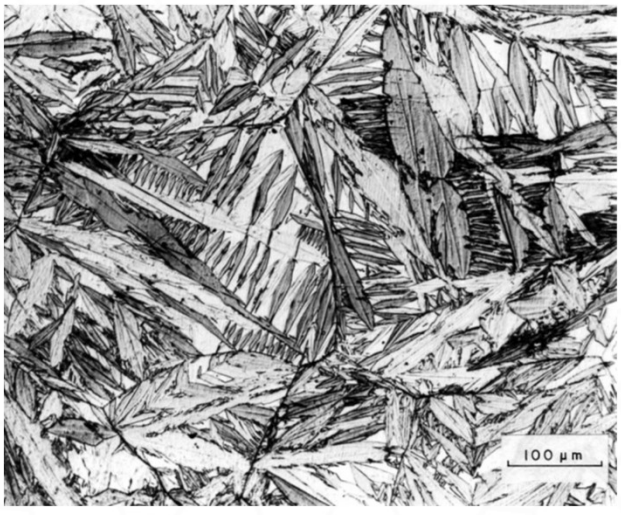


33

33

Martensite

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In metallurgy, welding & fabrication.



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…)

34

34

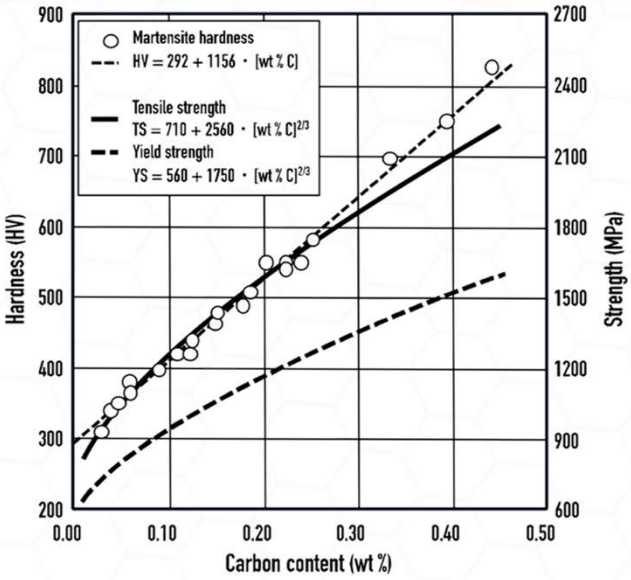
Martensite: hardness & Yield

GROEN TRAINING & CONSULTANCY
In metallurgy, welding & fabrication.

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….

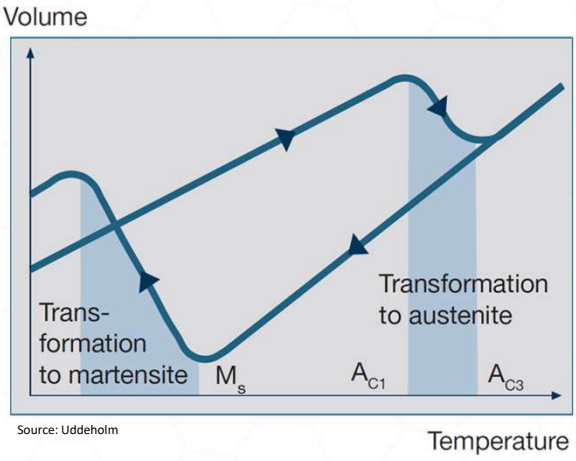


35

35

BCC ⟶ FCC and back

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In metallurgy, welding & fabrication.



Source: Uddeholm

Formation of Martensite is mainly influenced by the following factors:

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

← Generic graph by a Dilatometer

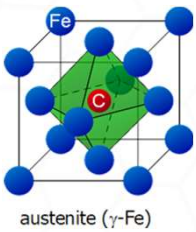
volume change:
transformation BCC ⟶ FCC and vice versa

36

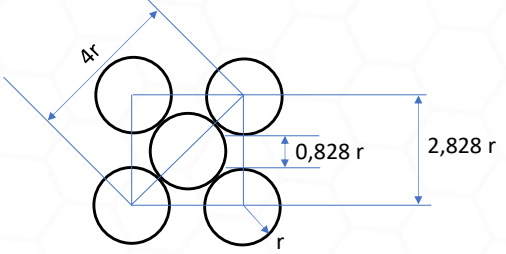
36

Interstitiële ruimte in BCC en FCC

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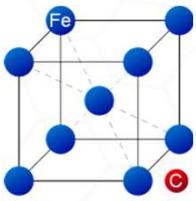


austenite (γ-Fe)

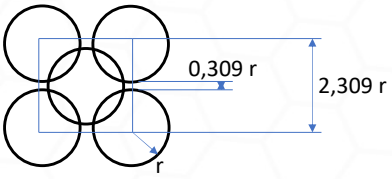


FCC:
hogere pakkings-graad dan BCC.

Interstitieel opgelost atoom
max grootte: 0,828*r



ferrite (α-Fe)



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

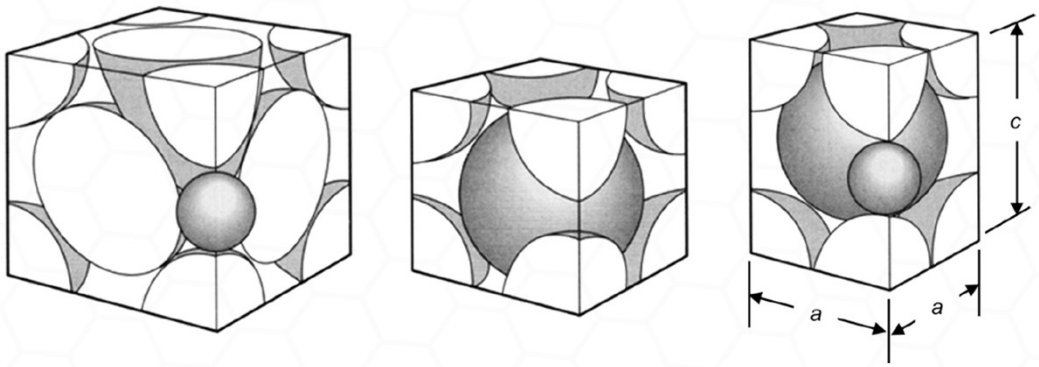
37

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Transformation FCC to BCT

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In metallurgy, welding & fabrication.

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.

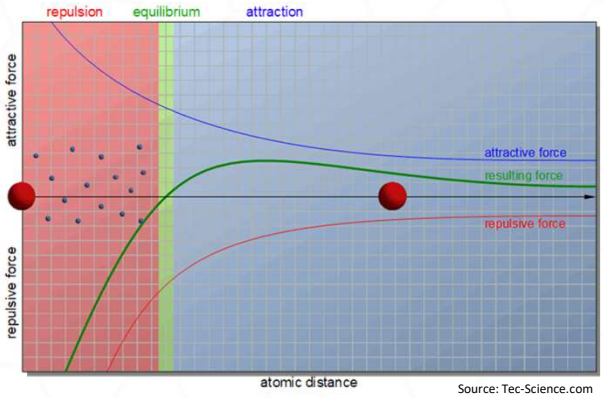
38

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Transformation FCC to BCT . . .

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In metallurgy, welding & fabrication.

- … 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

39

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Martensite types

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In metallurgy, welding & fabrication.

Packets with laths

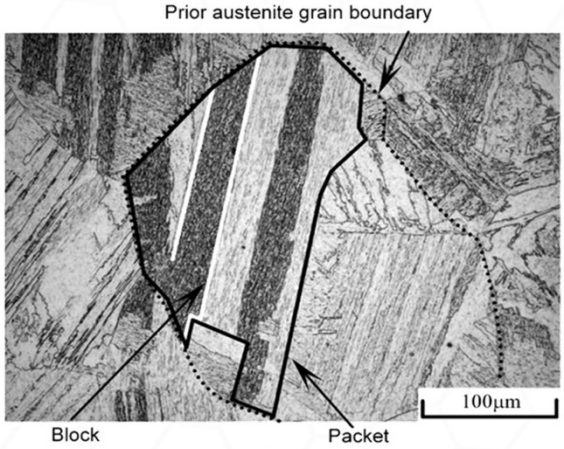
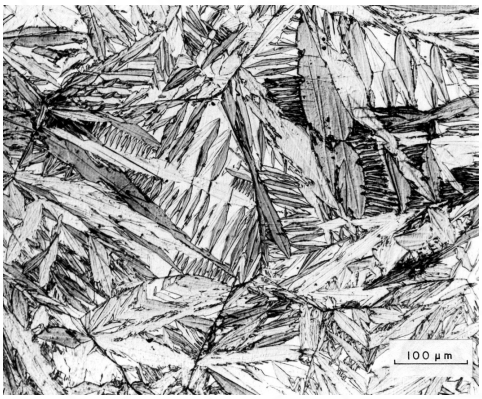


Plate- or Lenticular discs (lens-shape)



40

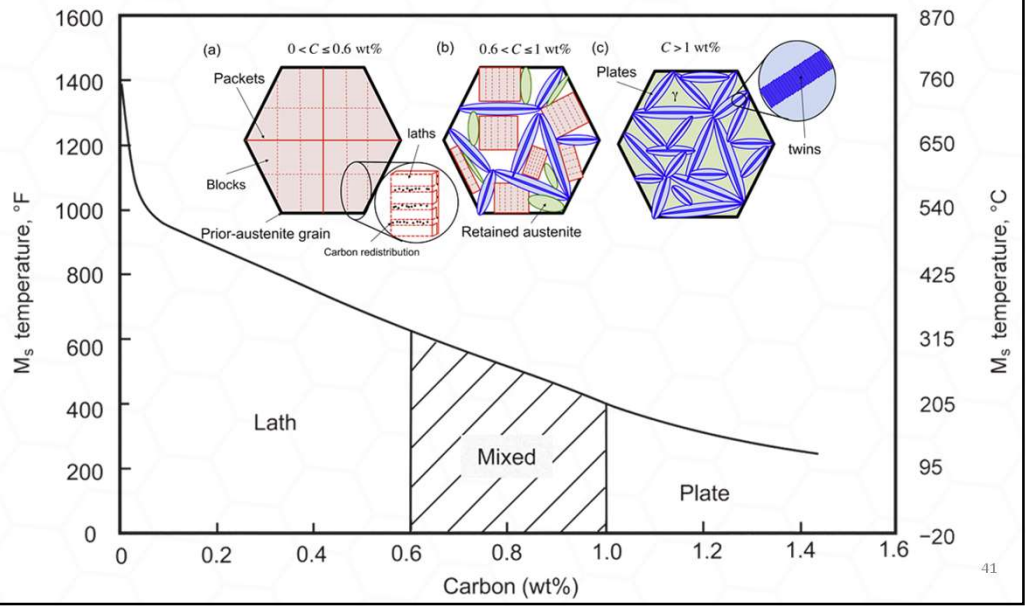
40

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.

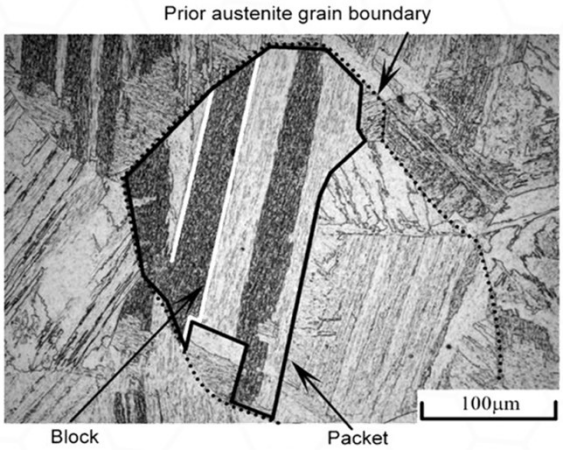


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Lath Martensite

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In metallurgy, welding & fabrication.



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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42

Lath Martensite

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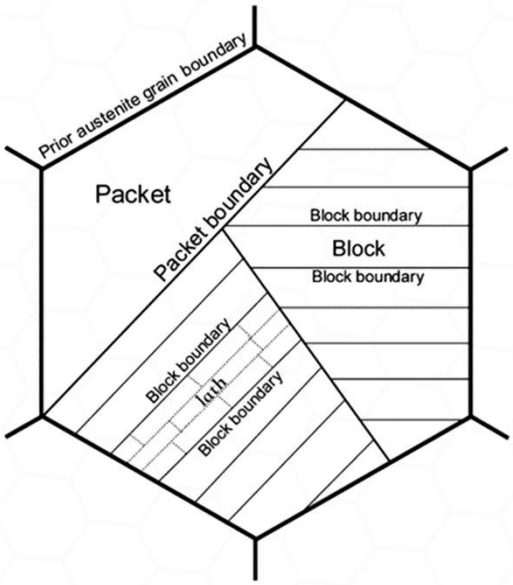
When %C is lower than approx. 0,6%, Martensite will form in the shape of **laths**.

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.

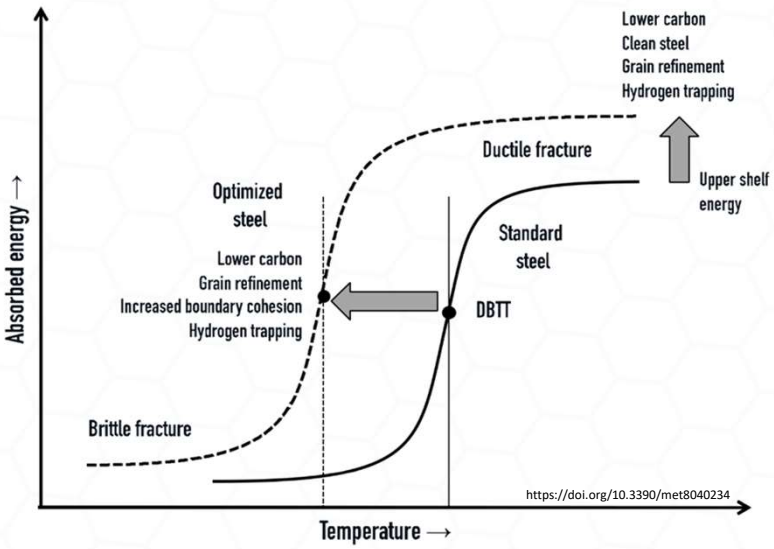


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Lath Martensite

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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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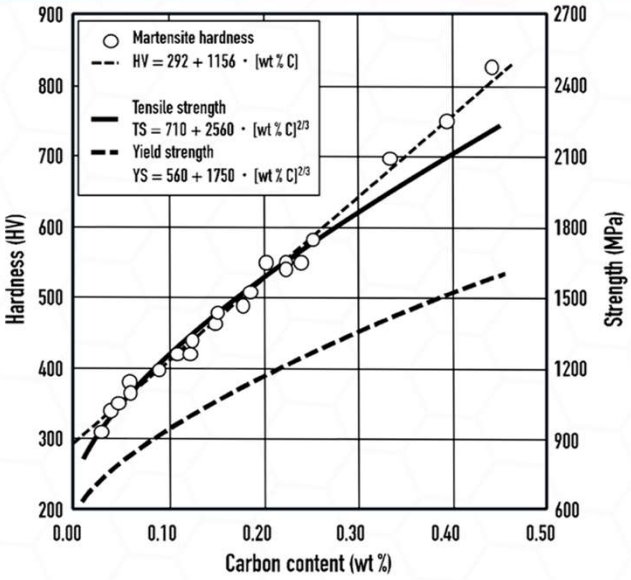
Martensite: hardness & Yield

GROEN TRAINING & CONSULTANCY
In metallurgy, welding & fabrication.

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.

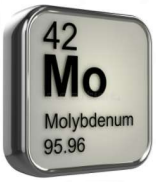


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Martensite: Alloying elements

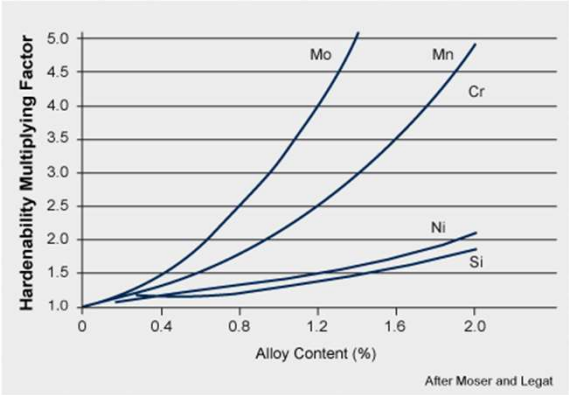
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In metallurgy, welding & fabrication.







- 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.

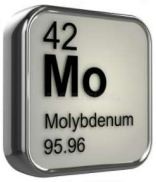


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Martensite: Alloying elements

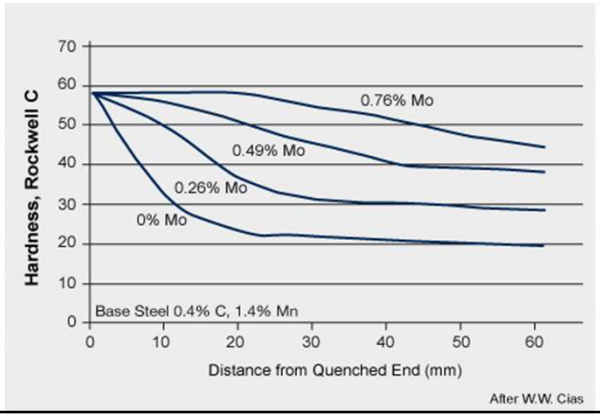
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- Mo amounts of 0,2 – 0,5 % are sufficient for through hardening when quenching.
- Mo increases parent austenite grain boundary cohesion: higher resistance against intergranular fracture

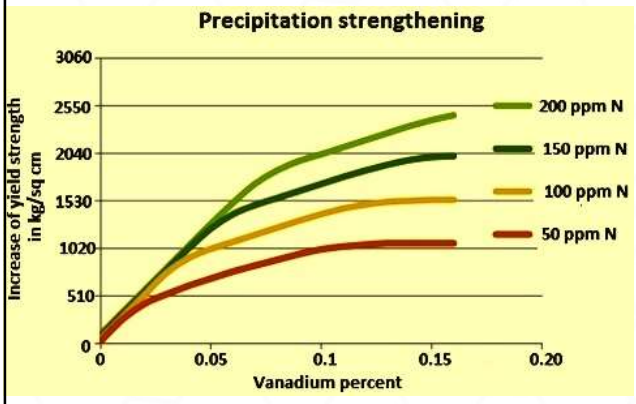


47

47

Martensite

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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

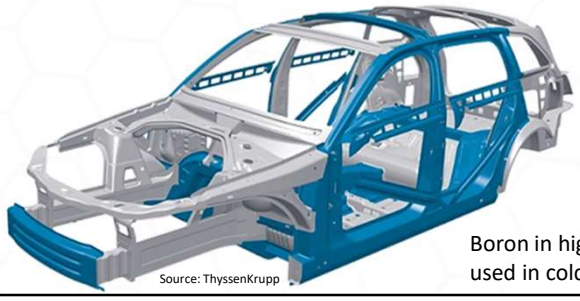
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In metallurgy, welding & fabrication.

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

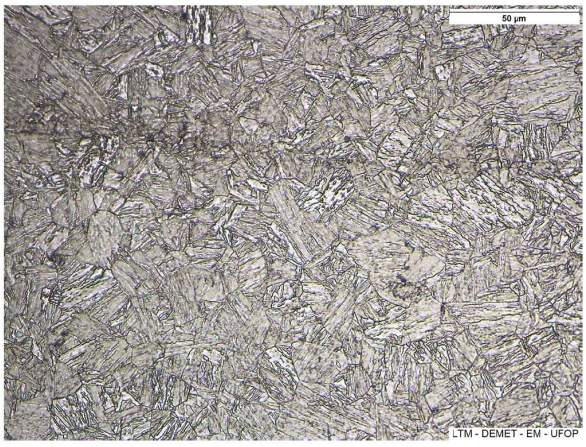


Figure 1. Optical micrograph of the studied steel in the initial state. Nital 2%. 500x.

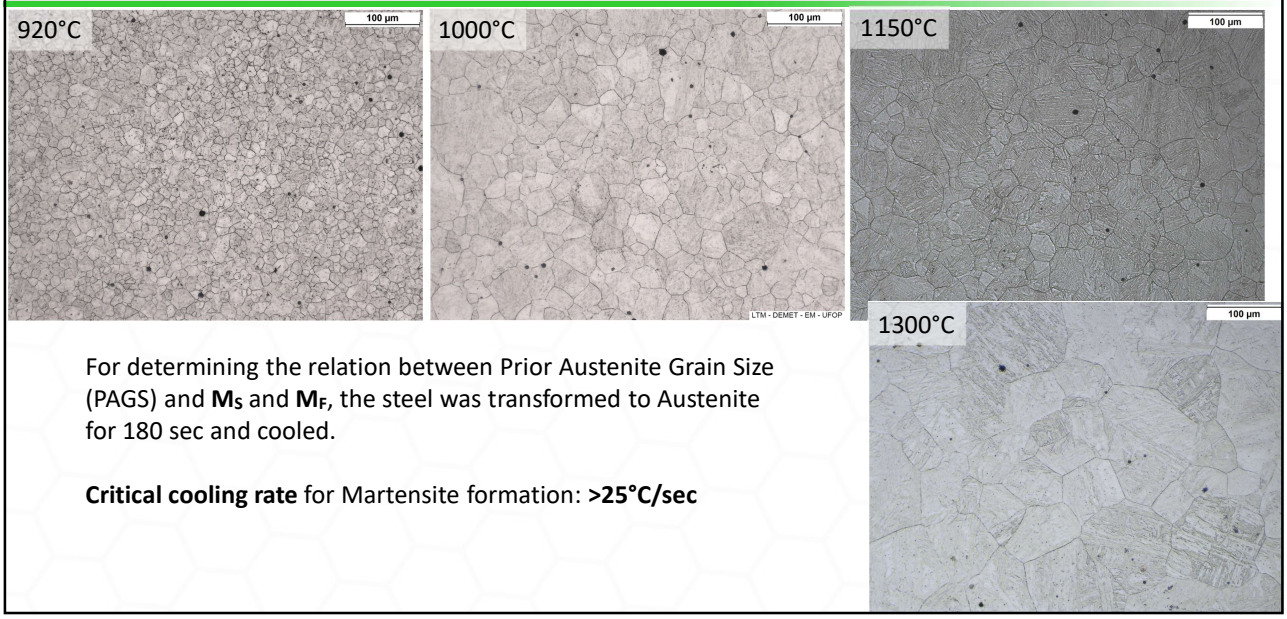
Source: https://doi.org/10.1590/1980-5373-MR-2019-0570

50

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Austenite size & M_S / M_F

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In metallurgy, welding & fabrication.



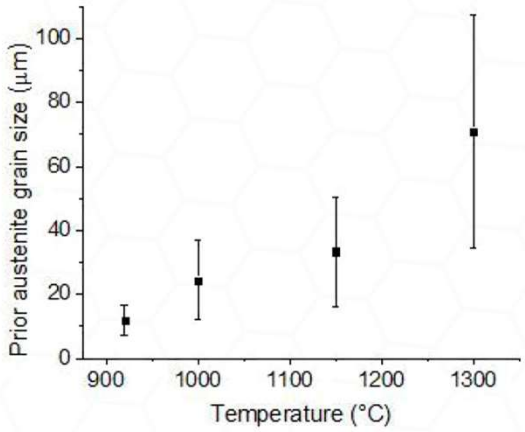
For determining the relation between Prior Austenite Grain Size (PAGS) and **M_S** and **M_F**, the steel was transformed to Austenite for 180 sec and cooled.

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

51

Austenite size & M_S / M_F

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In metallurgy, welding & fabrication.



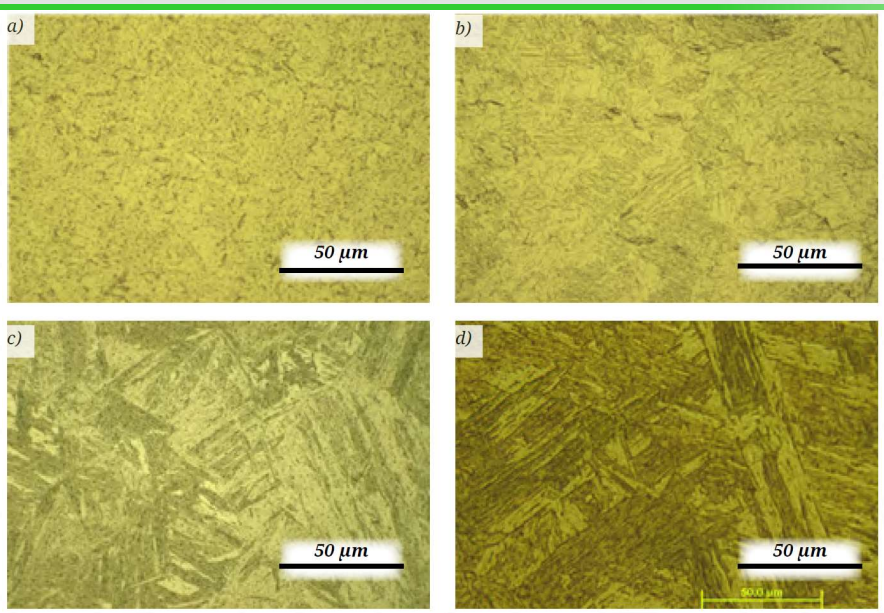
Cooling rate (°C/s)							
25°C/s		50°C/s		75°C/s		100°C/s	
M_S	M_f	M_S	M_f	M_S	M_f	M_S	M_f
484	333	457	311	446	304	436	293

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Austenizing temperature

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In metallurgy, welding & fabrication.



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

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

53

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Tempered Martensite

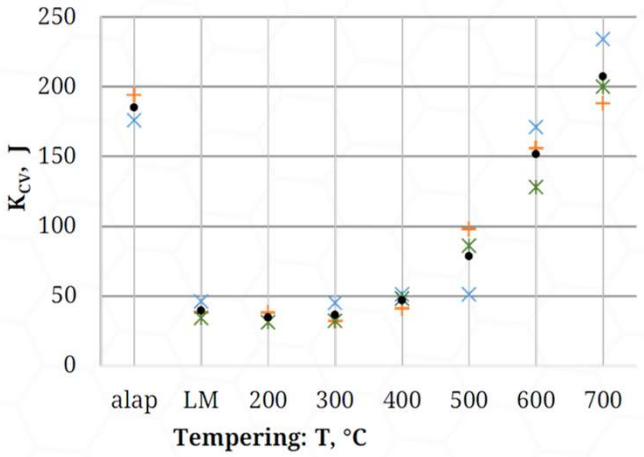
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In metallurgy, welding & fabrication.

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

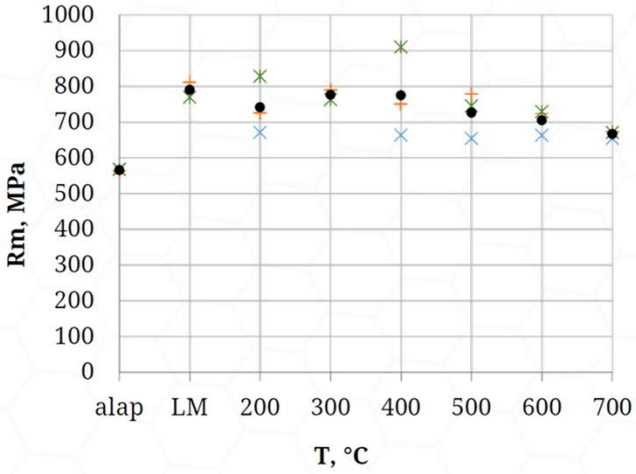
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In metallurgy, welding & fabrication.

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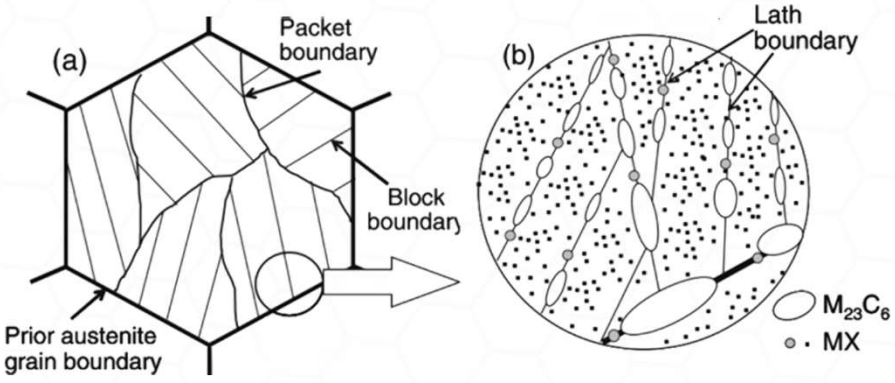
55

Tempered Martensite

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In metallurgy, welding & fabrication.

Heat treatment will:

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



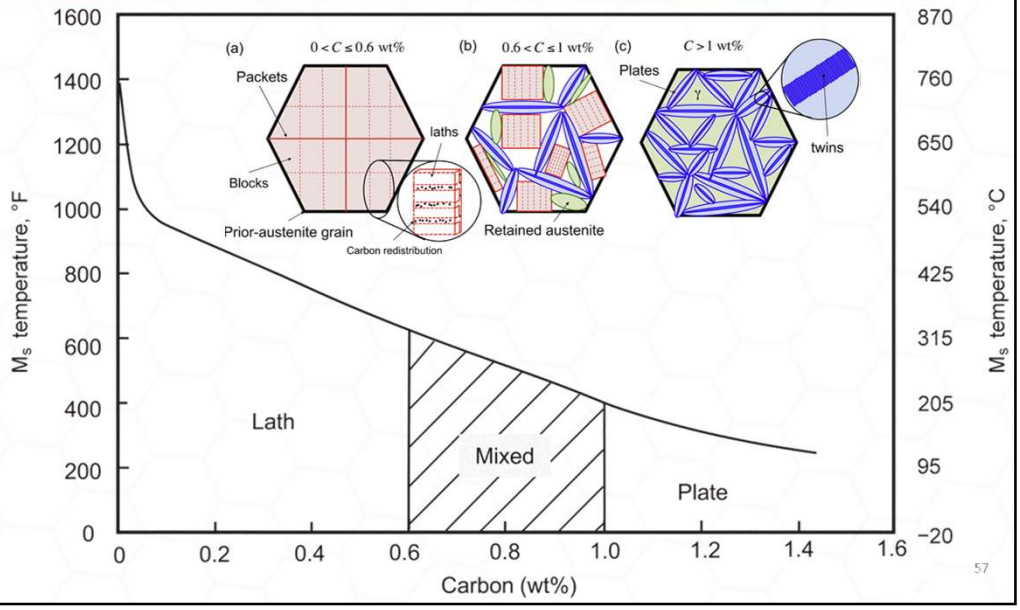
56

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Martensite types

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In metallurgy, welding & fabrication.

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

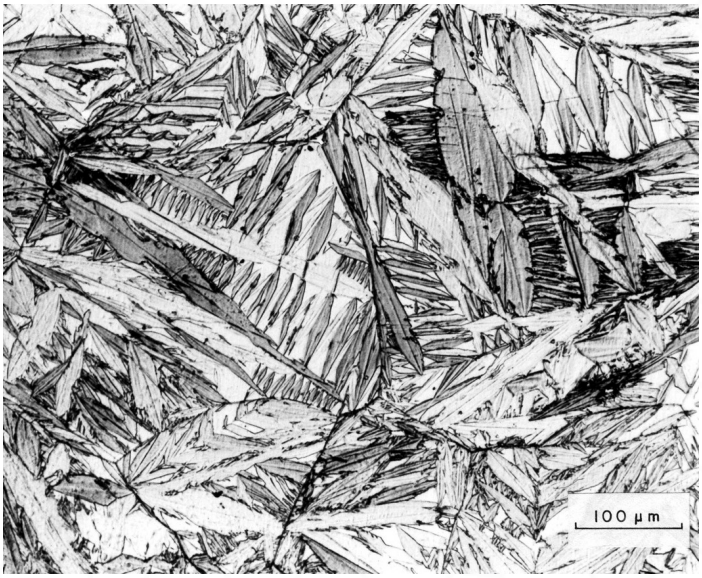


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Martensite - Lenticular

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In metallurgy, welding & fabrication.



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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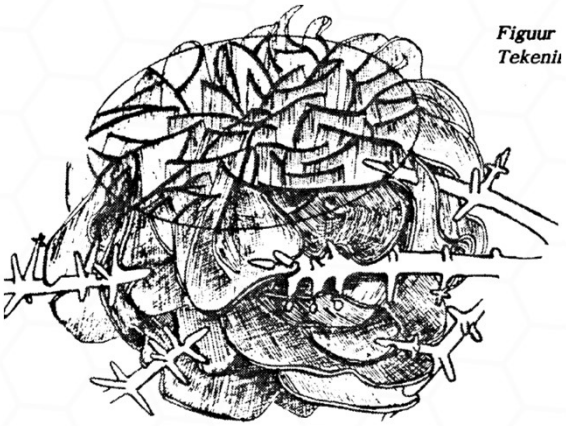
Martensite - Lenticular

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In metallurgy, welding & fabrication.

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** →



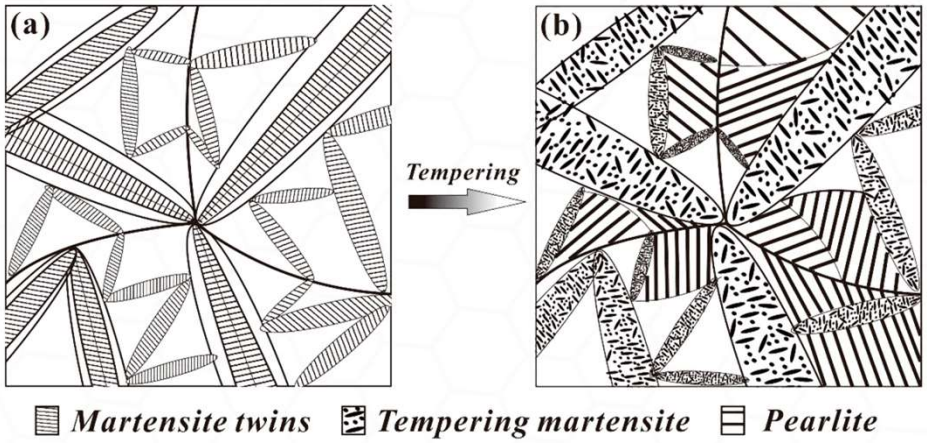
59

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Tempered Martensite

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In metallurgy, welding & fabrication.

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



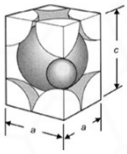
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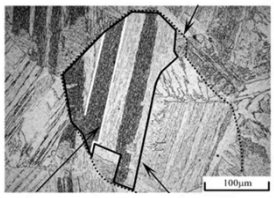
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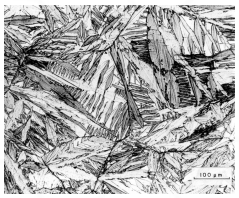
Martensite; Some final thoughts…

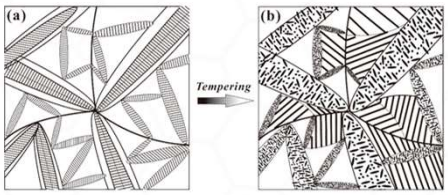
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- Rapid cooling from Austenite and the consecutive undercooling will retard FCC transformation into BCC.
- Carbon in the Ferrite matrix will shape BCC into BCT, including high internal stresses.
- Amount of Carbon determins the structure type the Martensite 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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Eskerrik asko Gràcies Tapadh leat
Gratias tibi Bedankt Merci Спасибо Terima kasih
ありがとうございました אדאנק Thank you 谢谢
Dankie teşekkür ederim Þakka þér fyrir धन्यवाद
شكرا جزيلا faafetai Danke Schön Σας ευχαριστώ
Faleminderit Баярлалаа

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