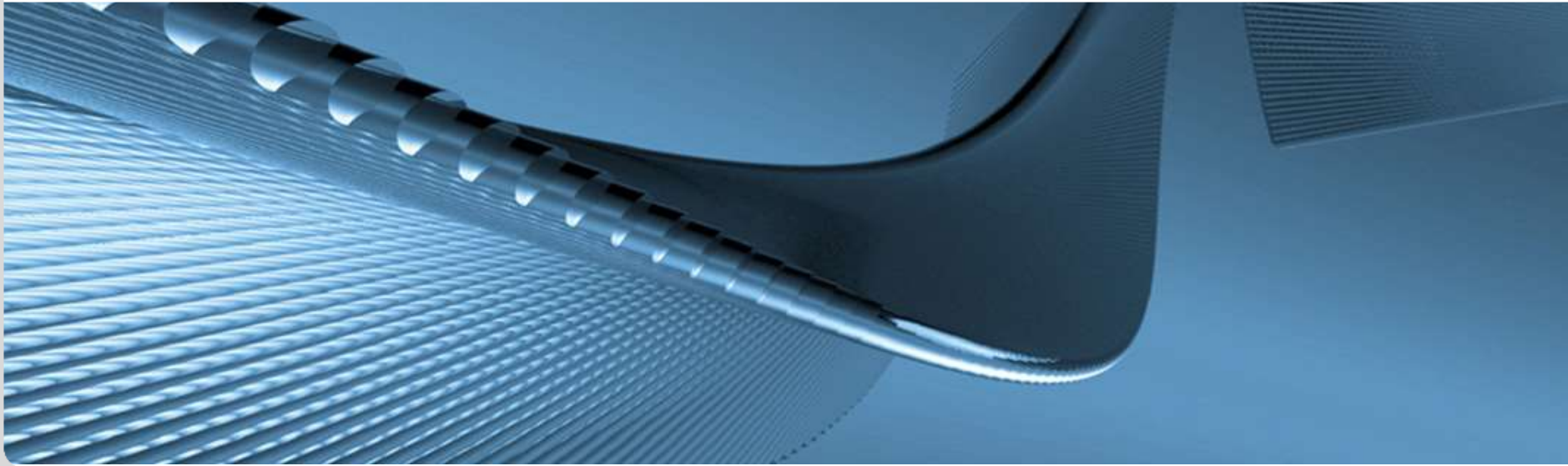


High-alloyed Steels

Structure, Phases, Properties, and Applications

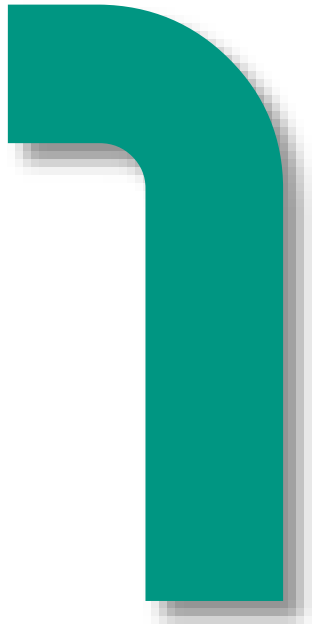
Michael Rieth, Anton Möslang, Ute Jäntsch

KARLSRUHE INSTITUTE OF TECHNOLOGY – Campus Nord, INSTITUTE FOR APPLIED MATERIALS – Applied Material Physics (KIT, IAM-AWP)



CONTENTS

- **Structure (bonds, lattice, defects, ...)**
- **Phases (basics, steel, ...)**
- **Decay of the Austenitic γ -Fe Phase (martensite formation, ...)**
- **Heat Treatments**
- **Deformation Mechanisms**
- **Applications (Eurofer, P92, 316, ...)**



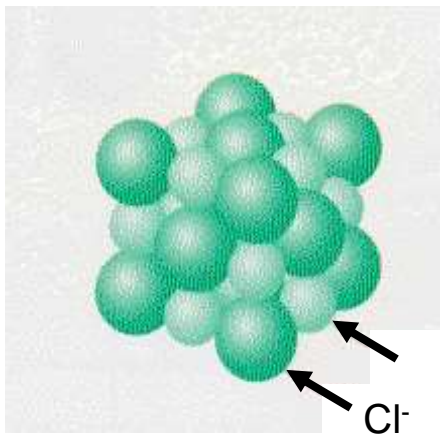
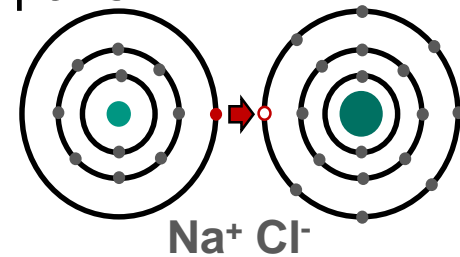
STRUCTURE

The Atomic Structure

Ionic Bonds

Most common bond type of non-metallic anorganic matter, like for example table salt (NaCl). Here sodium atoms transfer an electron to the chlorine atoms in order to reach closed electron shells. Therefore, all electrons are bound to the according atoms which build now ion pairs.

In solids, the negativ and positiv charged ions are arranged consecutively (in the case of NaCl in a cubic lattice).

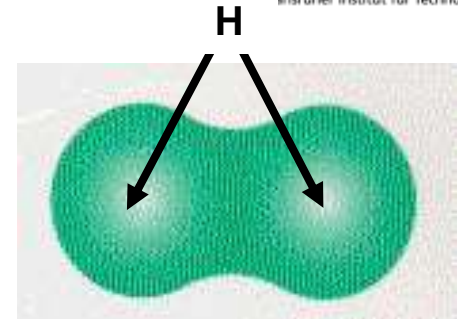


→ **As a consequence, plastic deformations are hardly possible, since the electrons are fixed. Also heat conductivity is not pronounced. Electric conductivity is not possible without matter transport.**

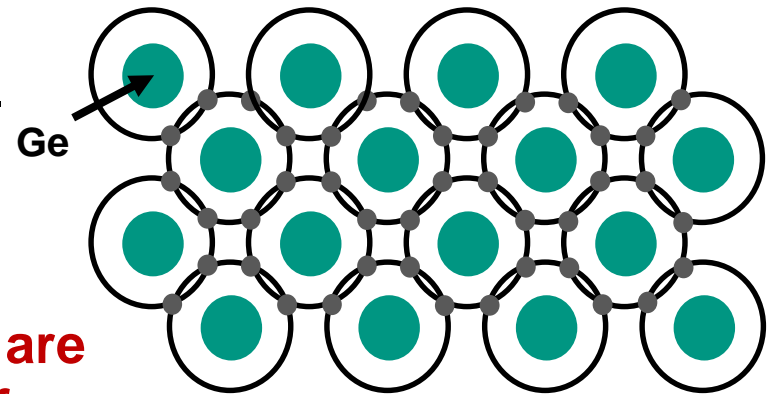
The Atomic Structure

Covalent Bonds

Most common bond type of gases and organic molecules; technically relevant for materials with 4 valence electrons, like for example carbon or semiconductors like silicon or germanium. In principle, a covalent bond consists of an electron pair, each from a neighbouring atom. By sharing the electrons, each bond partner reaches full electron shell



→ **As a consequence, covalent bonds are directional and localised, and therefore, plastic deformations are hardly possible.**



The Atomic Structure

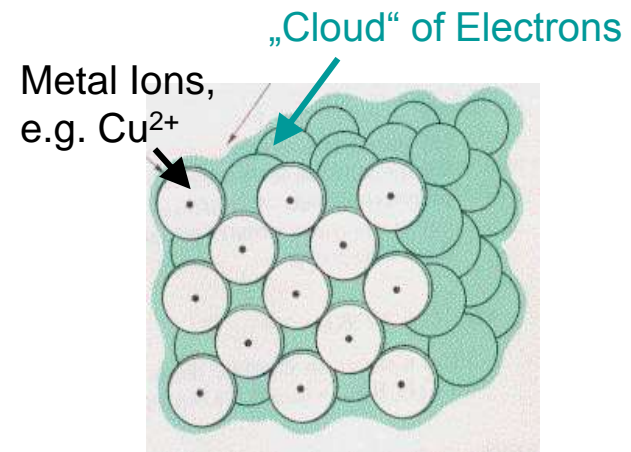
Metallic Bonds

A many-body system of pure metal atoms reaches a state of minimum energy, if the atoms are arranged periodically and dense, and if the valenz electrons are emitted to the inter-atomic space, where they form the so-called electron gas.

The metallic bond consists of the interaction between electron gas and atomic cores (metal ions):

- *positive charged ions are repelling as well as the negative electrons*
- *ions and electron gas are attracting*

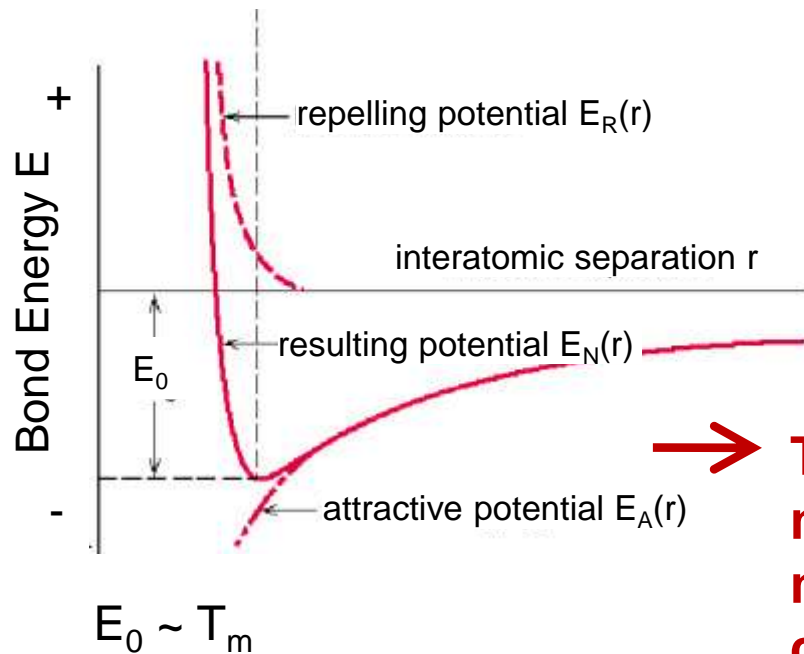
→ **As a consequence, metals are good heat and electrical conductors, and can be easily deformed (high ductility).**



Bond Energy

In a **crystal lattice** all atoms try to occupy positions where the attracting and repelling forces are equal. At this point, the minimum energy of the particle system is reached.

The bond energy can be expressed depending on the separation of two atoms (pair potential). Generally, it is the sum of a repelling and an attractive term. The minimum E_0 gives the energy needed to separate two lattice atoms completely.



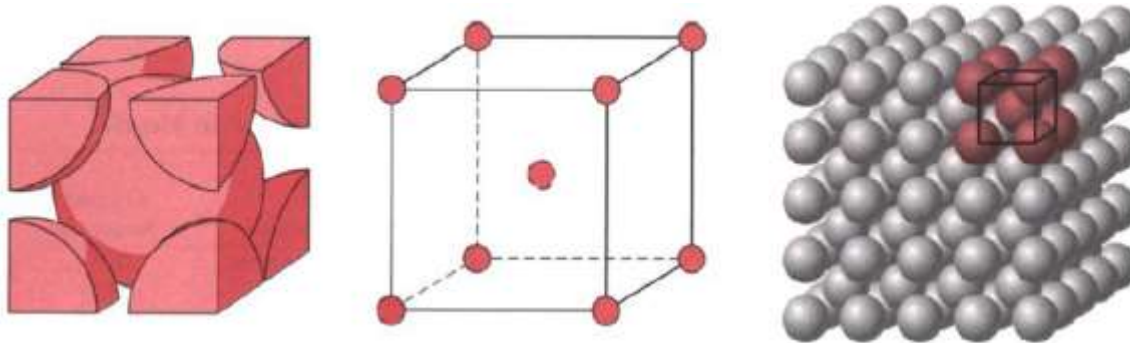
	Bond Type		
	Ionic	Covalent	Metal
Energy, kJ/mol	600 ... 1500	500 ... 1250	100 ... 800
Examples	Metaloxides	Diamond	Lead ... Tungsten

→ **The bond type in (transition or heavy) metals is not only of metallic nature. In most cases it is a mix of metallic and covalent bonds.**

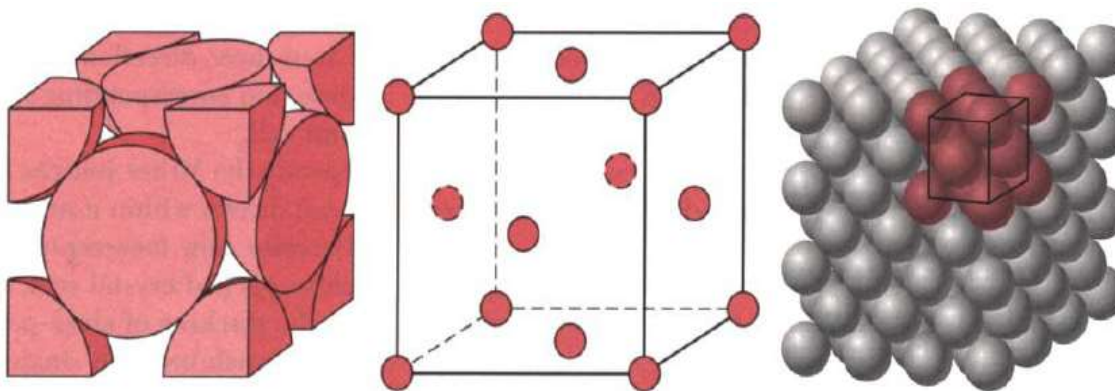
Lattice Structure of Perfect Crystals

Important Lattice Types

a) Body Centered Cubic (e.g. α -Fe, V, Cr, W, Ta, Mo)

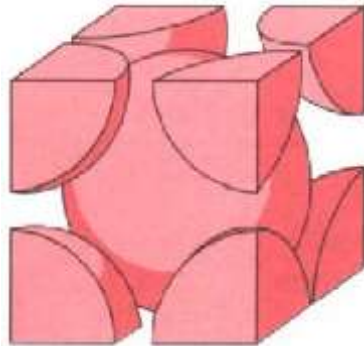


b) Face Centered Cubic (e.g. γ -Fe, Al, Cu, Ni, Ag, Au)



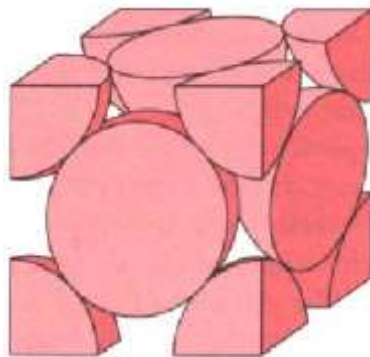
Properties of Important Lattice Types

bcc lattice



- Number of atoms per elementary cell:
 $1 + 8 \cdot 1/8 = 2$
- Densest direction: space diagonal [111]
- Densest plane: plane (110)
- Spatial density: 68 %

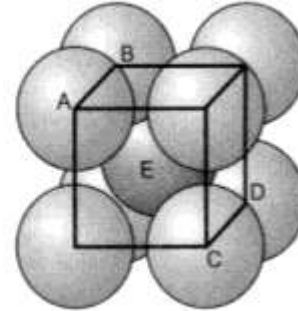
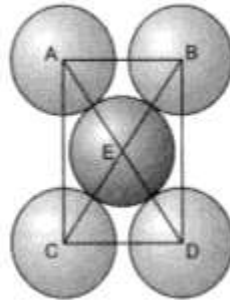
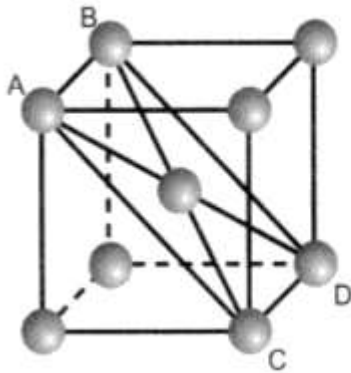
fcc lattice



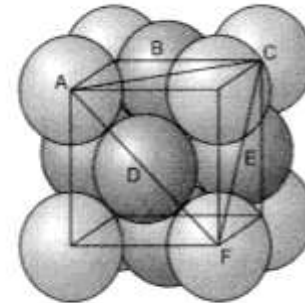
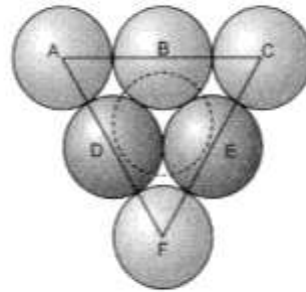
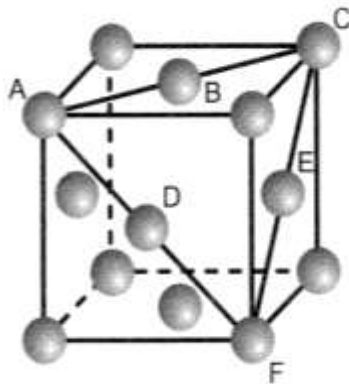
- Number of atoms per elementary cell: 6
 $\cdot 1/2 + 8 \cdot 1/8 = 4$
- Densest direction: face diagonal [110]
- Densest plane: closest packed plane (111)
- Density: 74 % (maximum)

Lattice Structure of Perfect Crystals

bcc lattice



fcc lattice



➔ **Dense planes have the highest distance. This has an important influence on the mechanical properties (deformation).**

Lattice Structure of Perfect Crystals

Related Material Properties

Within a perfect crystal lattice there are different distances between atoms (and planes) depending on the considered directions or orientations. This is the reason for the **anisotropy** of some material properties of single crystals.

Anisotropy means that a property depends on the considered direction.

Copper, for instance, shows a three times higher elastic constant in the direction of the space diagonal $\langle 111 \rangle$ compared to the face diagonal $\langle 110 \rangle$.

Most metals show just **one** crystal structure. But some change their lattice with temperature, that is, at different temperatures different lattice structures are stable. This is called **allotropy** or **polymorphy**. Iron is the most important example.

Lattice Constants in nm			
bcc		fcc	
Cr	0.288	Al	0.404
Mo	0.314	Cu	0.361
W	0.315	Ni	0.352
α -Fe	0.287	γ -Fe	0.36

Lattice Defects

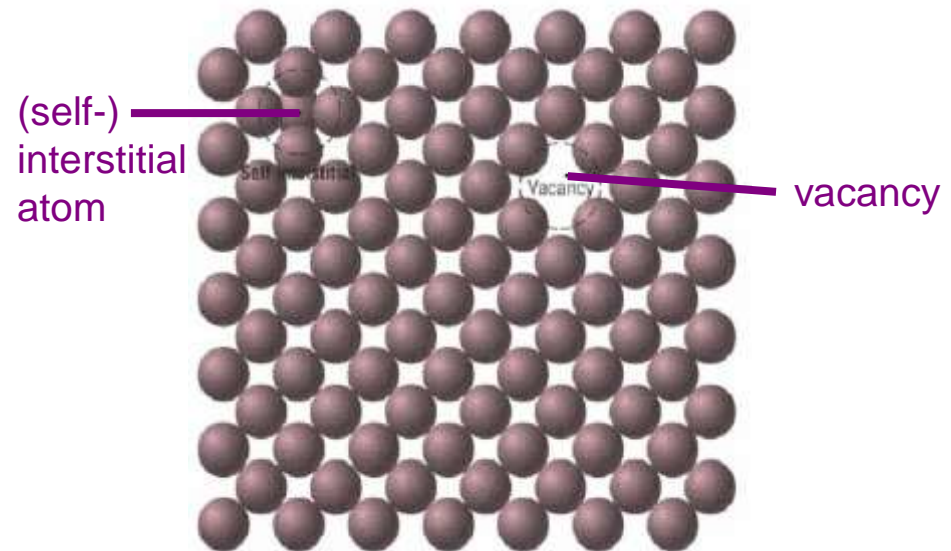
Lattice defects may be ordered according to their degree of dimensional extend:

- | | | |
|-------------------|---|--------------------------|
| - point defects |  | zero-dimensional defects |
| - line defects |  | one-dimensional defects |
| - plane defects |  | two-dimensional defects |
| - spatial defects |  | tree-dimensional defects |

a) Zero-dimensional defects: point defects, impurity atoms

Frenkel pair:

a pair of self-interstitial and vacancy, often caused by irradiation



Real Microstructure of Metals

Vacancies and Interstitials

Formation:

- during solidification
- atomic oscillations/fluctuations
- irradiation (with electrons, ions, neutrons)

Density of vacancies: $N_v = N \exp(-Q_v/kT)$

N: number of all atomic sites

Q_v : activation enthalpy

T: absolute temperature

k: Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K or 8.62×10^{-5} eV/K)

In metals the vacancy density N_v/N varies around 10^{-12} at room temperature and raises to about 10^{-4} near the melting point. That is, one of 10000 lattice sites is unoccupied near the melting temperature.

Of course, thermal activated processes (like for example diffusion) are essentially influenced by the vacancy density.

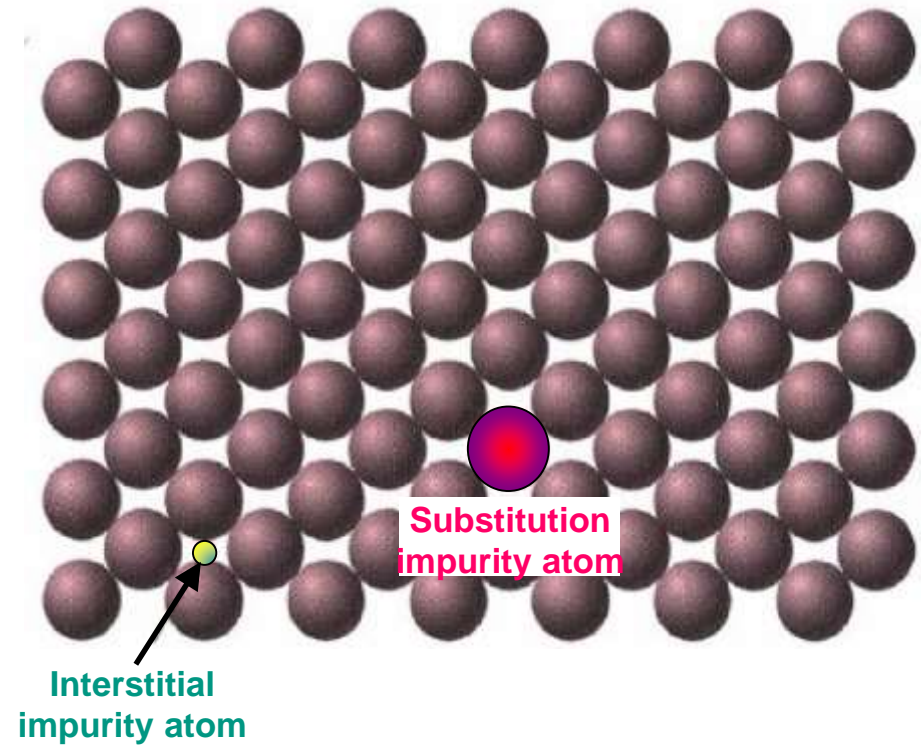
Real Microstructure of Metals

Impurities

Formation:

- as substitution atom
- as interstitial atom

Atoms, different than those of the lattice, are also lattice defects. They are solved in the lattice, that is, there is a solid solution. If the impurity atoms located at regularly lattice sites (that is, if they replace atoms of the host lattice) they are called substitution atoms. If the impurity atoms are located between the regular lattice positions, they are called interstitial atoms.

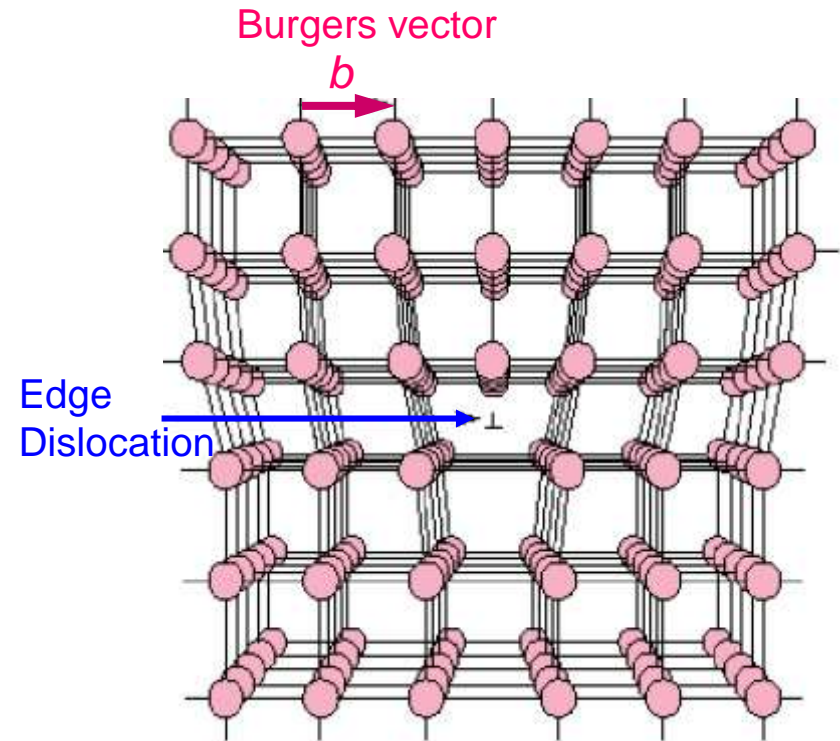
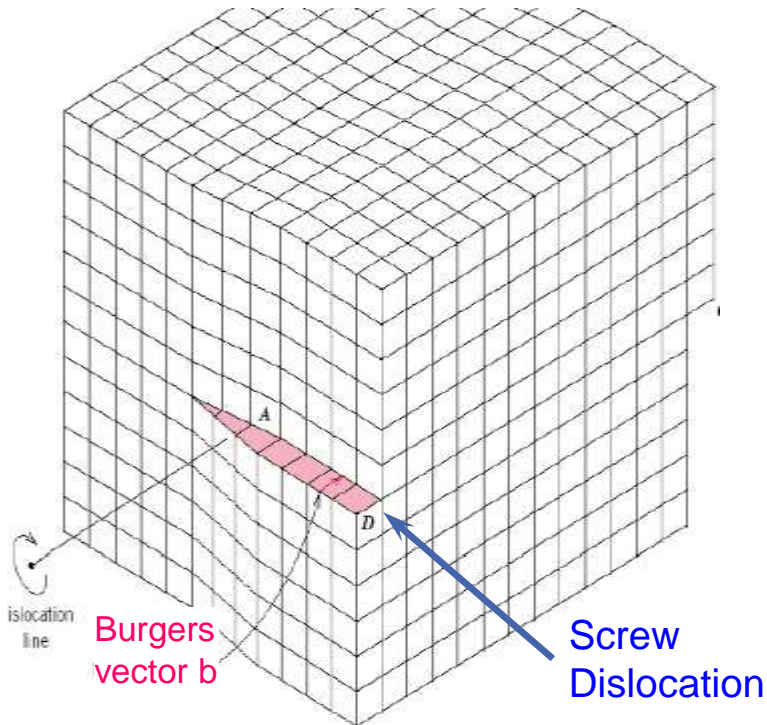


The effect of lattice deformation due to the amount of impurities is used for strengthening metallic materials.

Real Microstructure of Metals

b) One-dimensional defects: dislocations

There are two types of dislocations: **edge** and **screw dislocations**. Edge dislocations may be interpreted as an insertion of half planes, ending within the crystal. Screw dislocations form by shearing. The planes near the dislocation line are deformed screw-like.

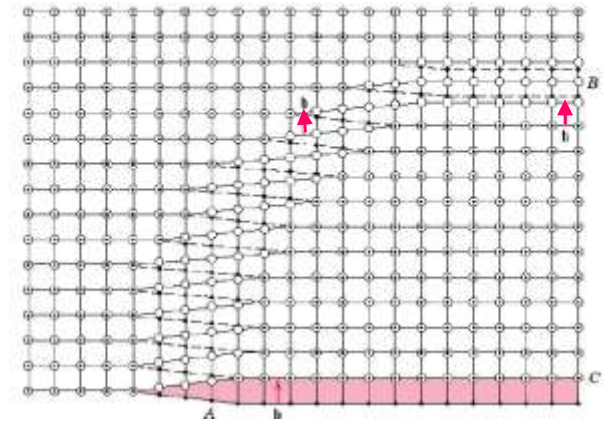
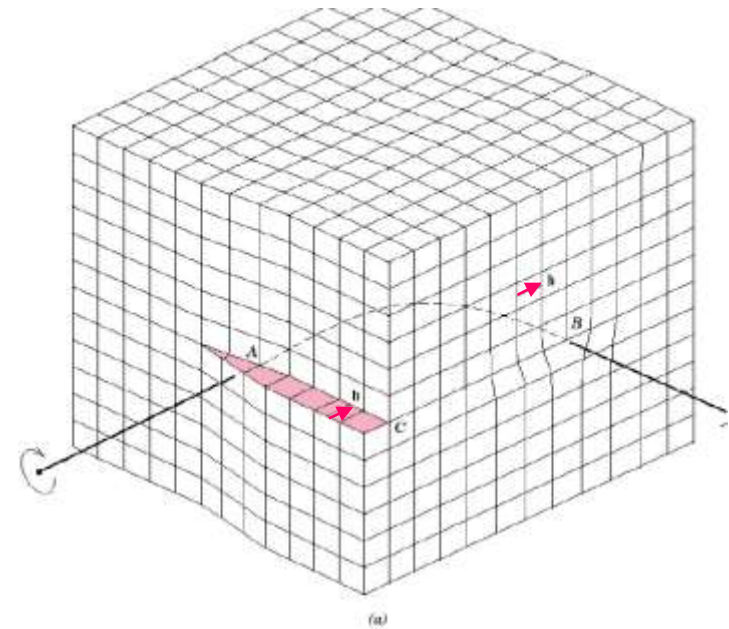
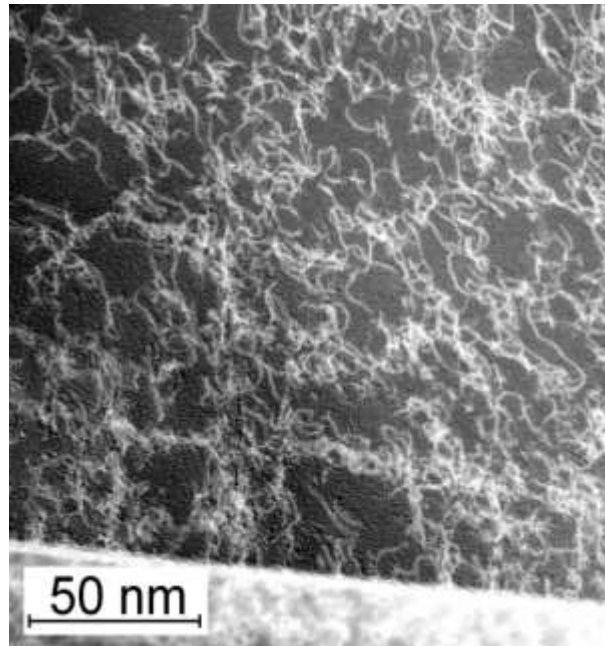


Real Microstructure of Metals

Mixed Dislocations

In general, dislocations are most often a mix of screw and edge dislocations.

Dislocations either start and end at crystal surfaces, or they form closed dislocation lines within the crystal. In that case, dislocation loops and networks appear.



Real Microstructure of Metals

Dislocations: Density and Dynamics

The frequency of dislocations, that is the dislocation density, is measured as line length per volume. In tempered metals, it is about 10^6 mm/mm³= 10^8 / cm². In other words, in a volume of 1 mm³ there are dislocations with a total length of 1 km. After cold work this line length may increase to 10,000 km! This corresponds to a dislocation density of 10^{12} / cm².

Dislocations clearly increase the lattice energy by about 10^{-12} J/mm (Energy per dislocation line length). Therefore, dislocations are never thermo-dynamically in equilibrium. Their long-range stress fields interact simply due to their frequency. Depending on the position, dislocation can attract or repel each other.

To move dislocations it needs relatively small forces. Therefore, it is easy to generate displacements within the lattice. This is the reason for the high plasticity of metals. The effect of cold work hardening results from generation of dislocations which then block each other.



MD-Video

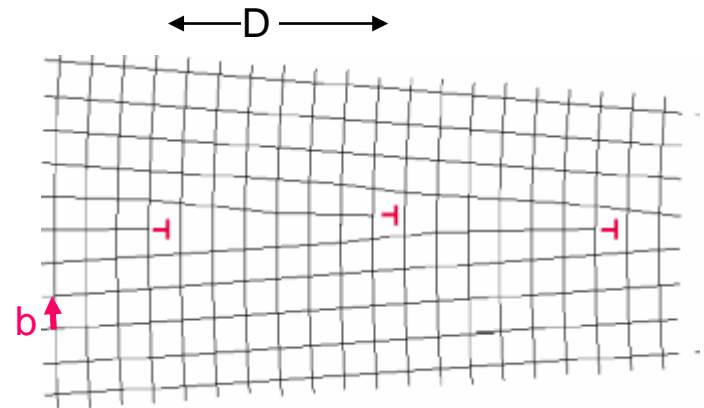
Real Microstructure of Metals

c) Two-dimensional defects: boundaries, stacking faults

At crystal surfaces atoms are less bonded. Therefore, surface atoms show different equilibrium positions compared to bulk atoms. Therefore, the energy content is higher and is called **surface energy** (in principle this is the energy needed to separate a crystal, i.e. to create new surfaces). Typical values are 10^{-6} J/mm² for iron and 2×10^{-6} J/mm² for gold.

Low Angle Grain Boundaries

Due to attraction edge dislocations may form rows which lead to a separation of the lattice. The separate parts are often called subgrains (usually smaller than 1 μm). The energy content of such a boundary can be up to 0.3×10^{-6} J/mm².



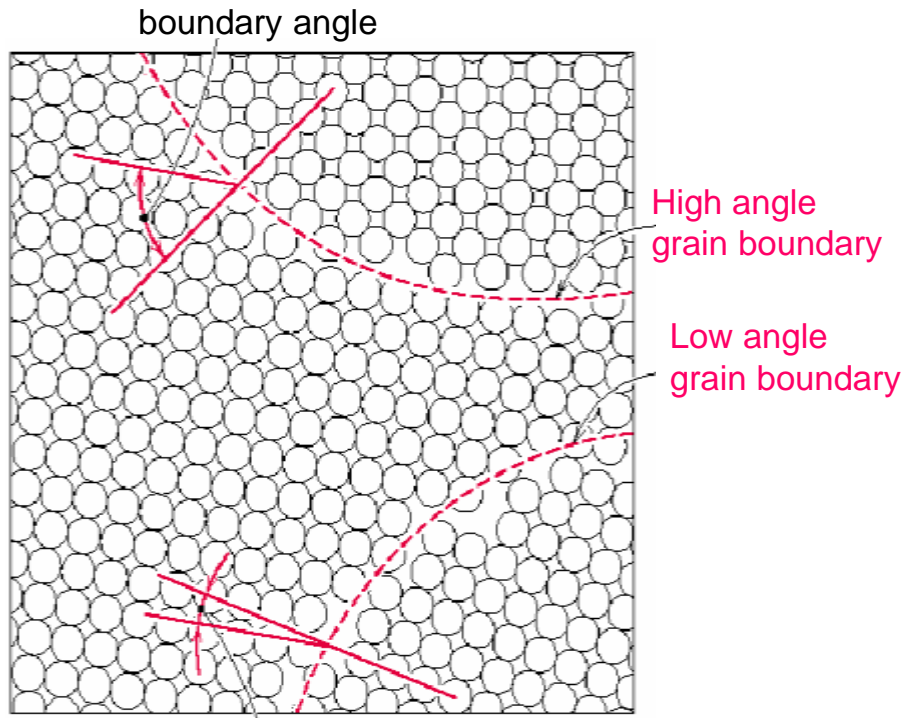
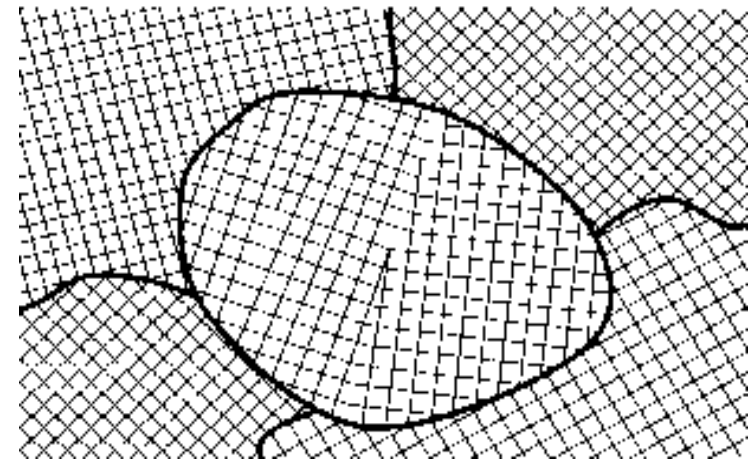
The boundary angle is typically around 1° . That is:

$$\sin \theta \approx \theta = \frac{b}{D}$$

Real Microstructure of Metals

High Angle Grain Boundaries

During solidification after melting or during recrystallization crystals grow and if they meet each other, the lattice plains show usually higher angles. These areas are called **grain boundaries**.



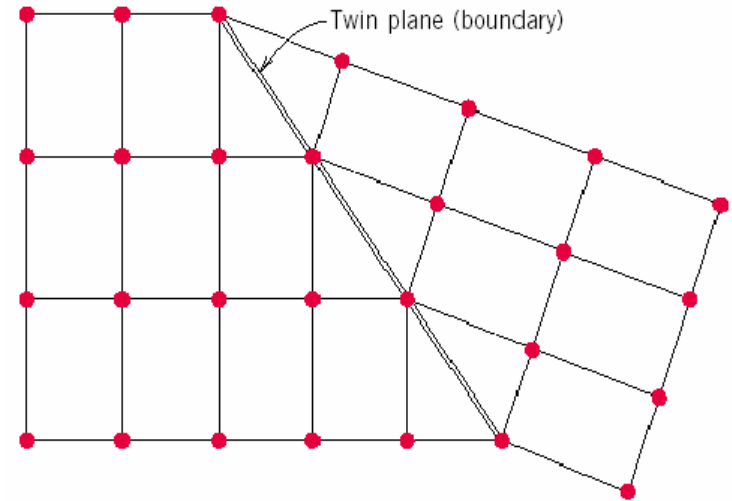
Grain boundaries consist off about 2-3 atomic layers which are structure-less (amorphous).

The energy of grain boundaries in metals is higher than that of the low angle grain boundaries. The value ranges maximal from 30 to 50 % of the surface energy.

Real Microstructure of Metals

Twin Boundaries

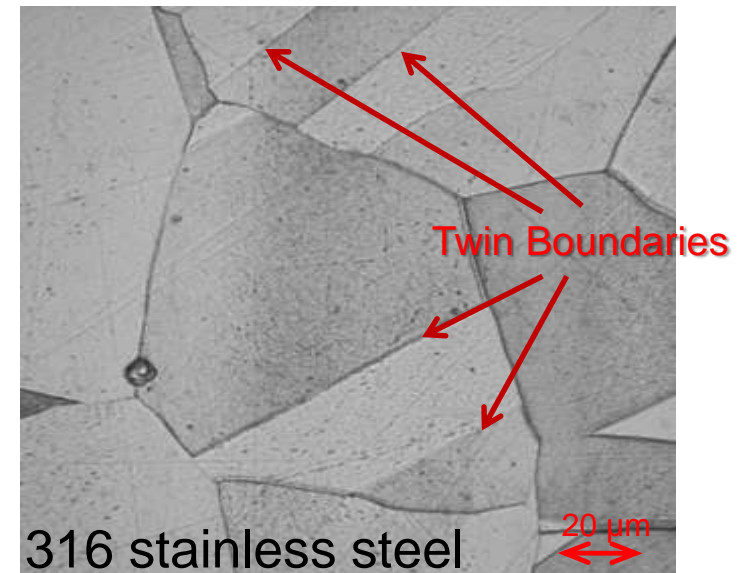
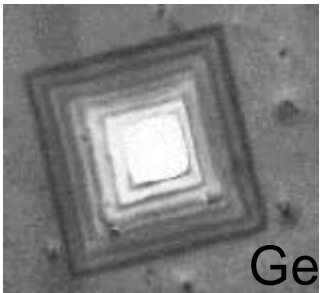
Under certain conditions, two crystals may form a grain boundary without distortion. This is the case for **twin grain boundaries**. Here the boundary is the symmetry plane for both crystals. Of course, the boundary energy is extremely low.



Stacking Faults

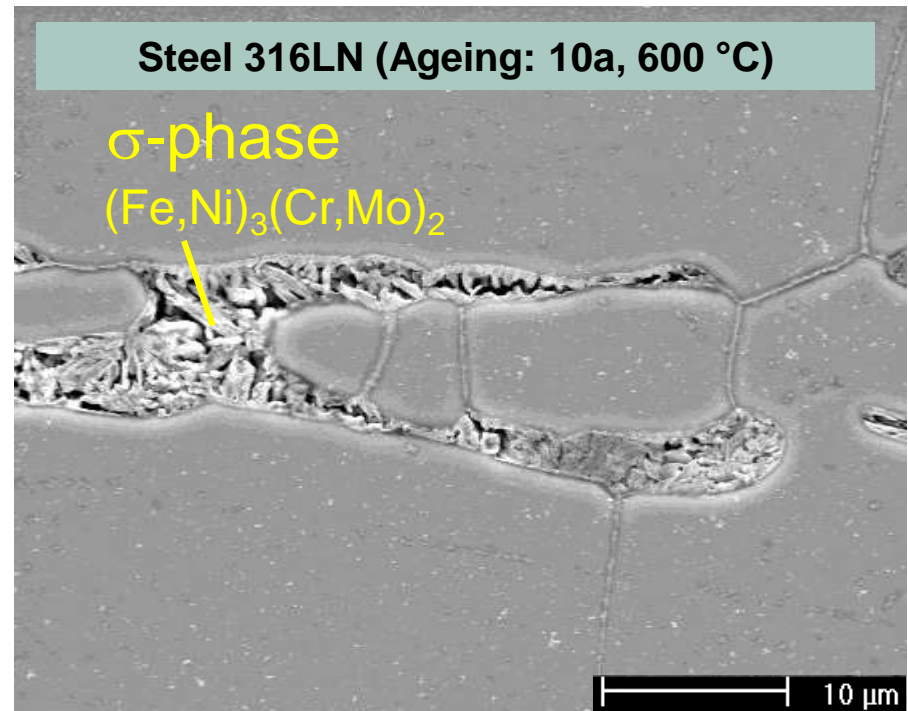
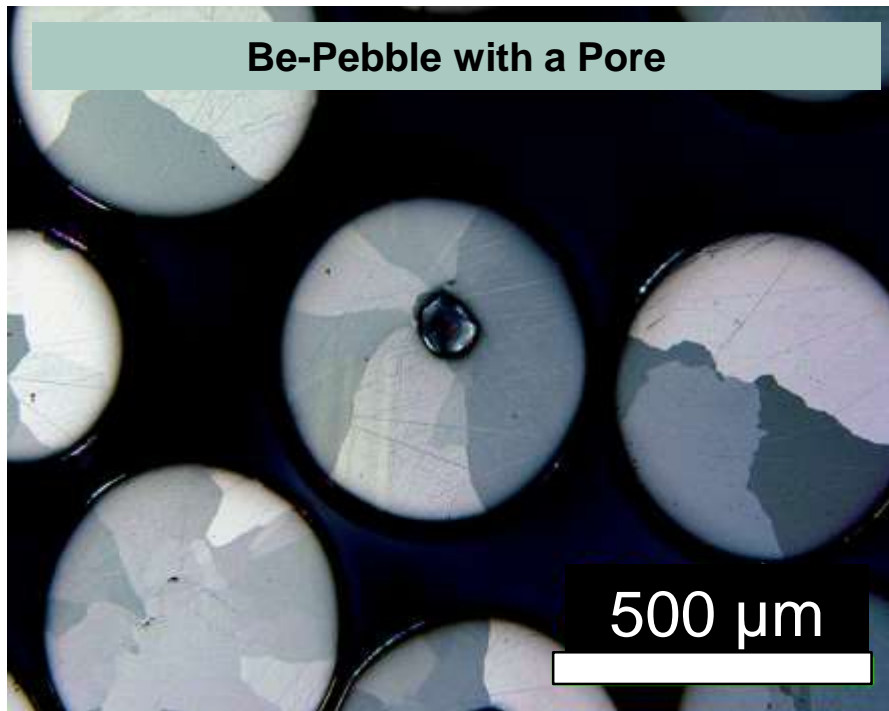
If the stacking sequence of a close packed lattice is changed at some area, it is called **stacking fault**.

In an fcc lattice this is the case, if, for example, the sequence changes from ...ABCABCABC... to ...ABCABABC... at some place.



Real Microstructure of Metals

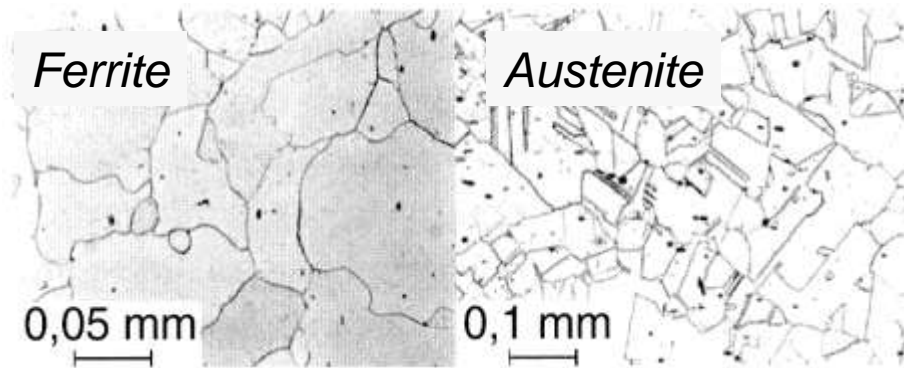
d) Three-dimensional defects: pores, precipitates



Real Microstructure of Metals

Polycrystalline Microstructure

Real, technically relevant metals show a polycrystalline microstructure, that is, they consist of grains with different lattice orientations. There are two possibilities to categorize the microstructure: **grain size** and **grain shape**.



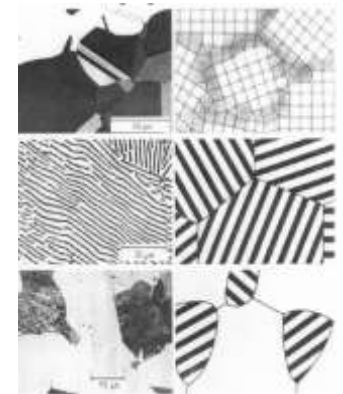
Usually metallic grains try to form spherically due to the lowest energy. Therefore, their shape is globular, like for example, in ferrites as well as in other materials with bcc lattice. The microstructure of

fcc materials, however, consists of angled grains with many twin boundaries.

Phases

Areas of constant structure and chemical composition are called **phases**. Real materials are usually alloys which tend to appear in different phases.

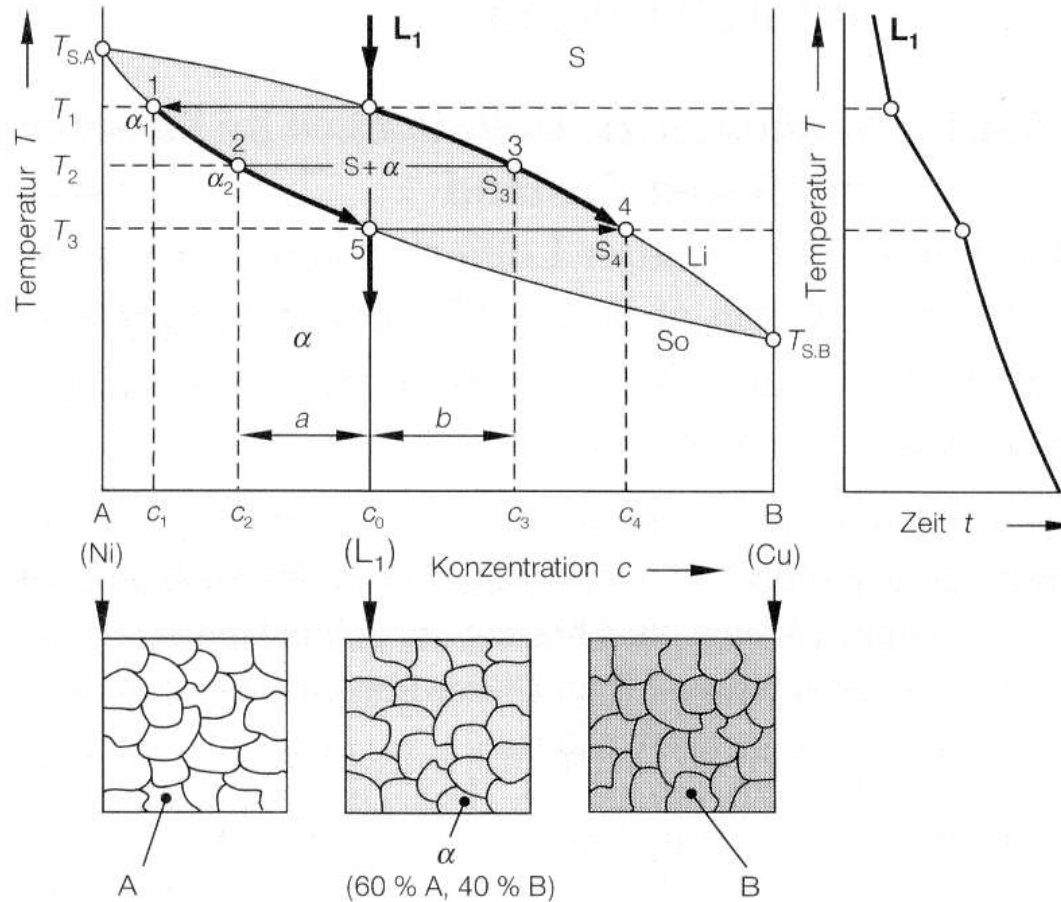
Two phase, lamellar, polycrystalline microstructure (Fe_3C and $\alpha\text{-Fe}$)



2

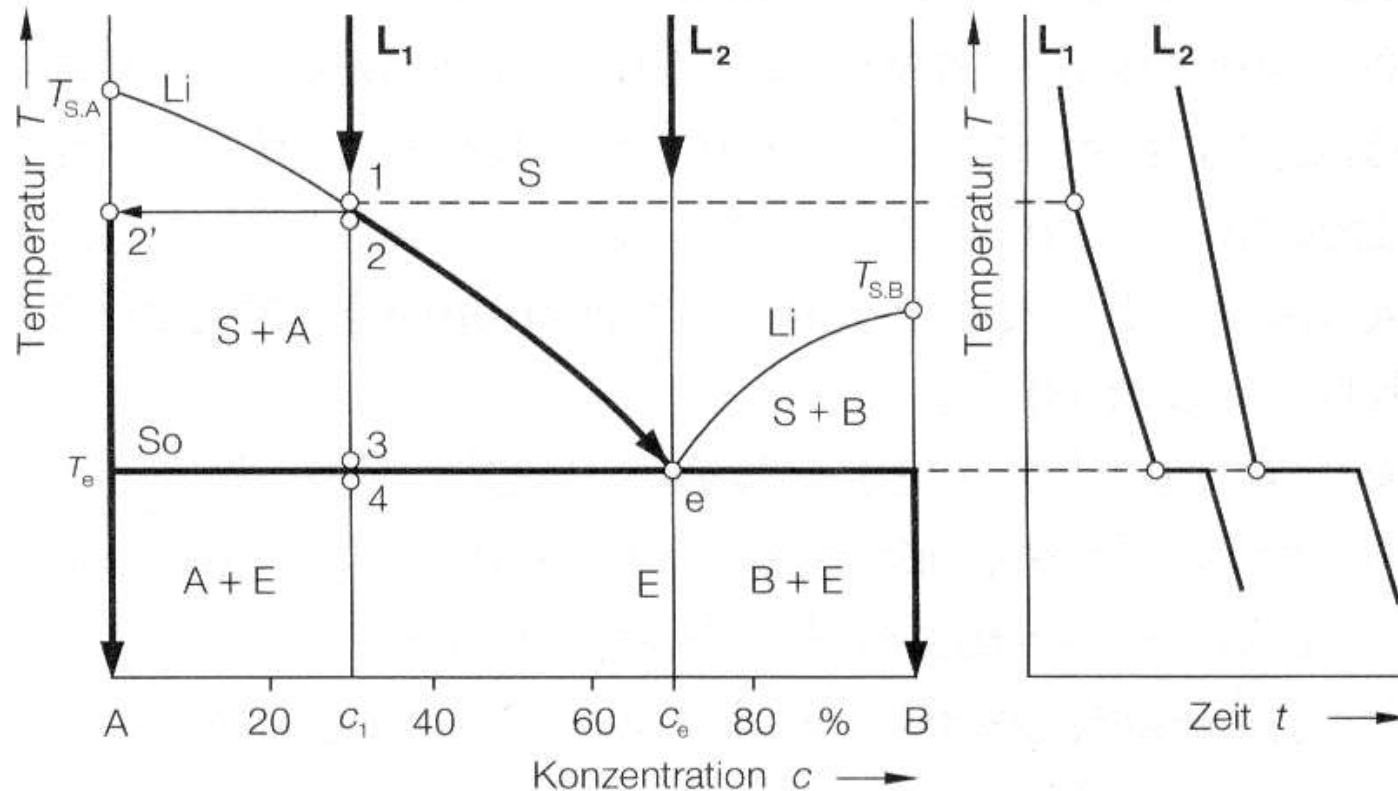
PHASES

Complete solubility in the liquid and solid state



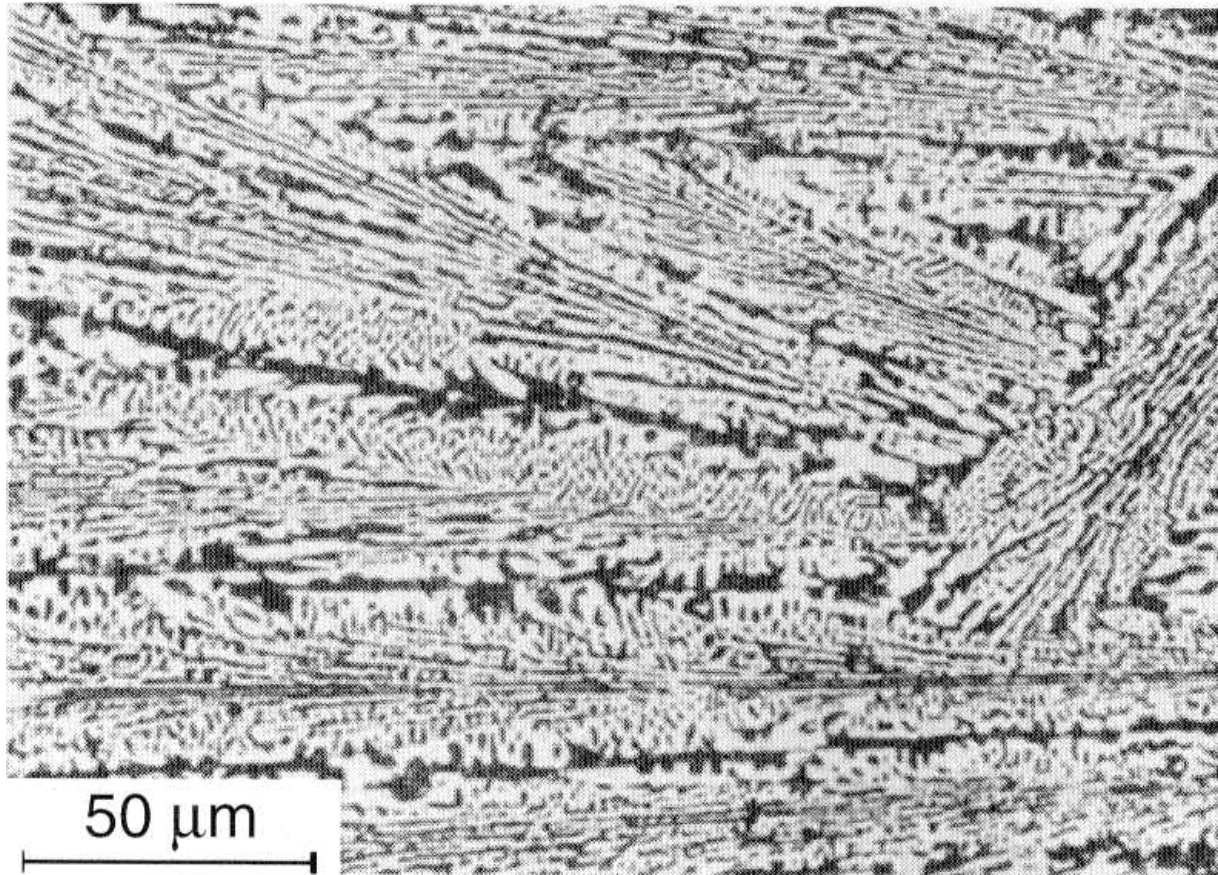
- Examples: W-Ta, Cu-Ni, Fe-Ni, Ag-Au

Complete solubility in the liquid and complete insolubility in the solid state



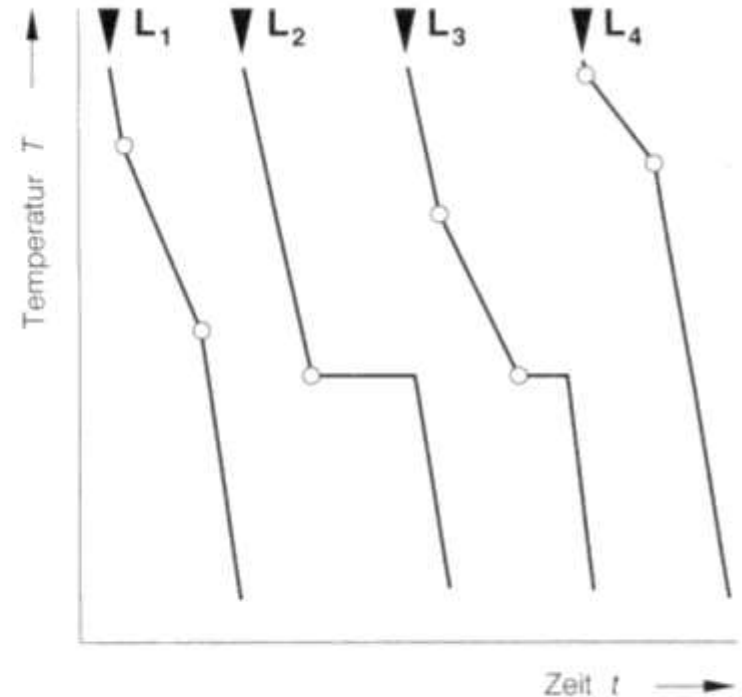
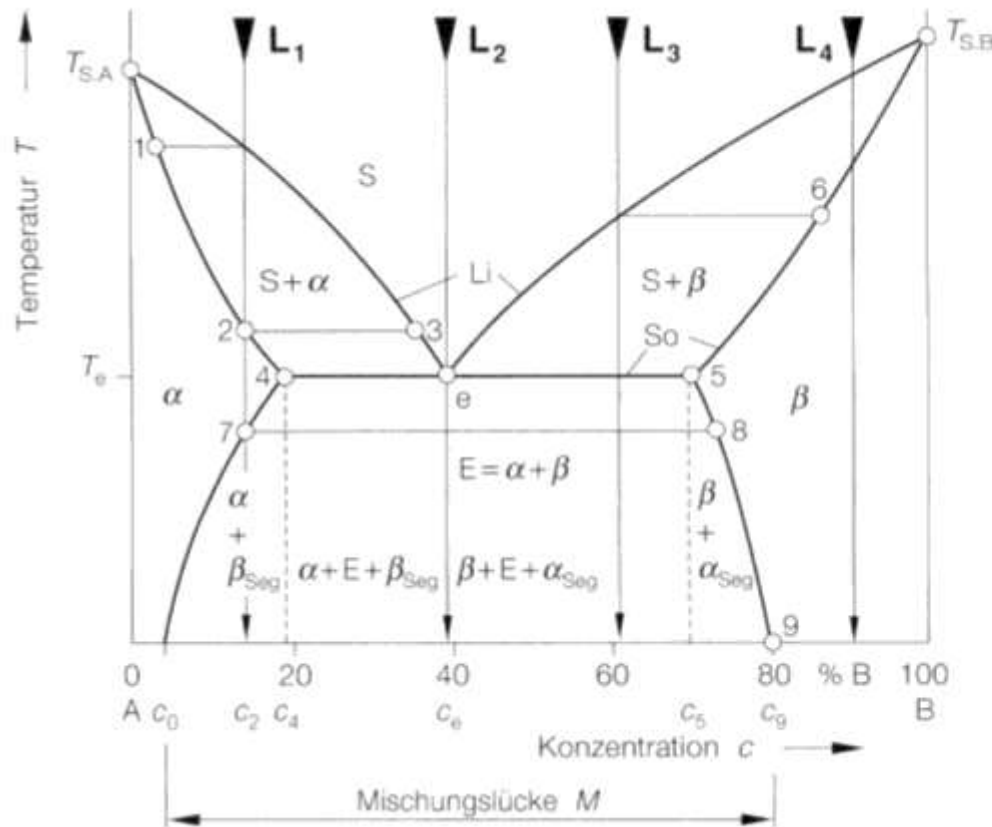
- Examples: Bi-Cd (Wismut-Cadmium), Pb-Sn (Blei-Zinn), Pb-Sb (Blei-Antimon)
- The isothermal $T=T_e$ is called **eutectic line**. An alloy with composition c_e is called **eutectic**.

Eutectic (das „Schöngestalt“)



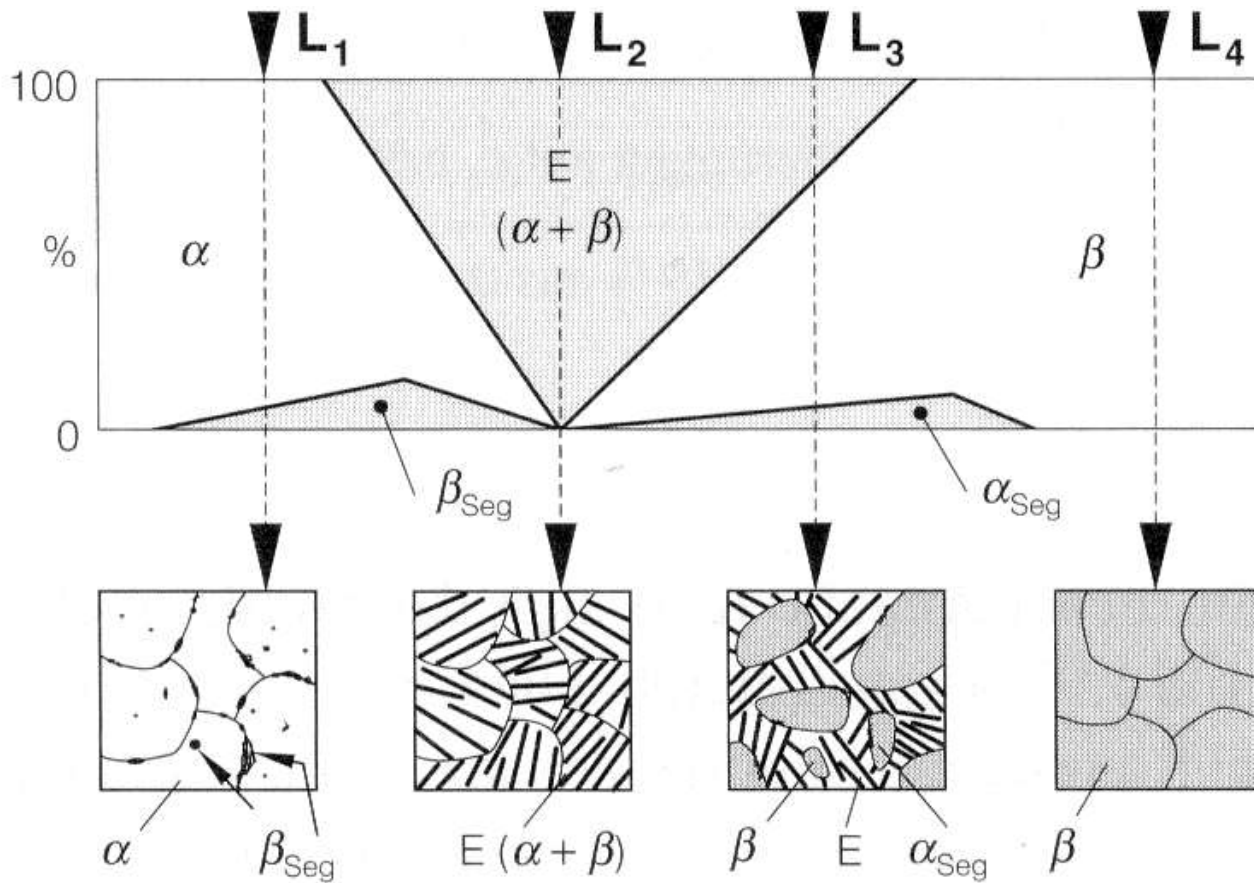
- Example: Ledeburite (weißes Gusseisen)
- Fine grained structure
- Characteristic crystalline orientation

Complete solubility in the liquid and limited solubility in the solid state: eutectic systems



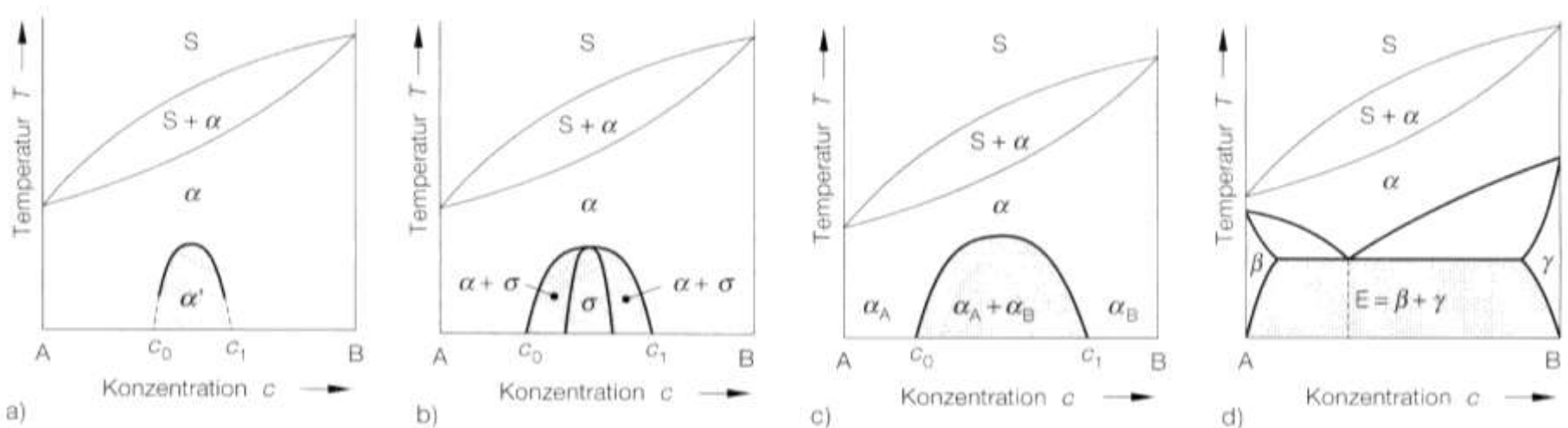
- Examples: Ag-Cu, Cu-Al
- The range from c_0 to c_9 is called **miscibility gap**. Lines 5-9 and 4- c_0 are the so-called **segregation lines**.

Complete solubility in the liquid and limited solubility in the solid state: eutectic systems



- Different concentration leads to different structures. Preferred segregation sites: grain boundaries, twins, or dislocations.

Solid State Phase Transformations



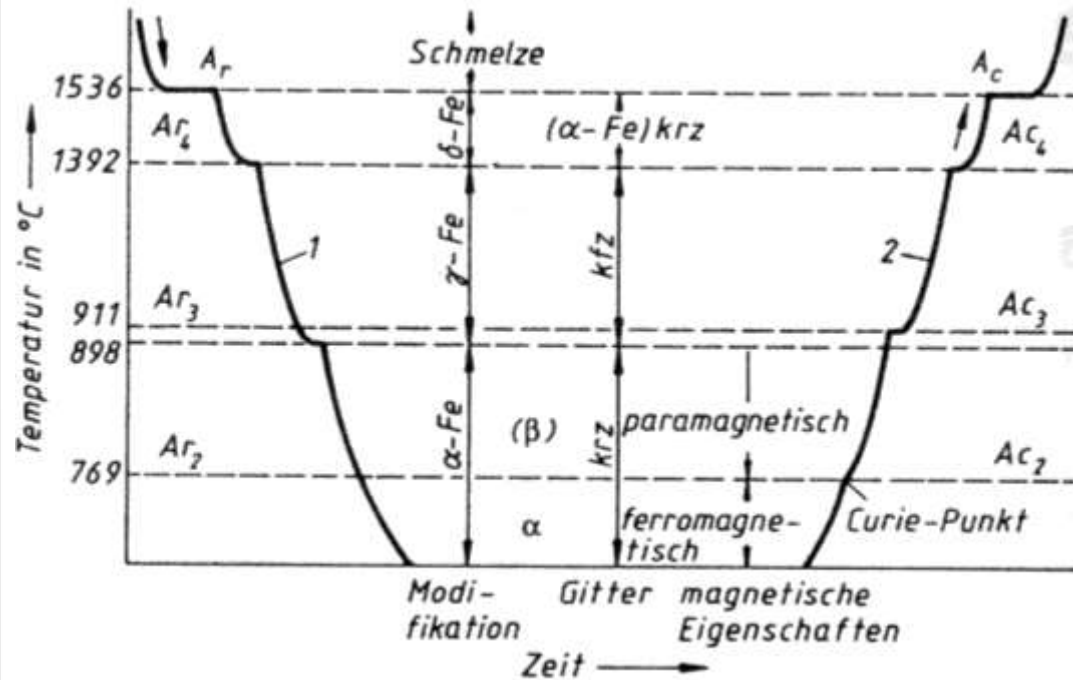
Zustandsschaubilder von Systemen mit Umwandlungen im festen Zustand:

- Bildung einer Überstruktur α' aus α -Mischkristallen: $\alpha \rightarrow \alpha'$
- Bildung einer intermediären Phase σ aus α -Mischkristallen: $\alpha \rightarrow \sigma$
- Entmischungsvorgänge in einem Mischkristall: $\alpha \rightarrow \alpha_A + \alpha_B$
- Zerfall des α -Mischkristalles in zwei Phasen: $\alpha \rightarrow \beta + \gamma$

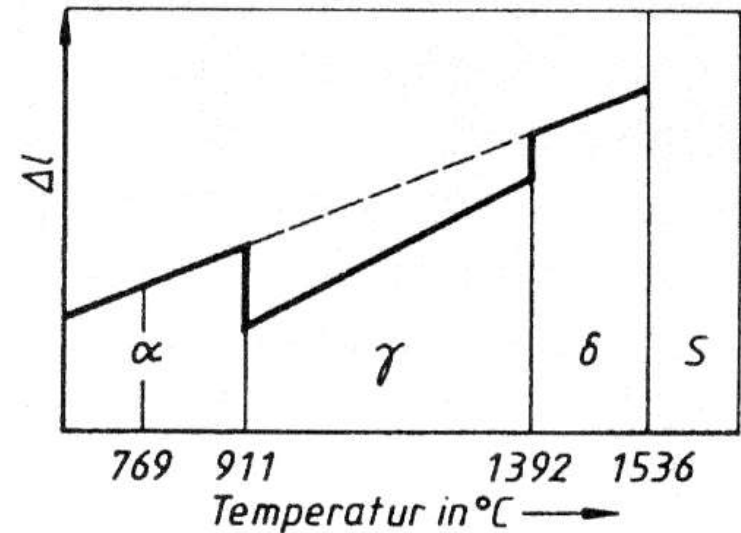
- Case d) \rightarrow **eutectoid decomposition**
- The resulting structure is called **eutektoid**. It is similar to the **eutectic**.
- Example: decomposition of γ -Fe \rightarrow α -Fe + Fe₃C (Pearlite)

Cooling, Heating, and Expansion of Fe

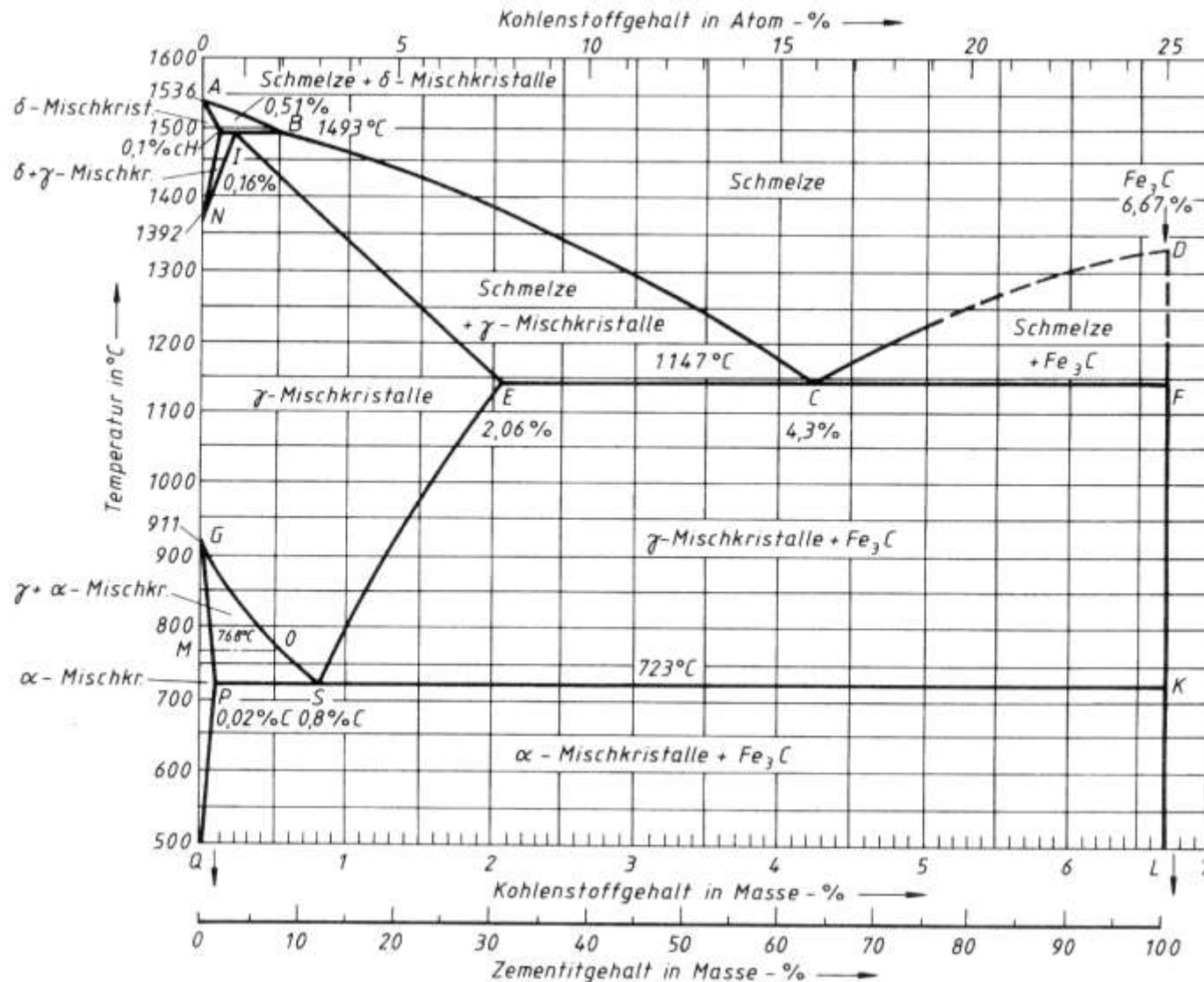
Calorimetry, etc.



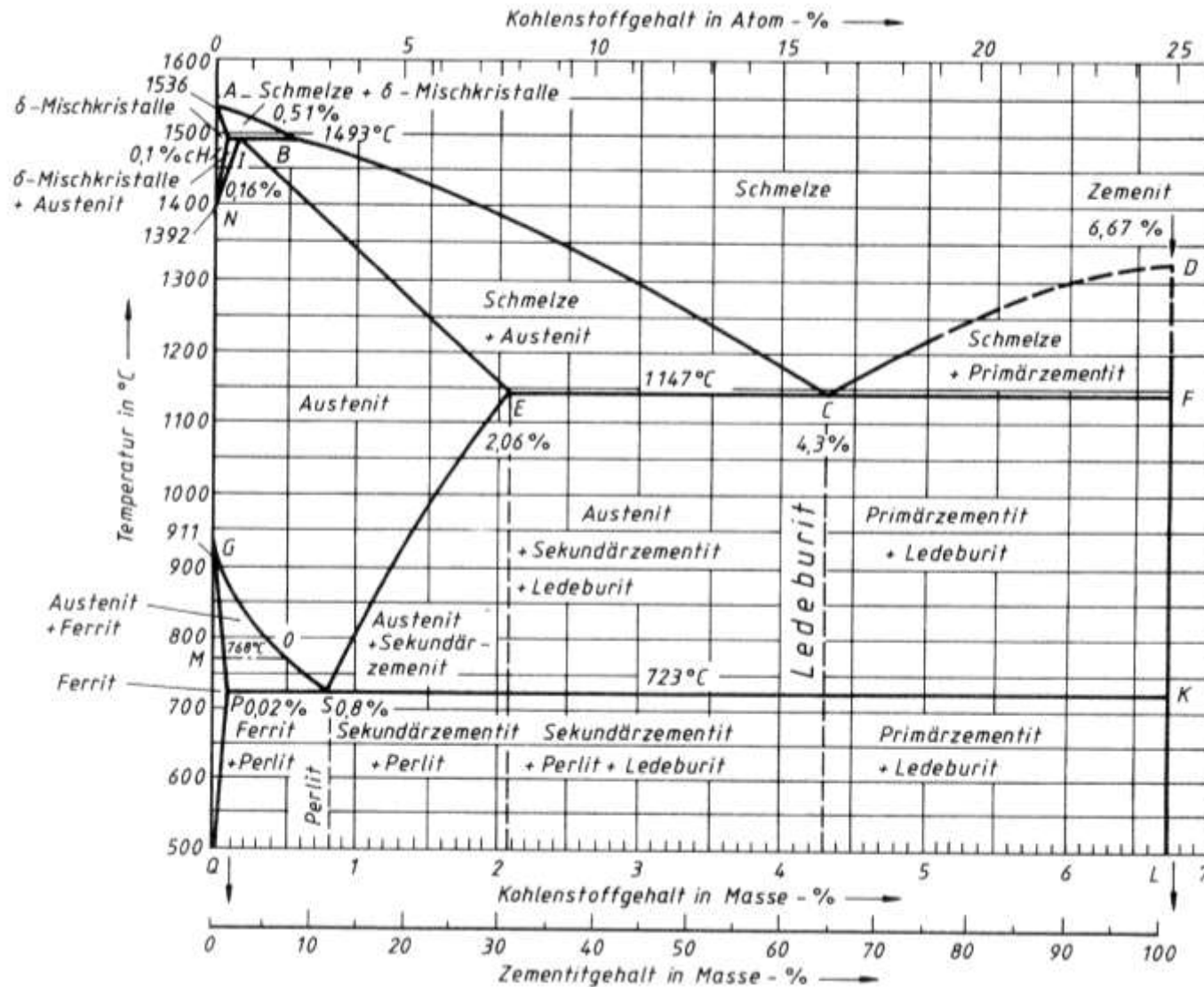
Dilatometry, etc.



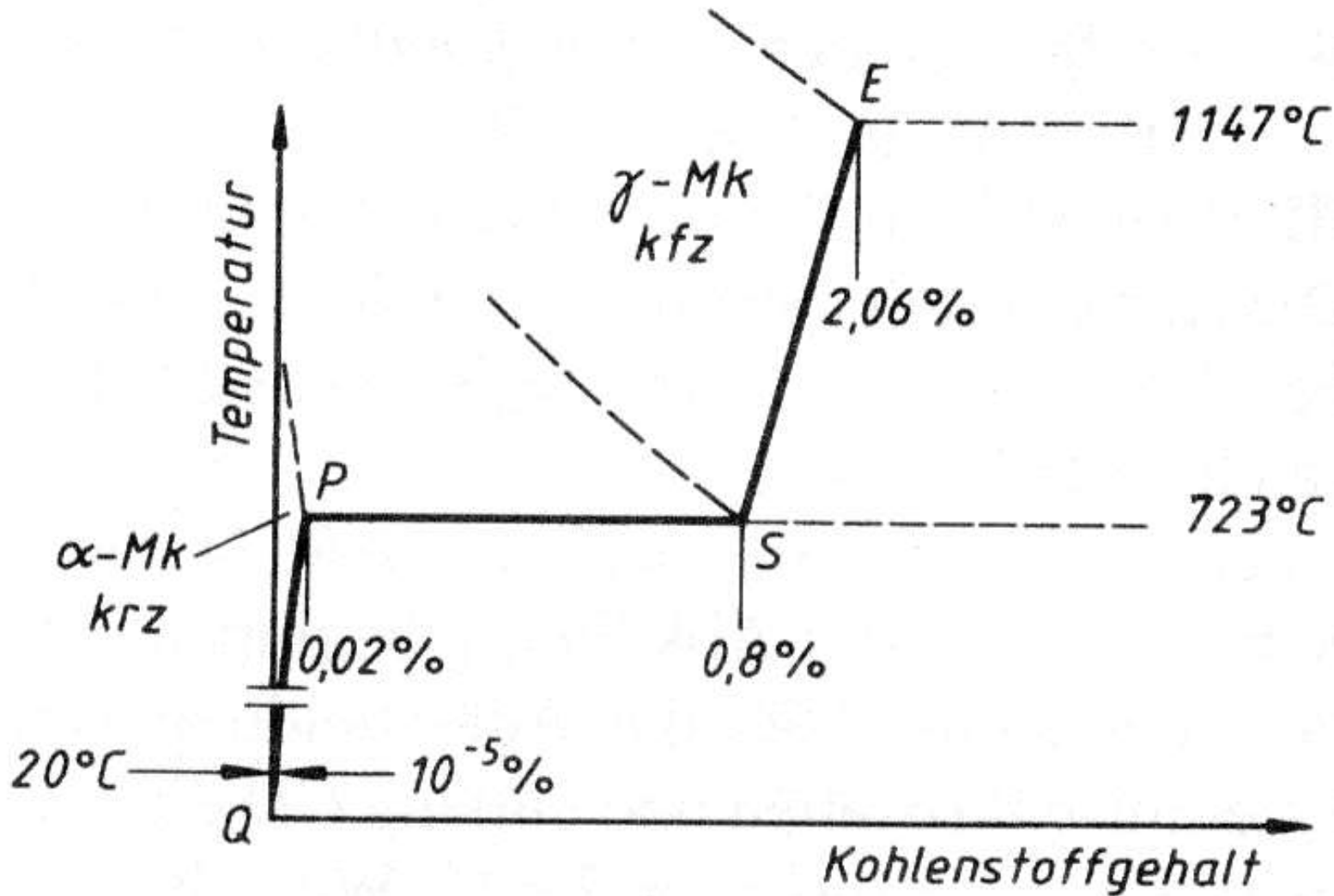
Phases of the Iron-Carbide System



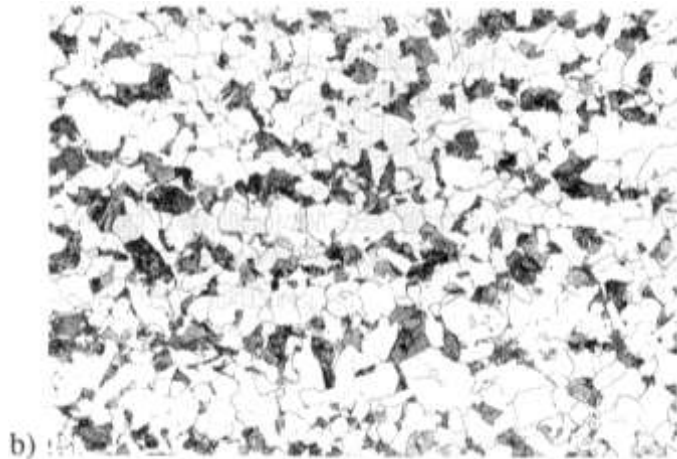
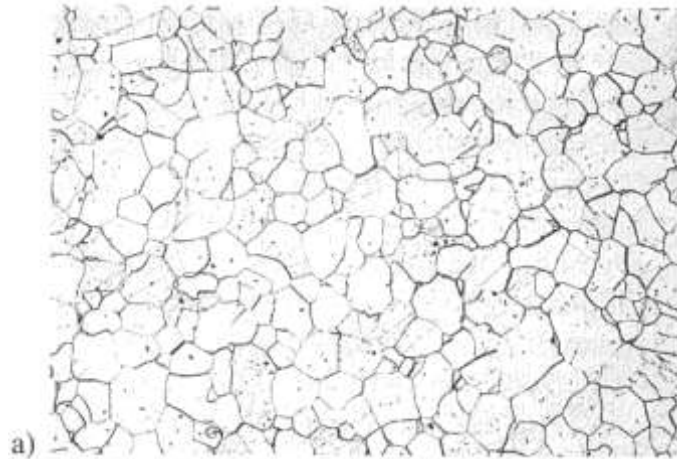
Phases of the Iron-Carbide System



Carbon Solubility in Solid Iron

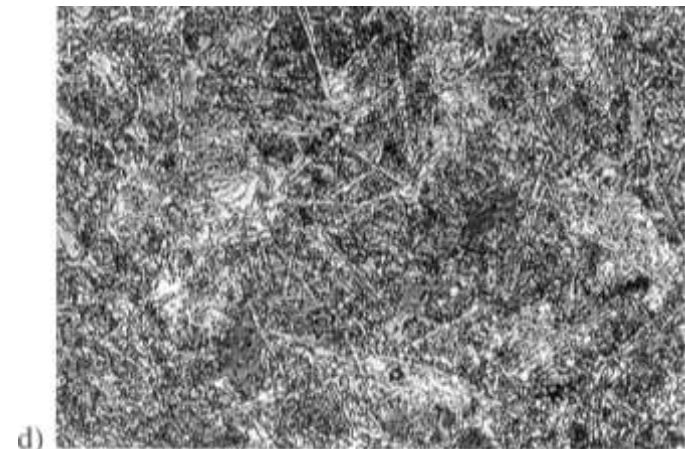
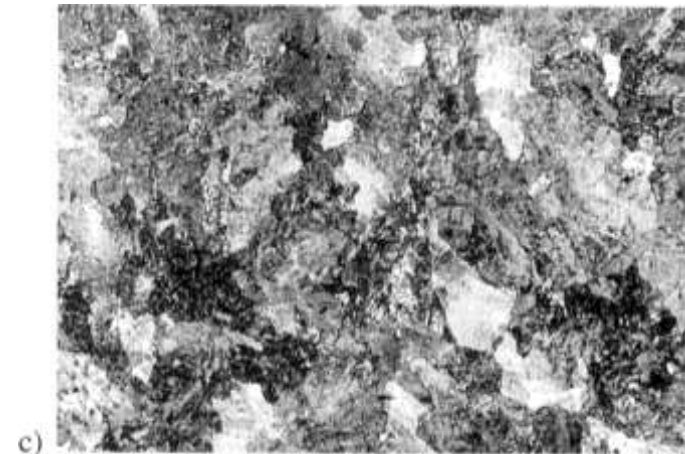


Stable Structures (in equilibrium)



a) Ferrite

b) Ferrite + Pearlite (0,3% C)



c) Pearlite (0,8% C)

d) Pearlite + Cementite (1,3% C)

B

DECAY OF THE AUSTENITIC PHASE

Austenitisation / Solution Annealing

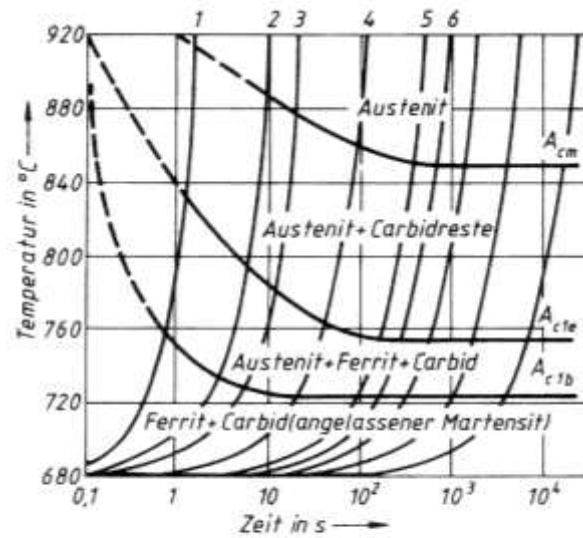
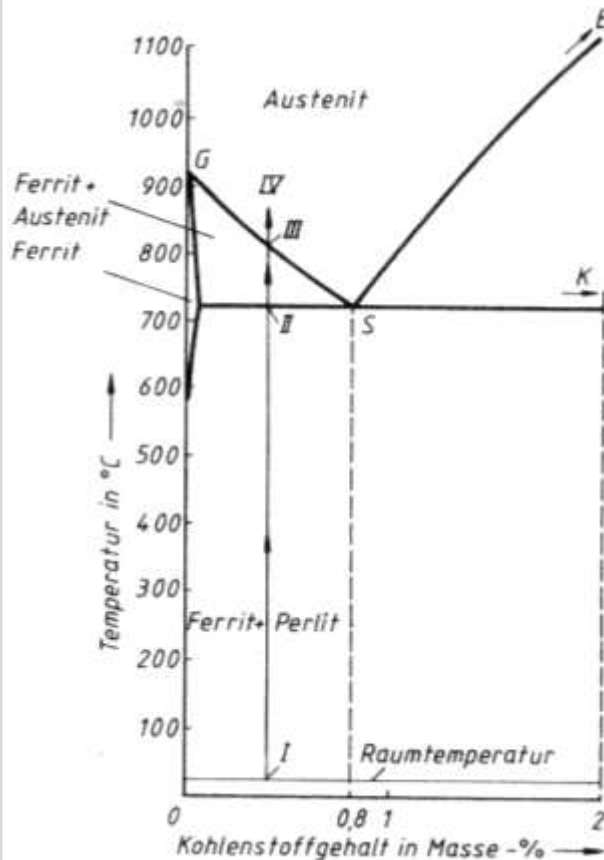


Bild 4.1-2 Zeit-Temperatur-Auflösungsdiagramm eines eutektoiden Stahles (kontinuierlich) 1 bis 6 Erwärmskurven; geringer werdende Erwärmsgeschwindigkeit

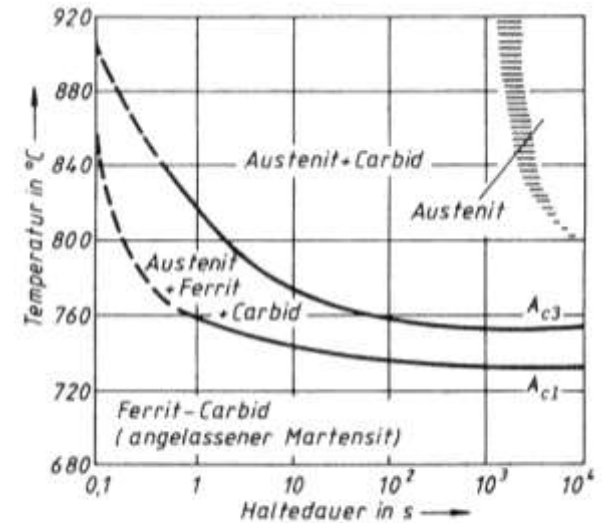


Bild 4.1-3 Zeit-Temperatur-Auflösungsdiagramm eines eutektoiden Stahles (isothermisch)

- Time-Temperature-Austenitisation-Diagram (TTA-Diagram):
 - continuous (heating up)
 - isothermal (at constant temperature)

Quenching the Austenitic Phase

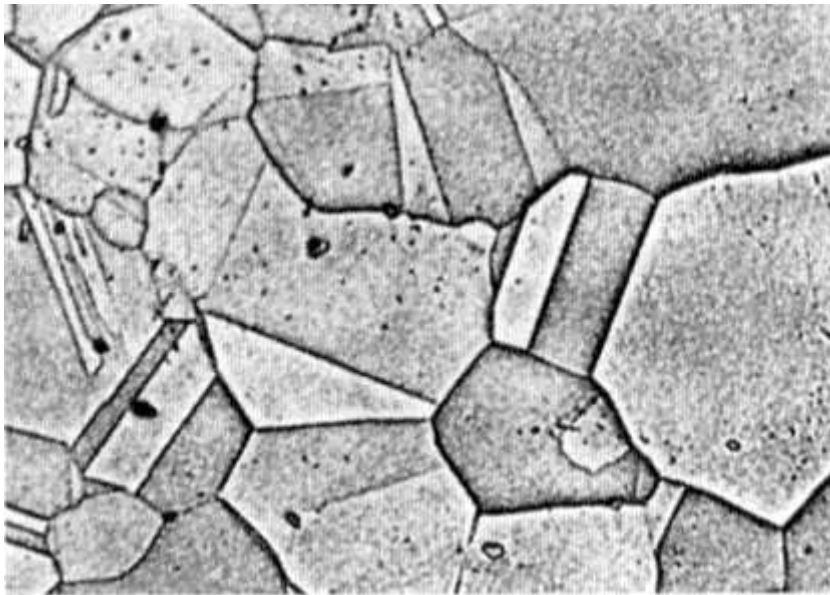


Bild 4.1-4 Austenit-Stahl X10CrNi18.9

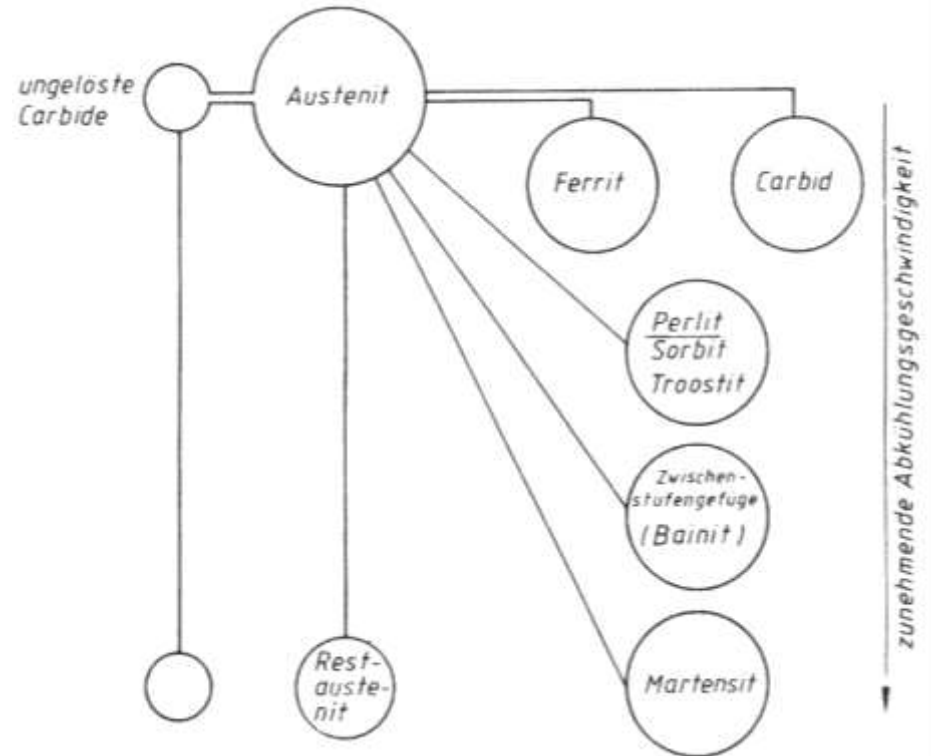


Bild 4.1-5 Produkte des Austenitzerfalls
(Gefüge, die bei Abkühlung aus dem
Austenitgebiet entstehen können)

- Decay of the austenitic phase or Austenite transformation

Effect of Cooling/Quenching Rate

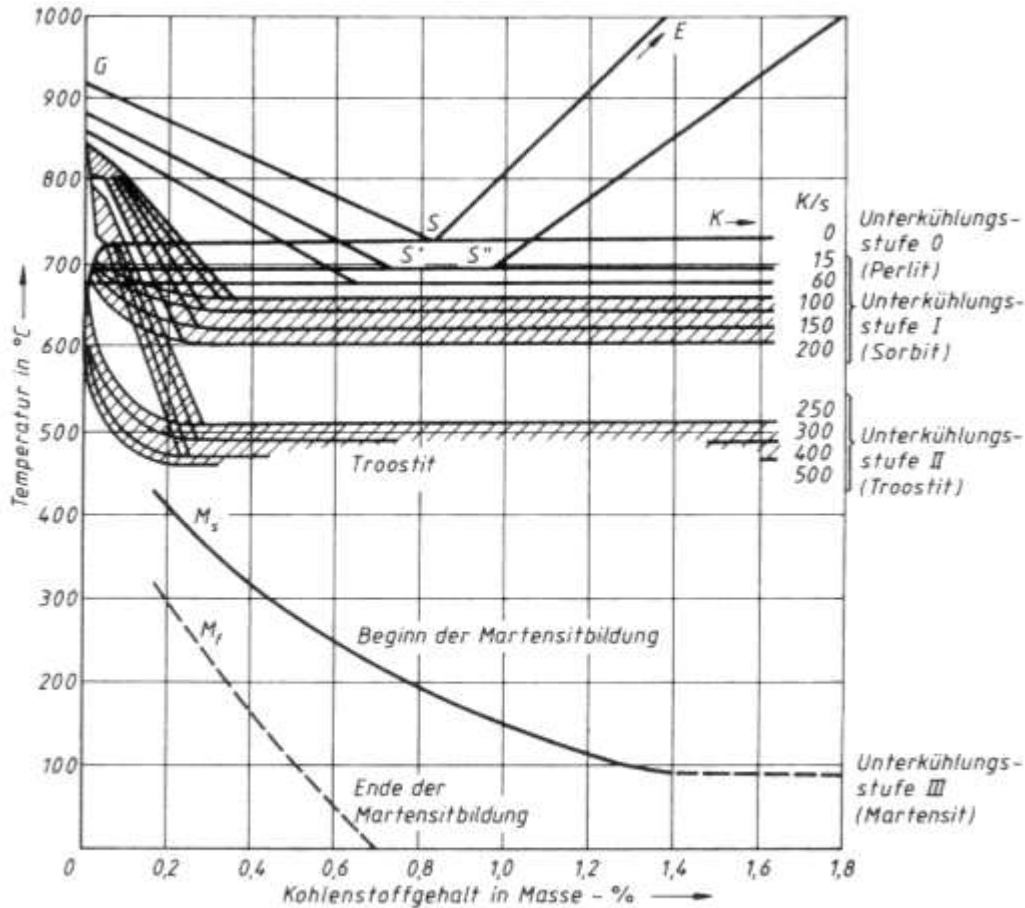


Bild 4.1-7 Veränderung der Umwandlungslinien im Fe-Fe₃C-Diagramm bei zunehmend rascherer Abkühlung

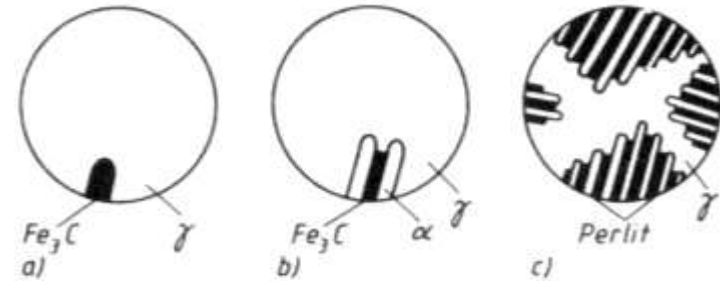
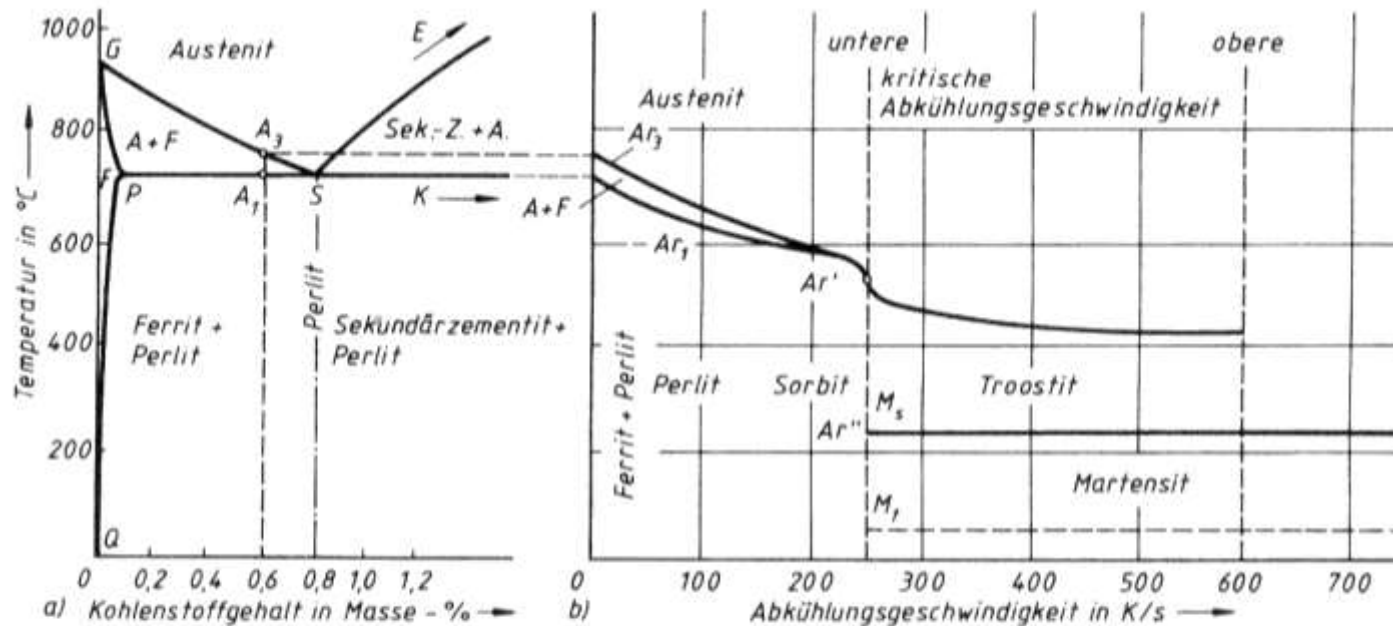


Bild 4.1-6 Entstehung des Perlits (schematisch)

Effect of Cooling/Quenching Rate



A Austenit
F Ferrit
Sek.-Z. Sekundärzementit

Bild 4.1-8 Veränderung der Umwandlungspunkte mit zunehmender Abkühlgeschwindigkeit
a) „Stahlecke“ des Systems Fe-Fe₃C
b) Einfluss der Abkühlgeschwindigkeit, Stahl mit 0,6 % C
M_s Beginn der Martensitbildung (s start)
M_f Ende der Martensitbildung (f finish)

- Higher quenching rates lower the transformation temperatures. The Pearlite structure grows finer. Result: strengthening/hardening.
- Above the critical quenching rate Martensite formation starts.

Martensite Formation

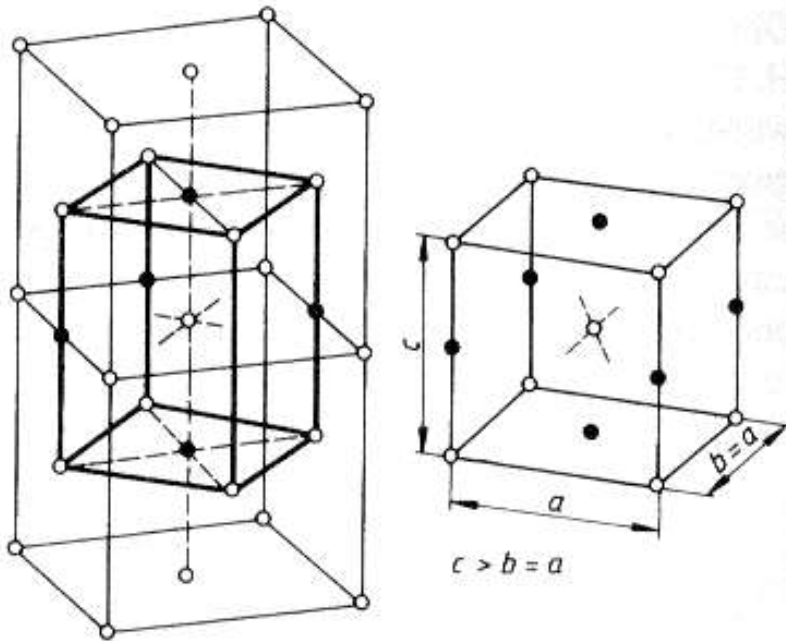


Bild 4.1–9 Gittermodelle zur Martensitstruktur
 a) kfz-Gitter (Austenit) mit tetragonal-raumzentrierter Elementarzelle
 b) tetragonal-raumzentrierte Elementarzelle (Martensit)

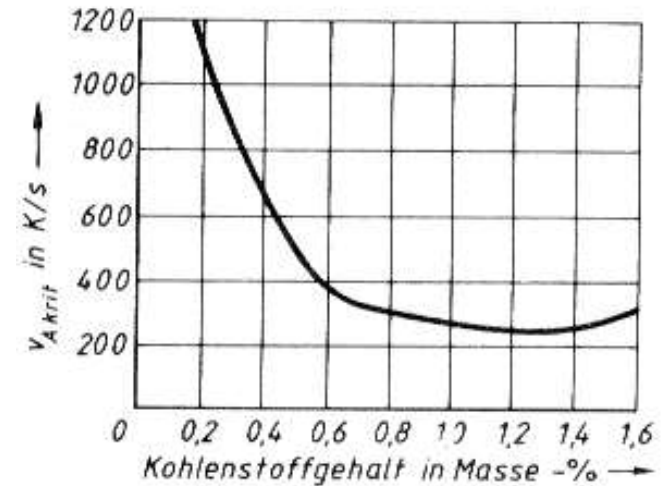
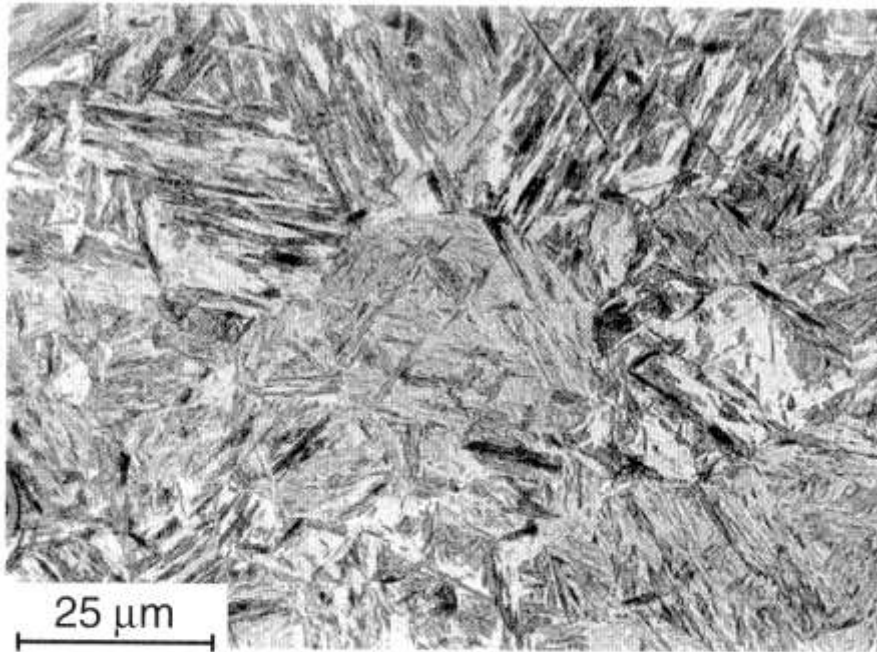
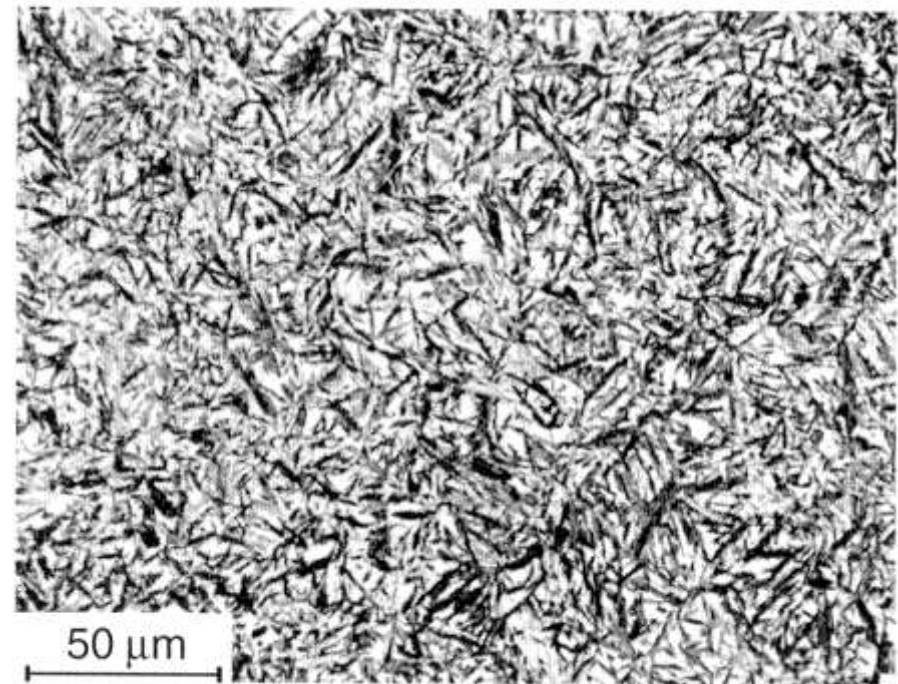


Bild 4.1–10 Einfluss des Kohlenstoffs auf die kritische Abkühlgeschwindigkeit unlegierter Stähle

Martensitic Microstructure



*Bild 4.42
Mikrogefüge eines niedriggekohten massiven Martensits, mit
der typischen 60°- bzw. 120°-Anordnung der Lanzettpakete!
Werkstoff: niedriglegierter Feinkornbaustahl mit 0,03% C,
505 HV10*

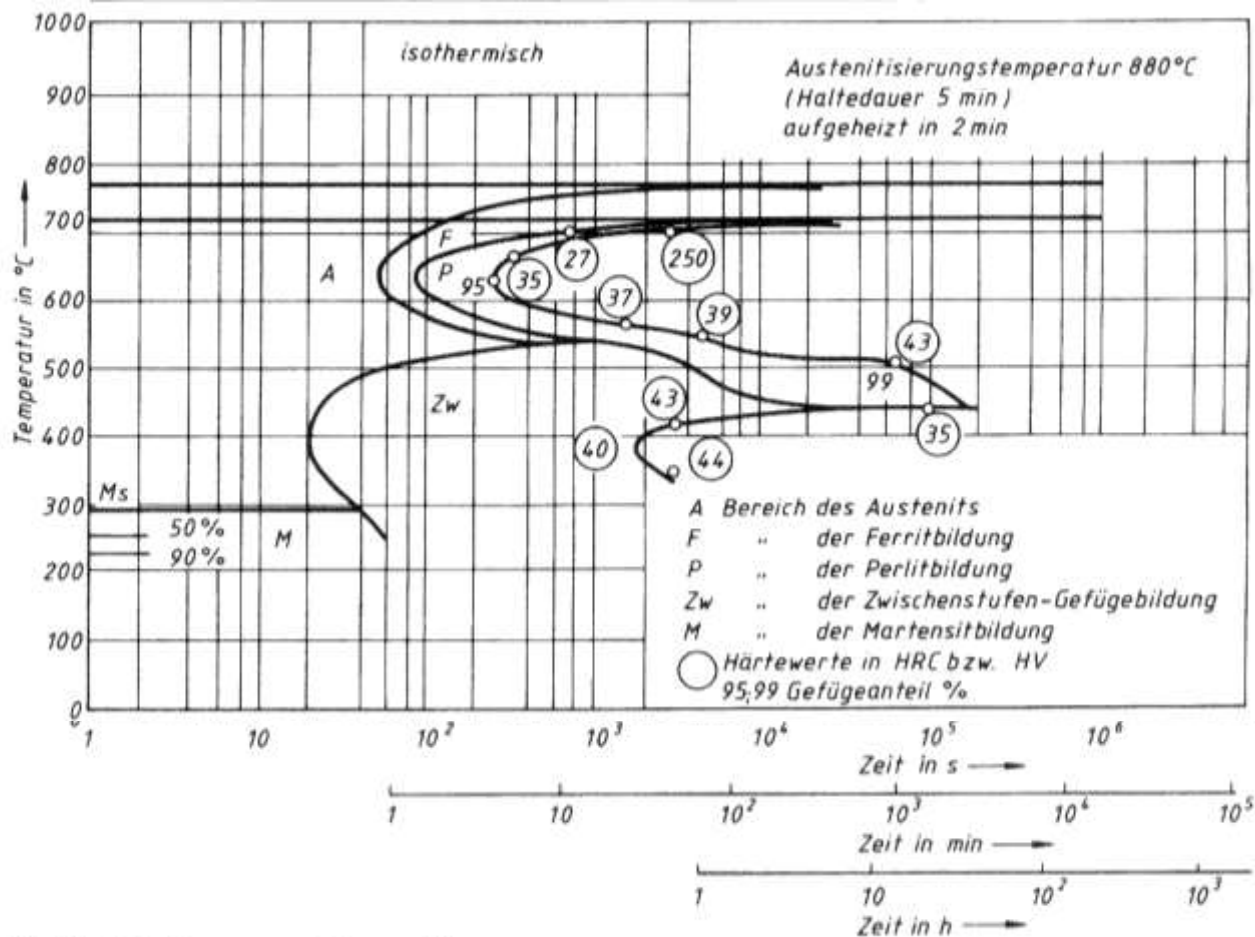


*Bild 4.43
Nadeliger Martensit*

- Low C-content → Massive or plate Martensite (“Lanzetten”-Struktur)
- High C-content → Lath or needle Martensite

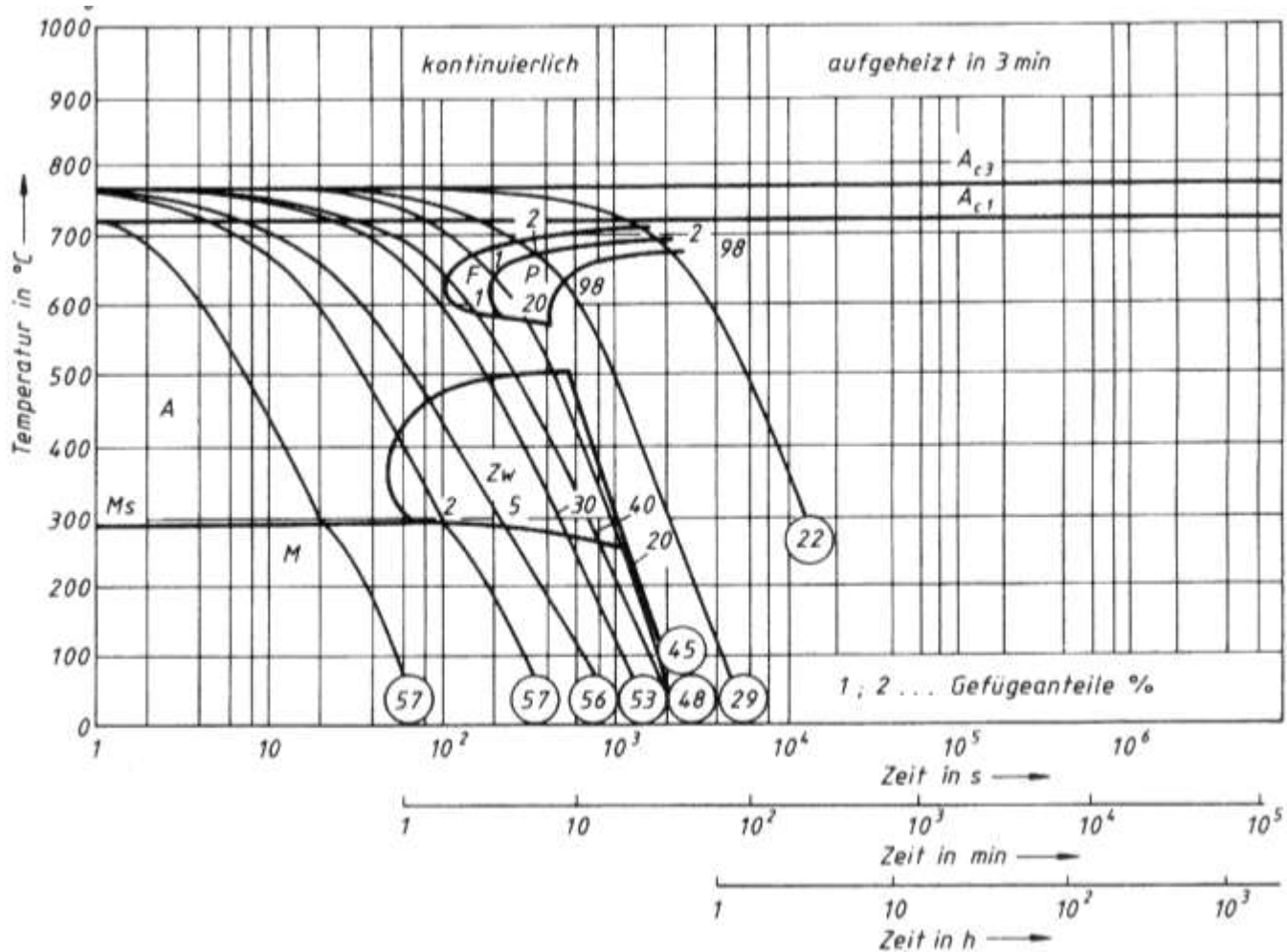
Isothermal Time-Temperature-Transformation

Chemische Zusammensetzung	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
	0,47	0,35	1,04	0,032	0,012	1,20	0,16	0,05	0,05	0,12



Continuous TTT-Diagram

Chemische Zusammensetzung	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
	0,47	0,35	1,04	0,032	0,012	1,20	0,16	0,05	0,05	0,12



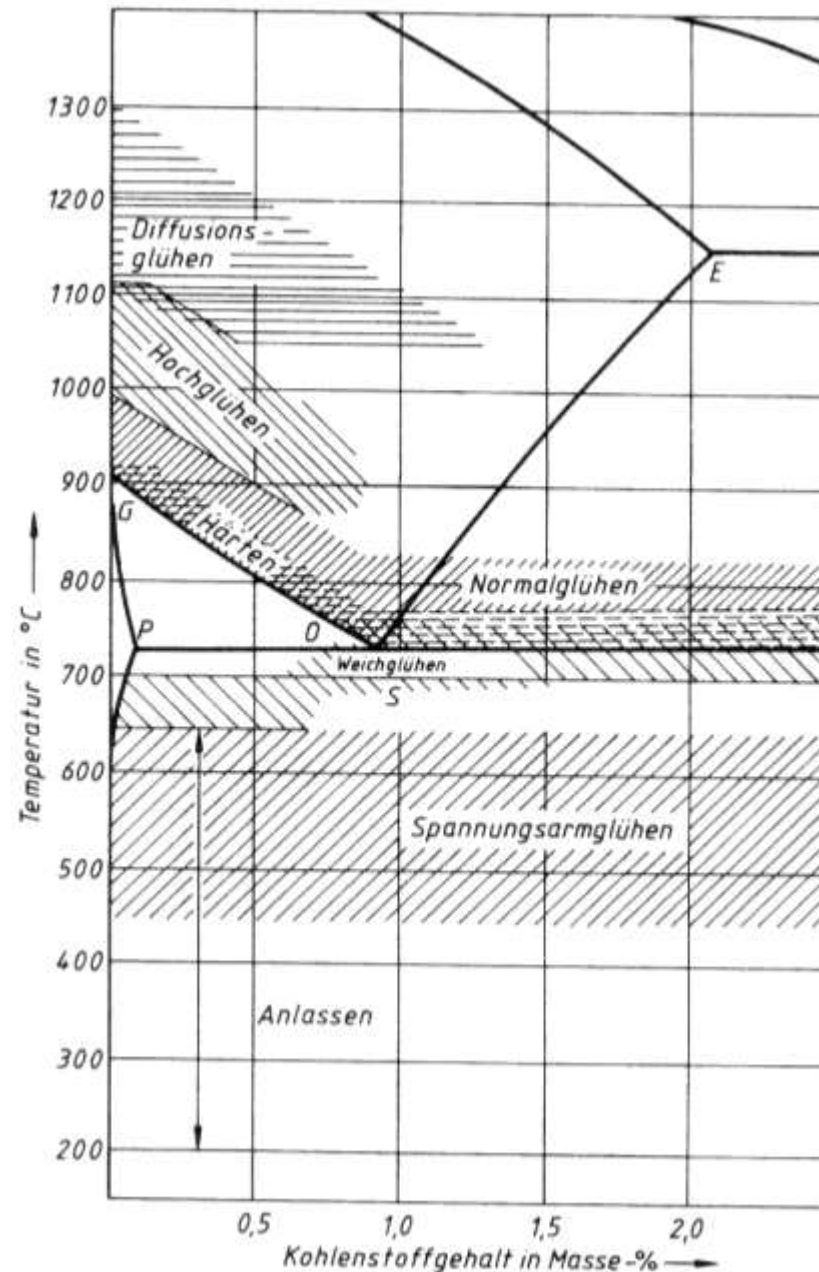
4

HEAT TREATMENT

Heat Treatments Overview

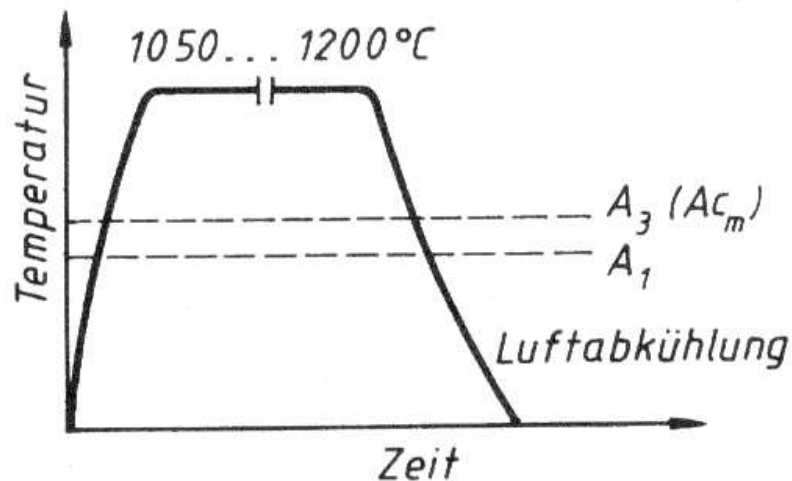
Solution annealing
(austenitisation)

Tempering



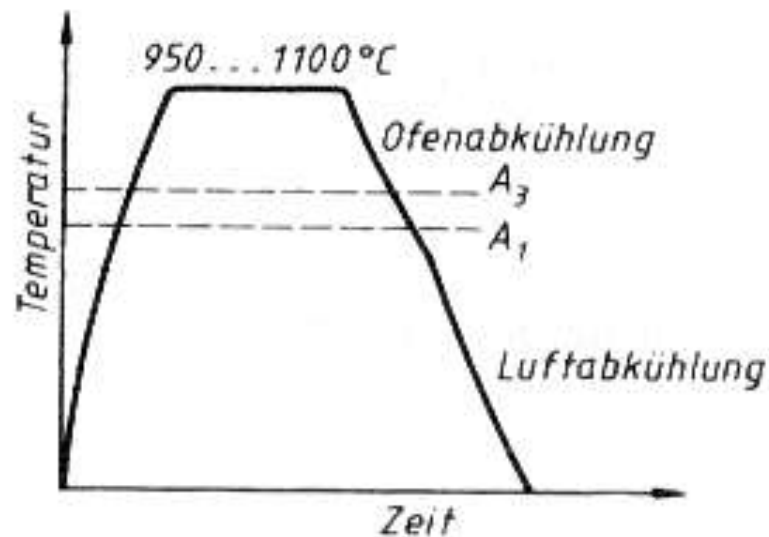
Diffusionsglühen

Diffusionsglühen erfolgt sehr hoch im Austenit-Bereich, es dient dem Konzentrationsausgleich der Teilchen (homogenisiert die feste Lösung).



Grobkornglühen

Grobkornglühen (Hochglühen) ist ein absichtliches Überhitzen der Stähle im Austenit-Bereich, um kohlenstoffarme Stähle besser spanbar zu machen.



Normalglühen

Normalglühen (Normalisieren) ist ein relativ kurzzeitiges Erwärmen ins Austenitgebiet auf 30 ... 50 K über die Umwandlungstemperatur. Ziel des Verfahrens ist es, ein gleichmäßiges, möglichst feinkörniges Gefüge zu erhalten. Das Verfahren wird häufig angewendet.

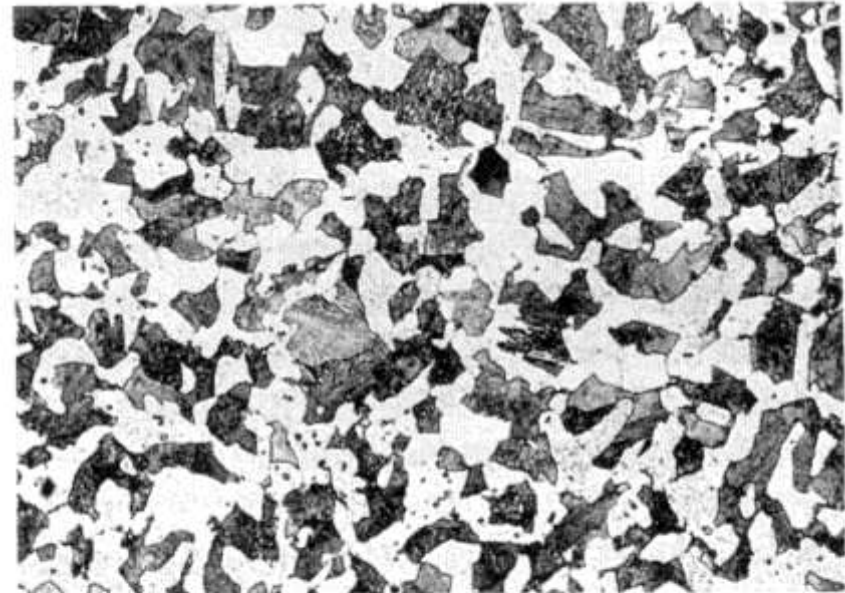
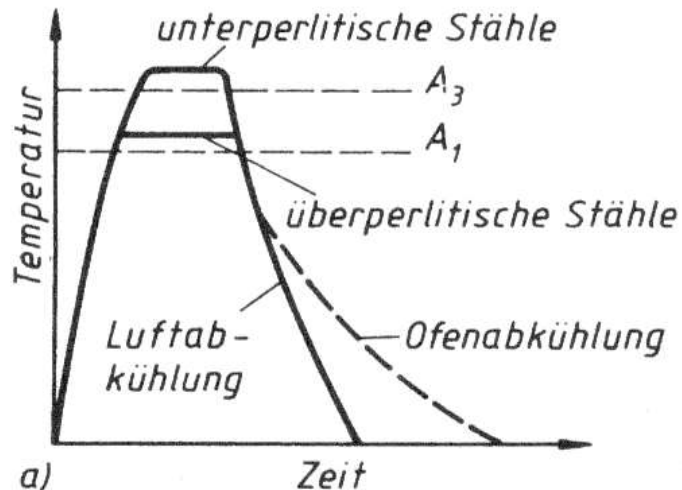


Bild 4.2–5 Normalglühen (Normalisieren)
 a) Temperatur-Zeit-Verlauf
 b) Gefüge eines normalisierten Stahles;
 Ferrit + Perlit; 200 : 1

Recrystallisation

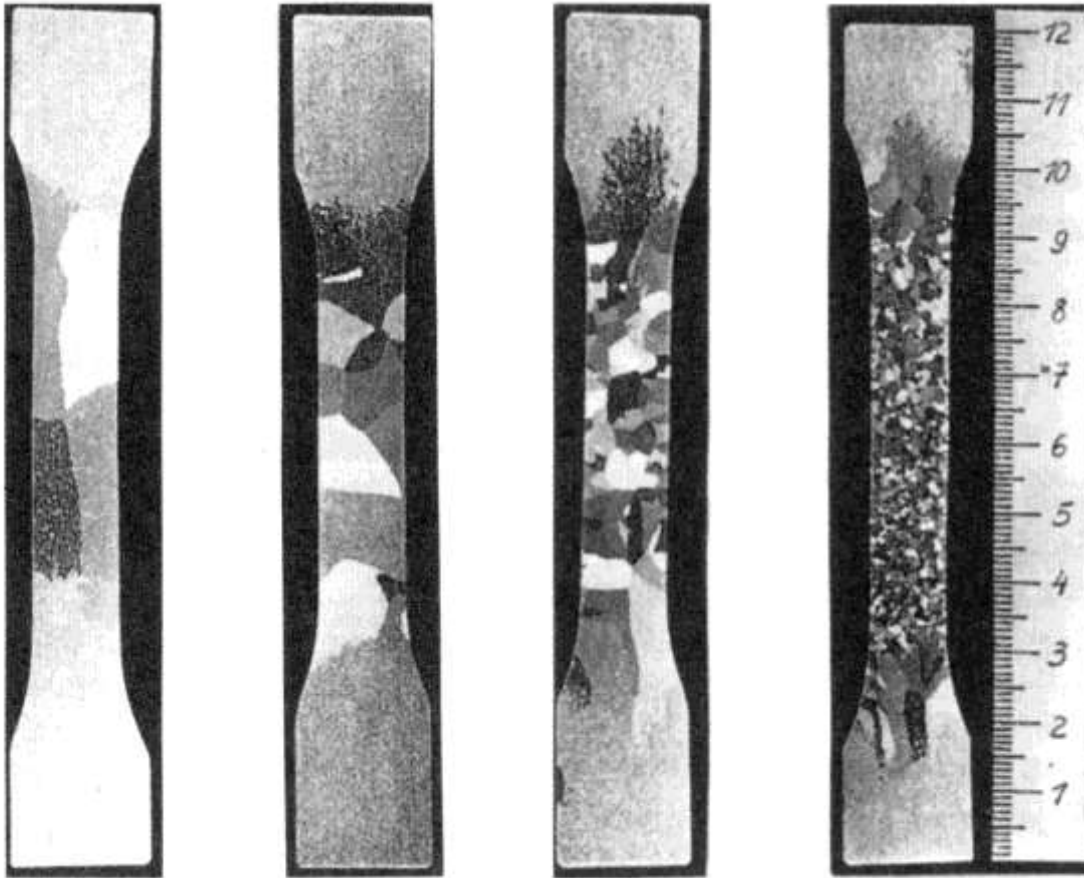


Bild 4.2–10 Gefügestruktur nach erfolgter Rekrystallisation (Zugproben aus Al mit unterschiedlichem Umformgrad)

Metals which don't show phase transformation, can only be recrystallised after cold work!

Examples: ferritic and austenitic steels, ...

Solution annealing + Quenching

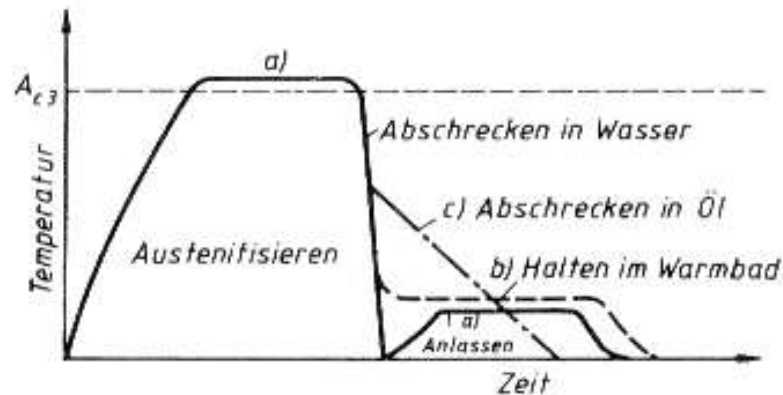


Bild 4.2–11 Temperatur-Zeit-Verlauf beim Härten

- a) Härten mit Anlassen (Entspannen)
- b) Warmbadhärten
- c) gebrochenes Härten

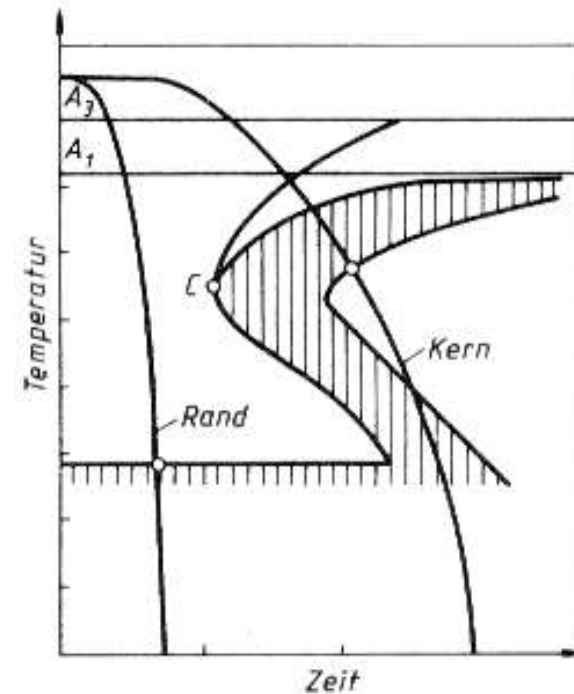


Bild 4.2–12 Reale Abkühlkurven eines Werkstücks (Rand härtet, Kern wird perlitisch)

“Vergüten”: quenching & tempering

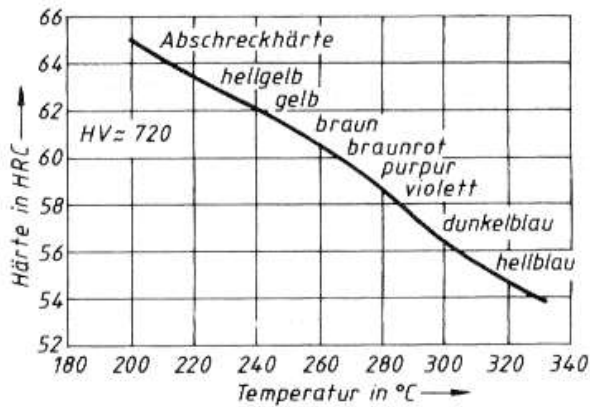


Bild 4.2-16 Abfall der Härte beim Anlassen – Zuordnung der Anlassfarben (HRC Härte nach Rockwell C) für unlegierten Stahl

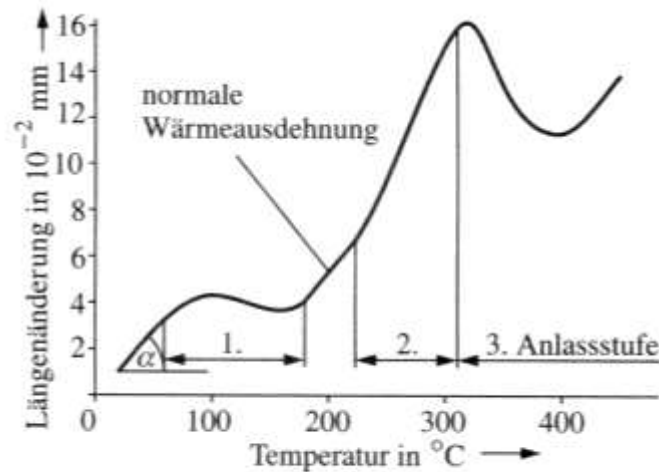


Bild 4.2-17 Dilatometerkurve für C 130 (950 °C, 10 min, Wasser)

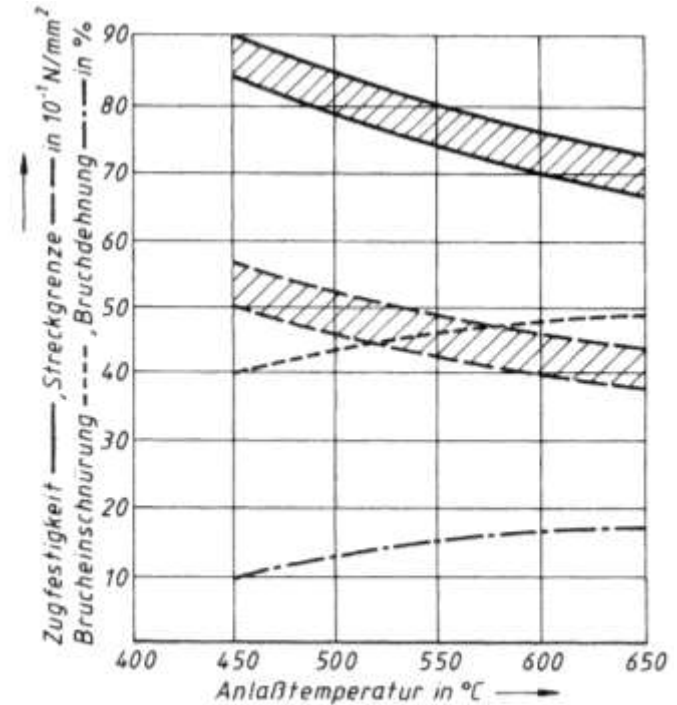


Bild 4.2-18 Vergütungsdiagramm eines Stahles mit 0,44 % C

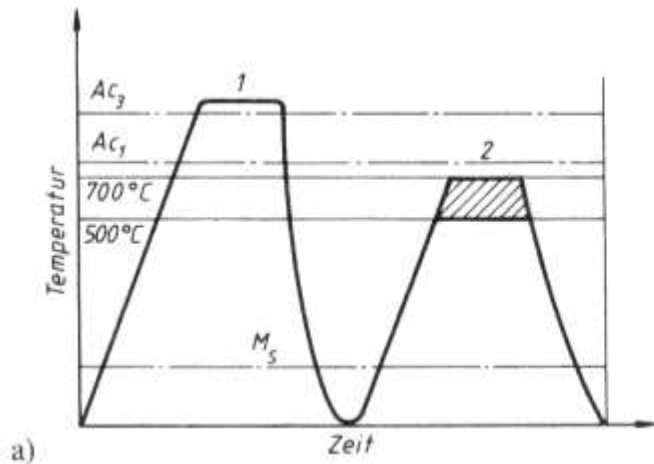


Bild 4.2–19 Vergüten

a) Temperatur-Zeit-Verlauf (1 Härten, 2 Anlassen bei hohen Temperaturen)

b) Gefüge vor dem Härten; C 45 normalgeglüht (30 min, 850 °C/Luft), Ferrit + Perlit, 500 : 1

c) Gefüge nach dem Härten; gleicher Stahl (840 °C/Wasser), Martensit, 500 : 1

d) Vergütungsgefüge, gleicher Stahl (500 °C/Luft), 500 : 1

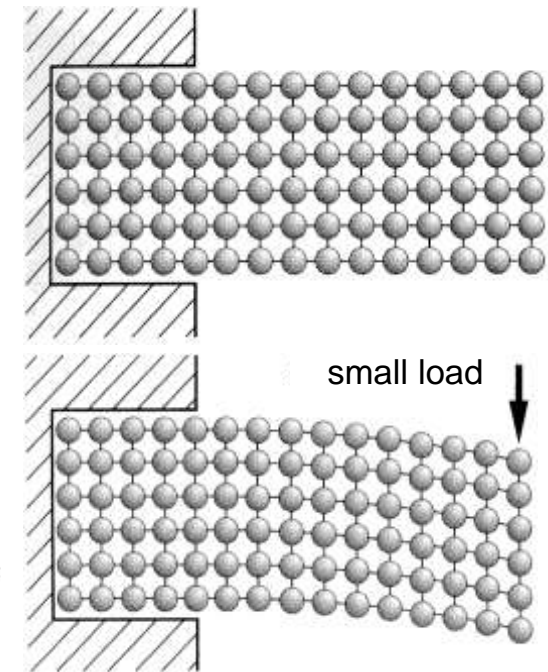
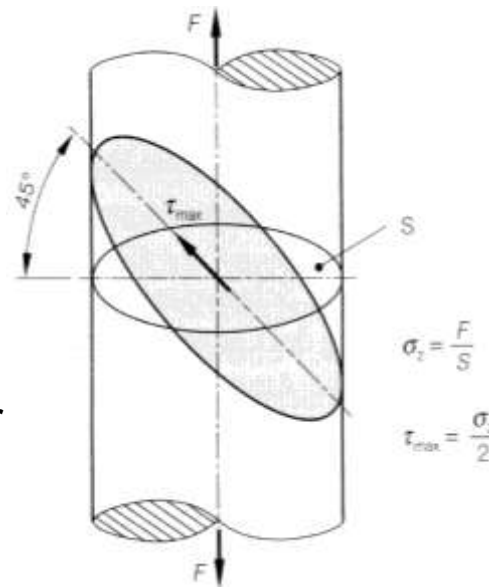
5

DEFORMATION MECHANISMS

Deformation of Metals

Elastic Deformation

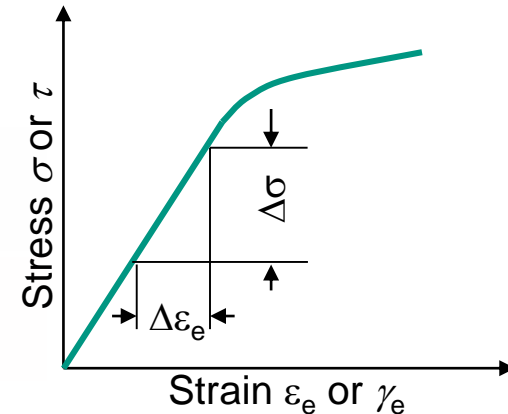
Technically there are two forms of deformation: changes in length (strain) and changes in angle (shear). In a lattice only shear is possible since straining the atomic distances would need high forces, which would immediately lead to fractures. Further it can be easily shown that the shear stress is lower than the according tensile stress.



For elastic, i.e. reversible deformation:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_e} \quad E = \text{elastic modulus (Young's Modulus)}$$

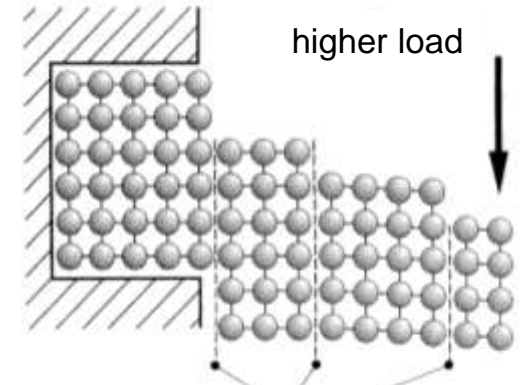
$$G = \frac{\Delta\tau}{\Delta\gamma_e} \quad G = \text{shear modulus (gliding modulus)}$$



Deformation of Metals

Plastic Deformation

Above a critical stress level (**yield limit**) the atoms of a lattice plane jump to neighboring lattice sites. They remain on these sites even if the stress is removed. The deformation is permanent or **plastic**.

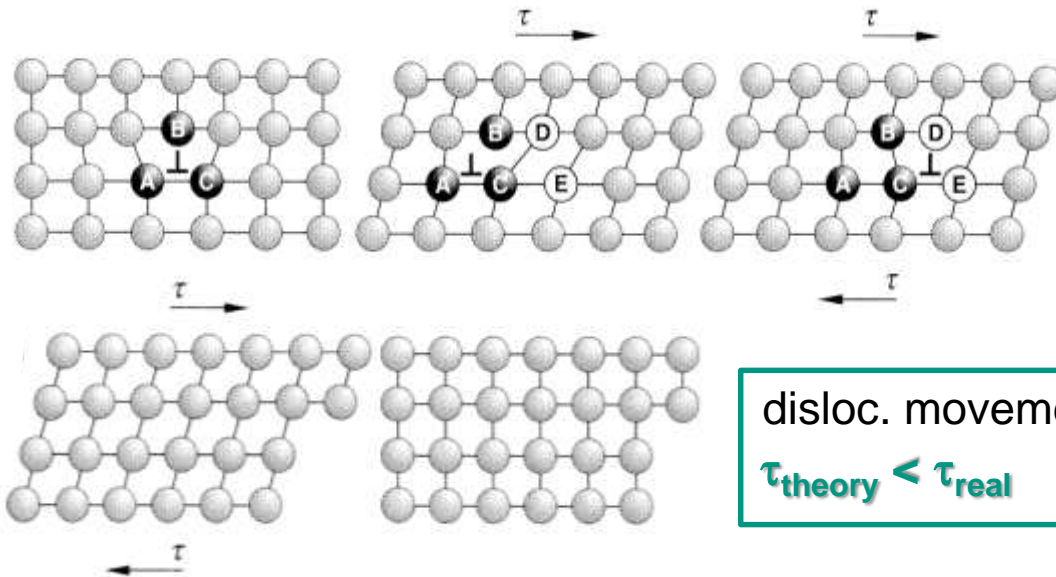


Deformation Mechanisms

a) Dislocation Gliding

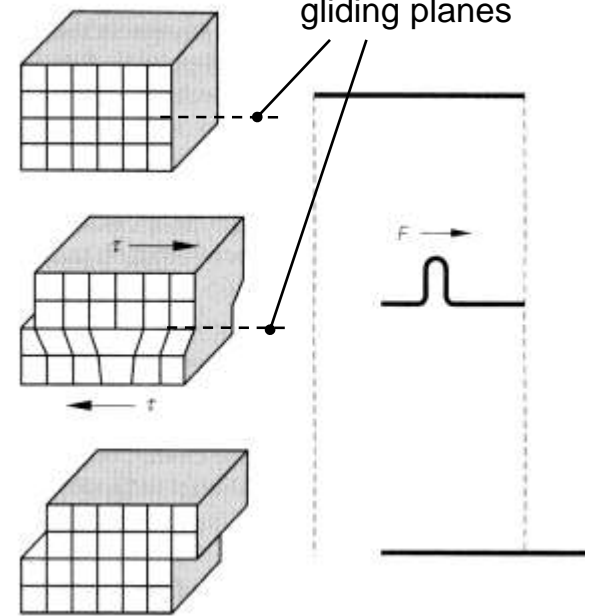
gliding:

$$\tau_{\text{theory}} \gg \tau_{\text{real}}$$



disloc. movement:

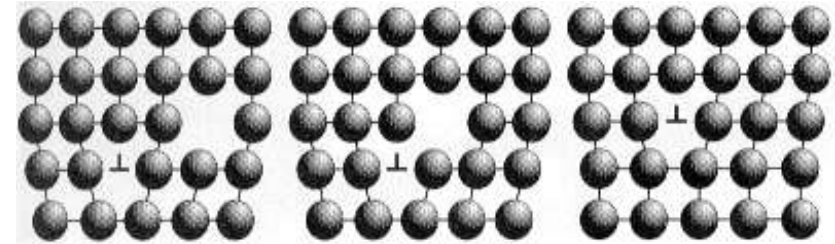
$$\tau_{\text{theory}} < \tau_{\text{real}}$$



Deformation of Metals

b) Dislocation Climbing

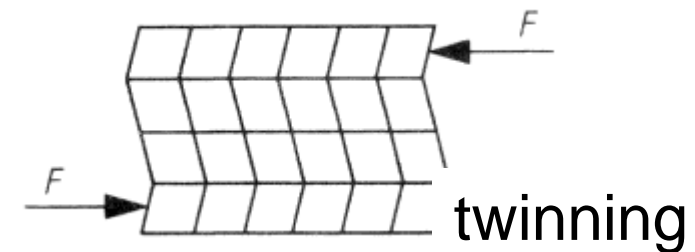
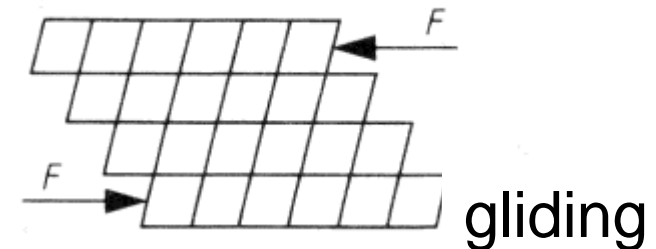
With the help of vacancies, dislocations may leave their glide plane. Since the vacancy concentration increases with temperature, climbing mainly is a *high temperature effect*.



climbing

c) Twin Formation

Another possibility of deformation is the formation of twins, so-called **deformation twins**. Especially at very low temperatures and for materials with a small number of gliding planes (hexagonal lattices, like Ti, Mg, etc.) deformation of twins is an easier alternative to gliding.

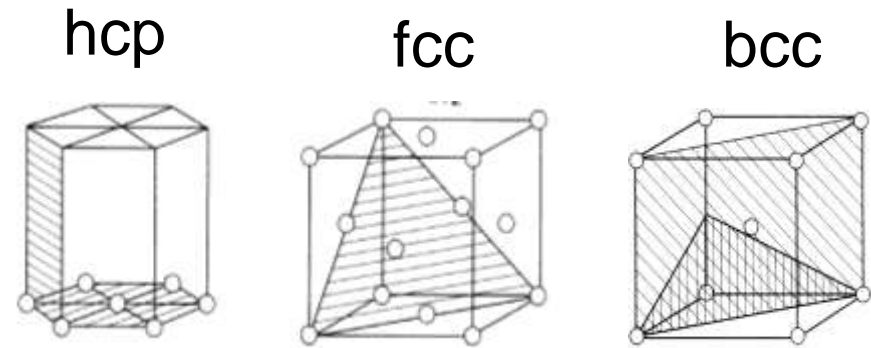


Deformation of Metals

Glide Systems, Gliding Possibilities

A glide system consists of possible gliding planes and glide directions. Gliding possibilities are the product of the number of gliding planes and directions in an elementary lattice cell.

Lattice	fcc	bcc	hcp
Main Gliding Planes	4 (tetraeder planes → {111})	none	1 (base plane and parallel)
Further Gliding Planes	cube faces → {100}	6 → {110} 12 → {112} 24 → {123}	prism faces
Glide Directions	3 (along the face diagonal)	2 (along the space diagonal)	3
Glide Systems	12	12	3

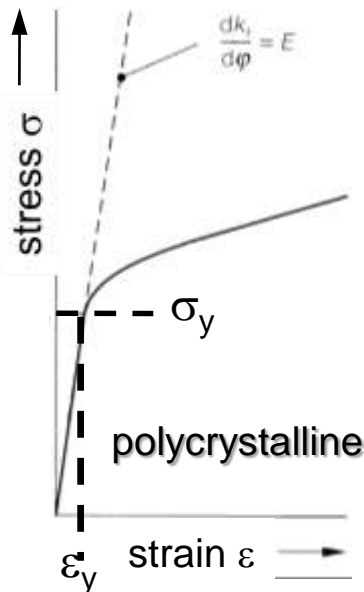
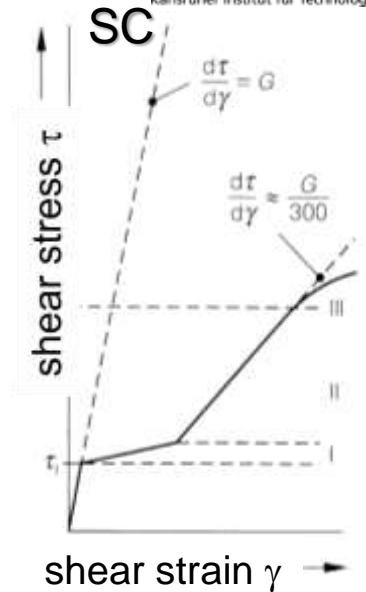
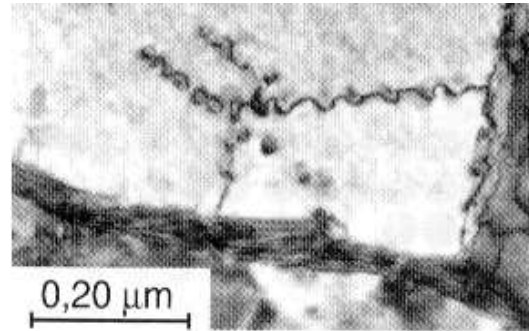
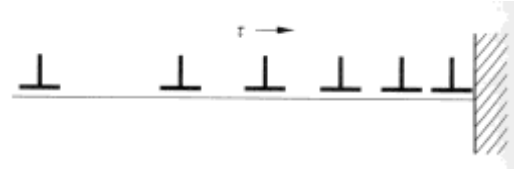


Fcc metals are rather ductile. Bcc metals have more glide possibilities but the glide planes are not close packed, that is, it needs much higher shear stresses to deform them. Hcp metals are not so ductile.

Strengthening/Hardening Mechanisms

1) Cold Work (disloc. density)

- Piling up of dislocations at obstacles
- Generation of new dislocations (e.g. Frank-Read sources)
- Strengthening by dislocation blocking (crossing)



$$\text{Hardening Exponent: } n = \ln(1 + \epsilon_y)$$

$$\sigma_d = M \alpha G b \sqrt{\rho_d}$$

Example: bcc-steel, polycrystalline

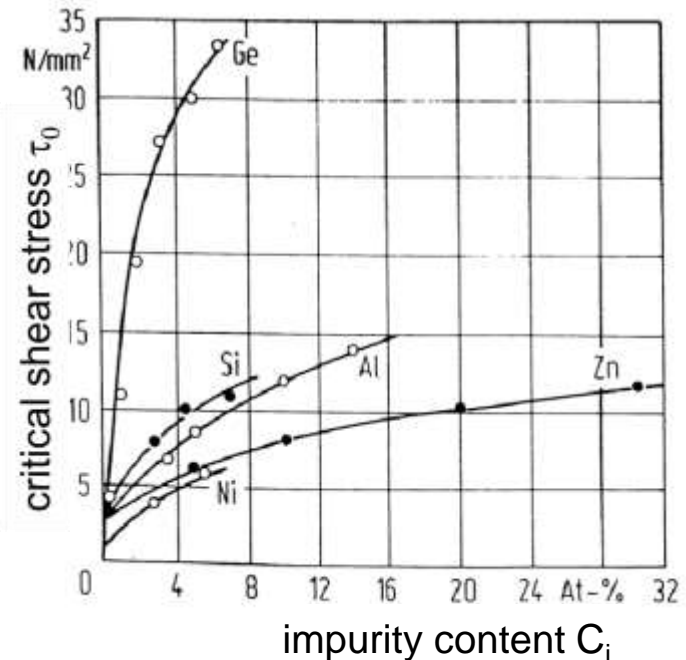
Taylor Factor M	= 2.2-2.85
Shear Modulus G	= 86000 MPa (T=Room temp.)
Burgers Vector b	= 0.245 nm (<111> Gliding)
Prop. Const. alpha	= 0.3
Disloc. Density rho_d	≈ 2x 10 ¹⁴ m ⁻²
Result:	sigma_d ≈ 250 MPa (≈ 42% of sigma_y)

Hardening Mechanisms

2) Solid Solution Hardening

Interstitial and/or substitution impurity atoms bend the host lattice. Therefore, the critical shear stress τ_0 for gliding is increased, that is, the material strength is higher. The effect depends on three parameters:

- **concentration of impurity atoms**
- **difference of the atomic radii**
- **type (interstitial > substitution)**



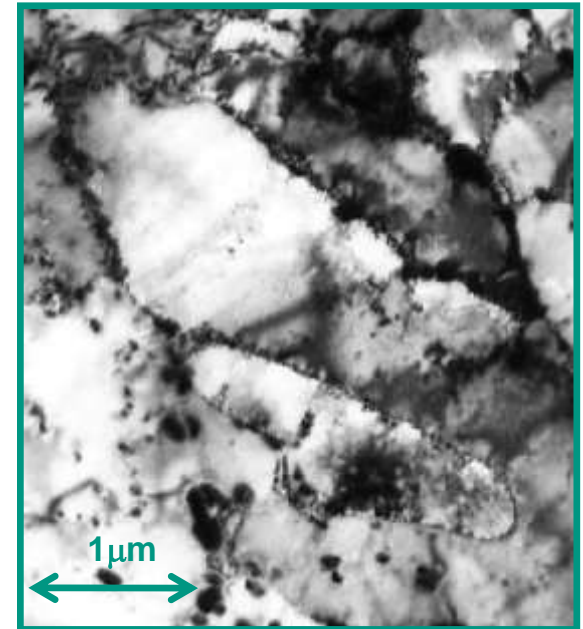
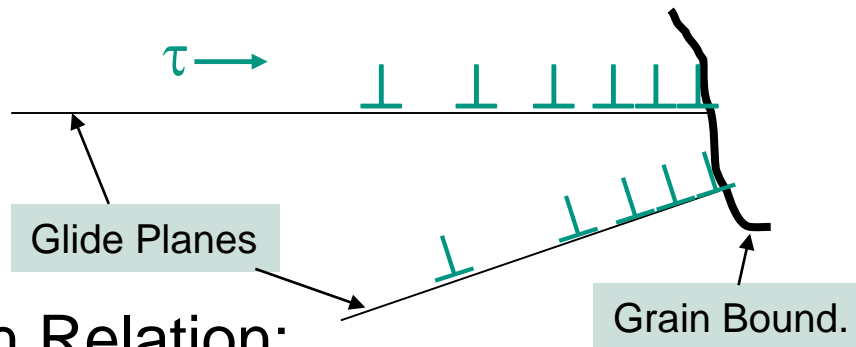
Interstitial Solution Hardening by Oxygen in Titanium (this is comparable to Carbon in Iron)				
O content, %	0.1	0.2	0.25	0.3
Yield Strength, MPa	200	250	360	420

$$\sigma_i = \text{const} \sqrt{C_i}$$

Hardening Mechanisms

3) Fine Grain Formation

Grain boundaries are barriers for gliding dislocations. Therefore, in smaller grains the dislocations reach faster the boundary where they are stopped. To overcome the grain boundary it needs much higher shear stresses, that is, the yield limit is increased. In addition, this is the only hardening effect that increases also ductility (since more glide planes are perfect aligned to load direction, 45°).



Hall-Petch Relation:

$$\sigma_{gr} = M\alpha'Gb\sqrt{\frac{1}{d_{gr}}}$$

Example: bcc-steel, polycrystalline
mean grain (here laths) size

$d_{gr} = 0.5 - 1\mu\text{m}$
 $\alpha' \approx 4380\text{ m}^{-0.5}$

Result: $\sigma_{gr} \approx 320\text{ MPa}$ ($\approx 55\%$ of yield strength σ_y)

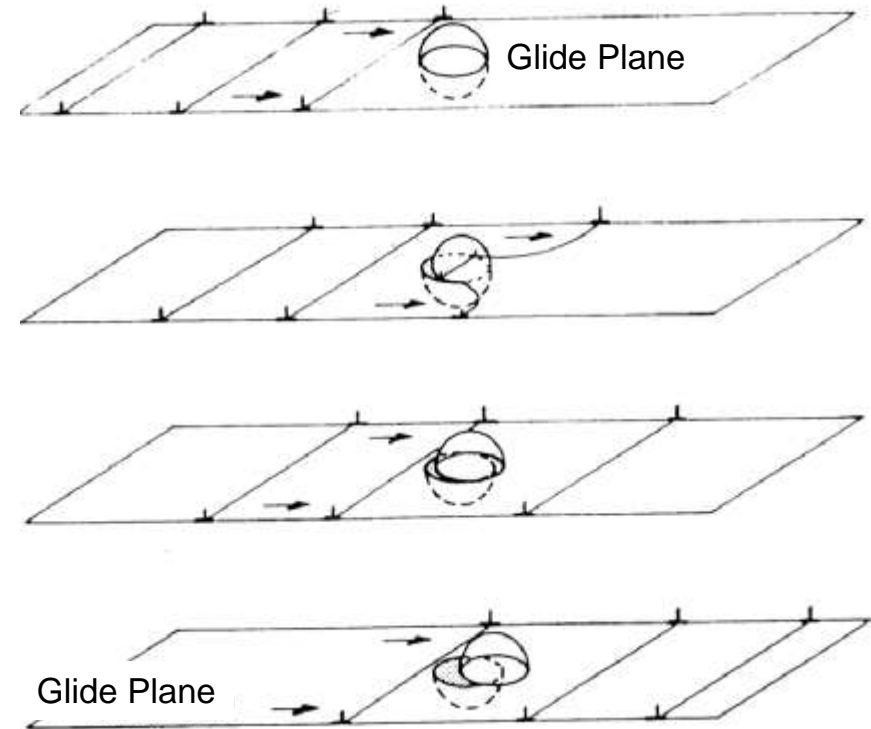
Hardening Mechanisms

4) Dispersion Strengthening

Precipitates or dispersion particles of mechanical alloying processes in the range of 10-100 nm can act as glide obstacles. Due to their small size they are at least partly coherent to the host lattice, that is, they can be passed by dislocations by shearing. But this needs higher stresses and, therefore, the material shows a higher strength.

$$\sigma_{finepr} \sim f_V^{1/2} \cdot r_{pr}^{1/2}$$

The volume fraction f_V is less relevant than the particle spacing r_{pr} (since f_V depends on r_{pr}) which has to be in the range of 100-500 nm to be effective.



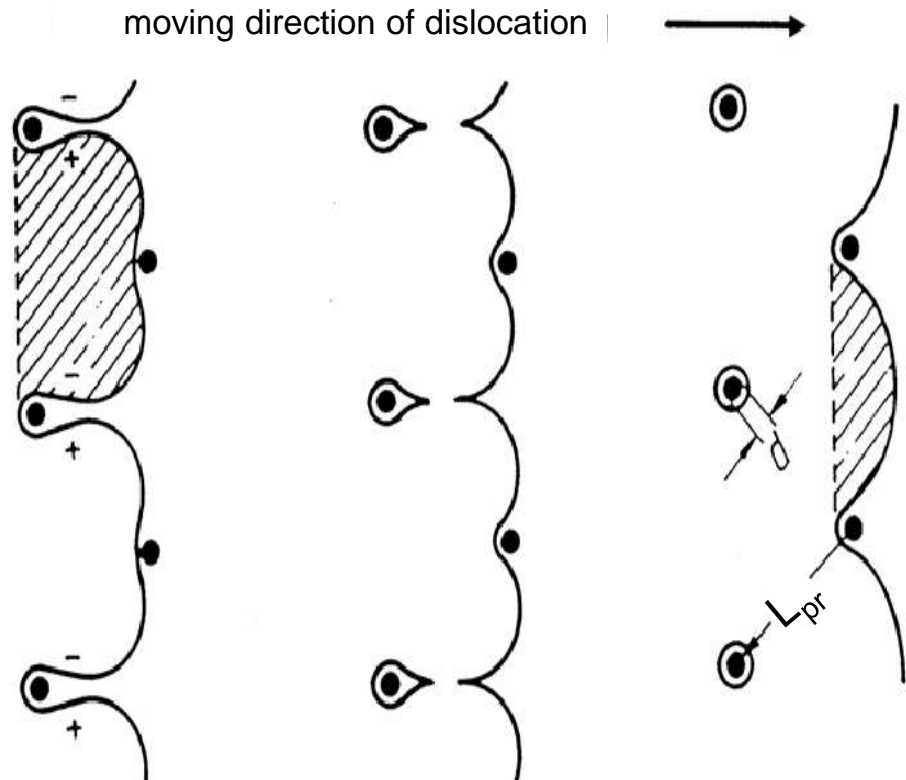
Hardening Mechanisms

5) (Incoherent) Particle Strengthening

Large precipitates, intermetallic phases, or dispersoids can also act as strong glide obstacles. They are most often incoherent to the host lattice, that is, they cannot be sheared by dislocations. But by a circumvention mechanism (after Orowan) the obstacles may be passed. This needs high stresses and, therefore, the material shows a higher strength.

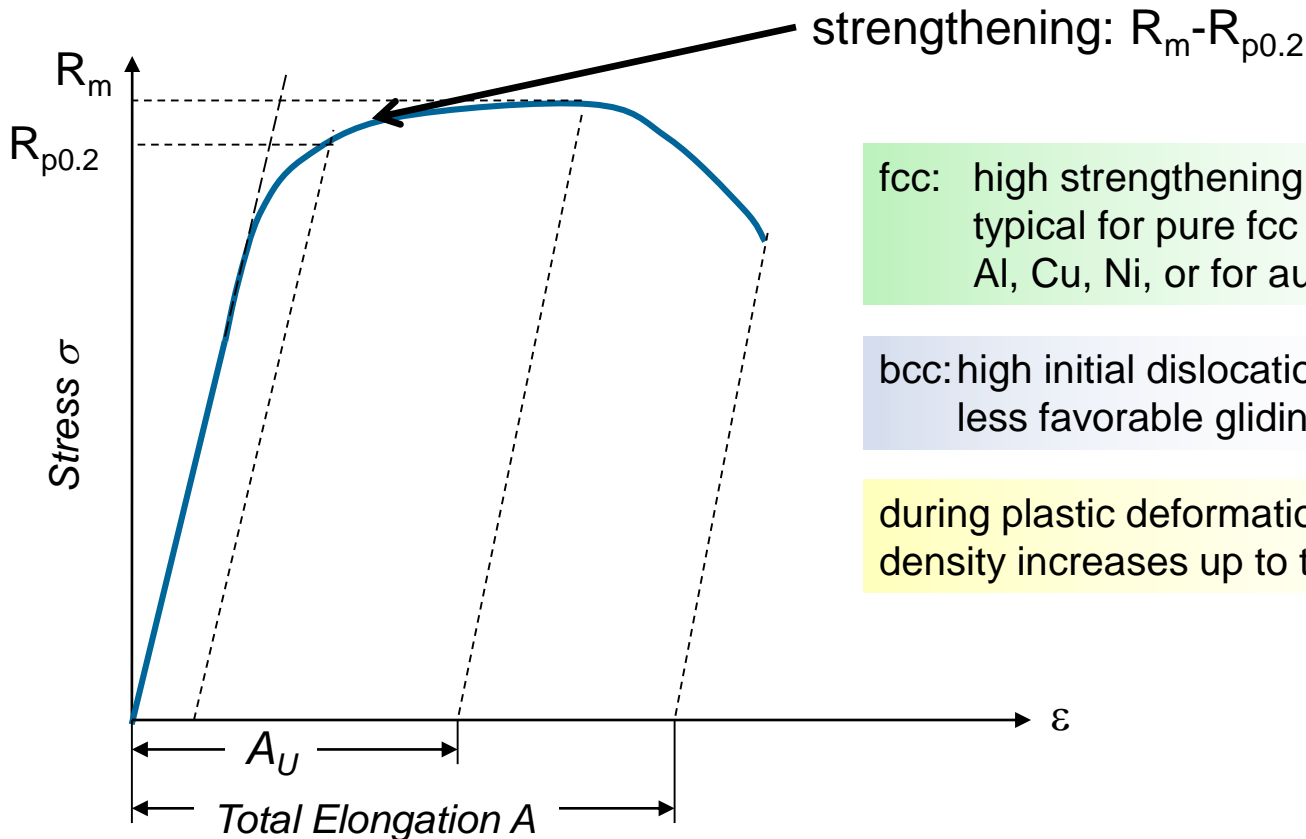
$$\sigma_{pr} = M \alpha_{OR} G b \frac{1}{L_{pr}}$$

($\alpha_{OR} = 0.36$; most relevant is the particle spacing L_{pr} .)



Mechanical Properties

Tensile Strength, Hardness



fcc: high strengthening values are typical for pure fcc metals like Al, Cu, Ni, or for austenitic steels

bcc: high initial dislocation density, less favorable gliding system

during plastic deformation the dislocation density increases up to the point of R_m (A_U).

- plastic deformation is irreversible
- no linear relation between stress and strain
- uniform elongation A_U is the start of reduction of area

5

ALLOYING STEELS

Stähle sind Eisen-Kohlenstoff-Legierungen mit weniger als 2 % Kohlenstoff. Nur einige chromhaltige Stähle bilden hiervon eine Ausnahme und haben einen etwas höheren Anteil.

Gemäß der *Einteilung nach der chemischen Zusammensetzung* unterscheidet man unlegierte und legierte Stähle. Man unterscheidet nach Grenzgehalten (Masseanteile in %) der enthaltenen Elemente (Tabelle 6.1–1).

- erreicht kein Element einen angegebenen Grenzgehalt, so liegt ein *unlegierter* Stahl vor
- werden die angegebenen Grenzgehalte erreicht (auch wenn das nur bei einem Element der Fall ist) bzw. überschritten, so spricht man von einem *legierten* Stahl

Tabelle 6.1–1 Grenzgehalte im Stahl (Auswahl)

Vorgeschriebene Elemente	Grenzgehalt in Masse-%
Al Aluminium	0,10
Co Cobalt	0,10
Cr Chrom	0,30
Mn Mangan	1,65
Mo Molybdän	0,08
Ni Nickel	0,30
Si Silicium	0,50
W Wolfram	0,10

- Kurzname mit Hinweis auf mechanische Eigenschaft
- Kurzname mit Hinweis auf chemische Zusammensetzung
- Werkstoffnummern

Einteilung der Stähle nach DIN EN 10 020

Hauptgruppe 1:

Kurznamen, die Hinweise auf die mechanischen oder physikalischen Eigenschaften oder die Verwendung der Stähle enthalten, z. B. P275, S355 usw.

Die Buchstaben bedeuten:

- P Stähle für den Druckbehälterbau
- S Stähle für den Stahlbau
- L Stähle für den Rohrleitungsbau
- E Maschinenbaustähle
- B Betonstähle usw.

Die Zahl entspricht dem Mindestwert der *Streckgrenze* in N/mm^2 für die kleinste Erzeugnisdicke. Die Streckgrenze ist ein Maß für die Festigkeit (= Belastbarkeit) des Stahles (Erläuterung dieser Kenngröße s. 12.2.2).

Der Kurzname kann darüber hinaus noch Zusatzsymbole enthalten. Hierfür einige Beispiele:

Gütegruppen: Kerbschlagarbeit in Joule [J]
(Maß für die Zähigkeit; s. Abschnitt 12.4)
z. B. bei 20 °C gilt
27 J: JR; 40 J: KR; 60 J: LR

Desoxidationsarten (Lieferzustand):

- G1 $\hat{=}$ FU unberuhigt vergossener Stahl
- G2 $\hat{=}$ FN unberuhigter Stahl nicht zulässig
- G3 $\hat{=}$ FF vollberuhigter Stahl (s. 5.7.3)

Eignung/besonderer Verwendungszweck

- C gut kaltumformbar
- D gut schmelztauchbar
- E emaillierbar
- L für tiefe Temperaturen
- W wetterfest

Symbole für besondere Anforderungen (Auswahl)

- +F Feinkornstahl
- +Z 25 Mindest-Brucheinschnürung 25 % (s. Abschnitt 12.2.2)

Symbole für die Art des Überzugs (Auswahl)

- +OC organisch beschichtet
- +S feuerverzinkt
- +ZN elektrolytischer Zink-Nickel-Überzug

Behandlungszustand (Auswahl)

- +A weichgeglüht (bisher: G)
- +C kaltverfestigt (z. B. durch Walzen oder Ziehen)
- +N normalgeglüht oder normalisierend gewalzt (bisher: N)
- +QT vergütet (bisher: V)
- +T angelassen (bisher: A)
- +U unbehandelt (bisher: U)
- +M thermomechanisch behandelt

Beispiel: S355JRG2C+N

- S355 Stahl für den allgemeinen Stahlbau
Streckgrenze 355 N/mm^2
- JR Kerbschlagarbeit 27 J bei +20 °C
- G2 beruhigt vergossener Stahl
- C gut kaltumformbar
- +N Behandlungszustand: normalgeglüht

Hauptgruppe 2:

Kurznamen mit Hinweisen auf die chemische Zusammensetzung

Unlegierte Stähle mit einem mittleren Mangengehalt < 1 % werden durch das Symbol C (für Kohlenstoff) und eine Zahl, die dem Hundertfachen des mittleren Kohlenstoffgehaltes entspricht, gebildet.

Der Kurzname für legierte Stähle setzt sich wie folgt zusammen:

Der Kohlenstoffgehalt wird in gleicher Weise angegeben, jedoch entfällt das Symbol C. Darauf folgen die chemischen Symbole der den Stahl kennzeichnenden Legierungselemente sowie Zahlen, die in der Reihenfolge der Elemente einen Hinweis auf ihren Gehalt geben. Die mittleren Massegehalte werden dabei multipliziert mit

- Faktor 4 bei Cr, Co, Mn, Ni, Si und W,
- Faktor 10 bei Al, Be, Cu, Mo, Nb, Pb, Ta, Ti, V und Zr,
- Faktor 100 bei Ce, N, P und S (auch C, wie bereits genannt),
- Faktor 1000 bei B.

Beispiele:

- C10 0,10 % Kohlenstoff
(Einsatzstahl, nicht härtbar)
- C35 0,35 % Kohlenstoff
(Vergütungsstahl, härtbar)
- C110 1,10 % Kohlenstoff
(Werkzeugstahl, härtbar)

Beispiele:

- 16MnCr5 Einsatzstahl, 0,16 % C, 5/4 % Mn = 1,25 % Mn, Cr-Gehalt niedriger (im Kurznamen nicht konkret angegeben)
- 34CrAlMo5 Nitrierstahl, 0,34 % C, 5/4 % Cr = 1,25 % Cr, Al- und Mo-Gehalt niedriger (fallende Tendenz von links nach rechts)
- 10S20 Automatenstahl (d. h., leicht spanbarer Stahl), 0,10 % C, 20/100 % S = 0,2 % S
- 11MoCrV7-2-4 Schweißzusatz, warmfester Stahl 0,11 % C, 7/10 % Mo = 0,7 % Mo, 2/4 % Cr = 0,5 % Cr, 4/10 % V = 0,4 % V
- 23B2 Borlegierter Feinkornstahl, 0,23 % C, 2/1000 % B = 0,002 % B

Einteilung der Stähle nach DIN EN 10 020

Hochlegierte Stähle enthalten insgesamt mindestens 5 % Masseanteil Legierungselemente. Sie werden mit X bezeichnet. Außer für Kohlenstoff gilt grundsätzlich der Faktor 1.

Beispiele:

X 20 Cr 13

Nichtrostender Stahl,
vergitbar,
0,20 % C, 13 % Cr

X6CrNiMo17-13

Hochwarmfester Stahl,
0,06 % C, 17 % Cr,
13 % Ni, Mo nicht angegeben
(kleinerer Anteil)

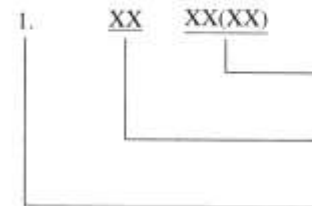
Eine Ausnahme bilden die Schnellarbeitsstähle. Deren Kurzname beginnt mit HS und es folgen, stets in der Reihenfolge W, Mo, V, Co die Massegehalte in ganzen, gerundeten Zahlen (s. a. Abschnitt 6.2.6).

Beispiel:

HS10-4-3-10

Schnellarbeitsstahl
(hochlegierter Stahl für
Werkzeuge)
10 % W, 4 % Mo, 3 % V
und 10 % Co.

Aufbau der Werkstoffnummern:



Zahlnummer (die in Klammern wiedergegebenen Stellen sind für möglichen, zukünftigen Bedarf vorgesehen)

Stahlgruppennummer

Werkstoffhauptgruppennummer (1 = Stahl)

Beispiele:

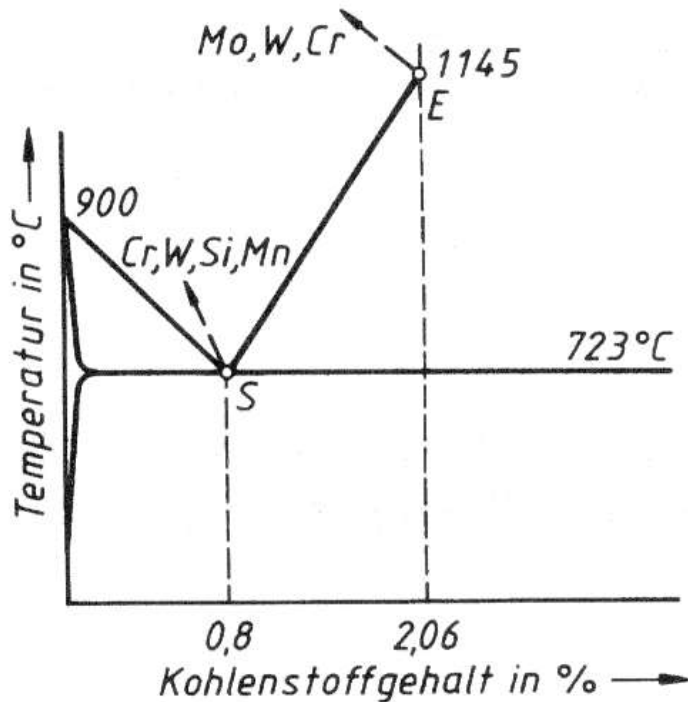
1.35.. Stahlgruppe 35:

Wälzlagerstahl

1.27.. Stahlgruppe 27:

Nickelhaltiger Werkzeugstahl

Influence of alloying different elements

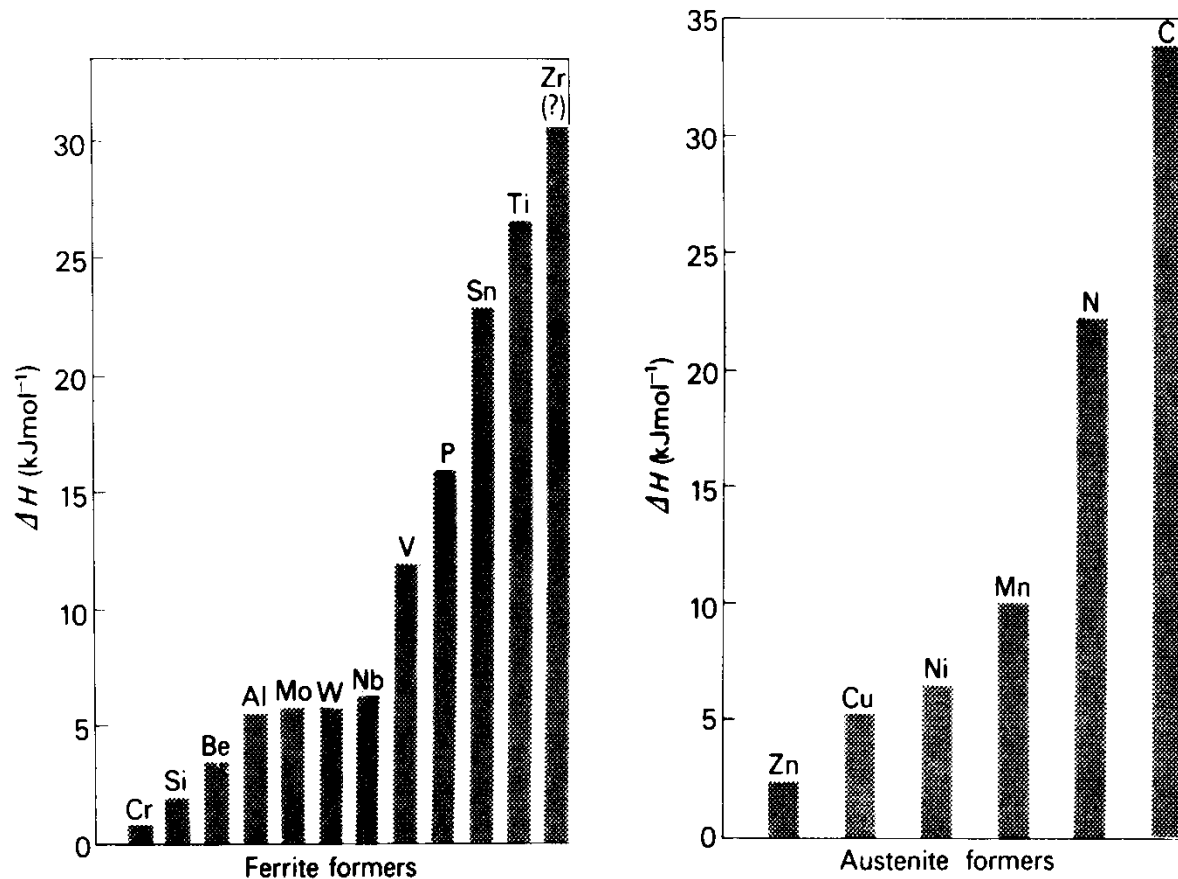


Unlegierter Stahl enthält neben Eisen stets Kohlenstoff, Silicium, Mangan, Phosphor und Schwefel als wichtigste Begleitelemente.

Bild 6.1–1 Verschiebung der Punkte *S* und *E* im System Fe-Fe₃C durch Legierungselemente

Physical Metallurgy

Ferrite Formers \rightarrow reduce γ -field: Zr, Ti, Sn, P, V, Nb, W, Mo, Al, Be, Si, Cr
Austenite Formers \rightarrow enlarge γ -field: C, N, Mn, Ni, Cu, Co, Zn



Ferrite- and Austenite Formers

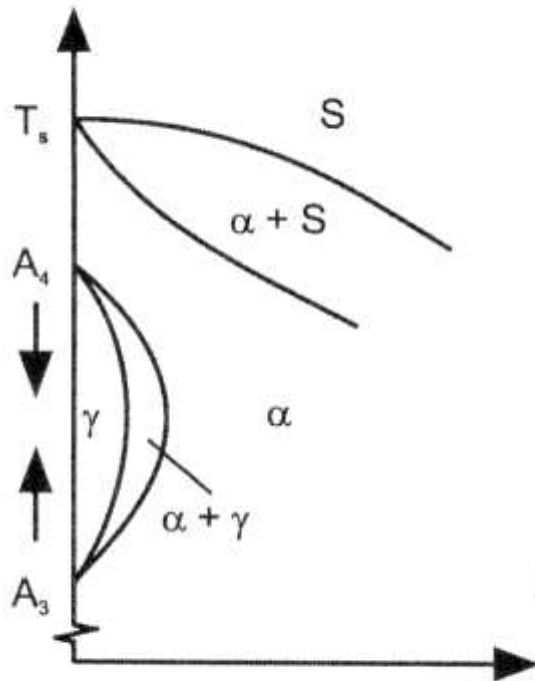


Abb. 6.17. α -stabilisierende Elemente: Cr, Mo, V, Si, Al, P, S, Sn, B

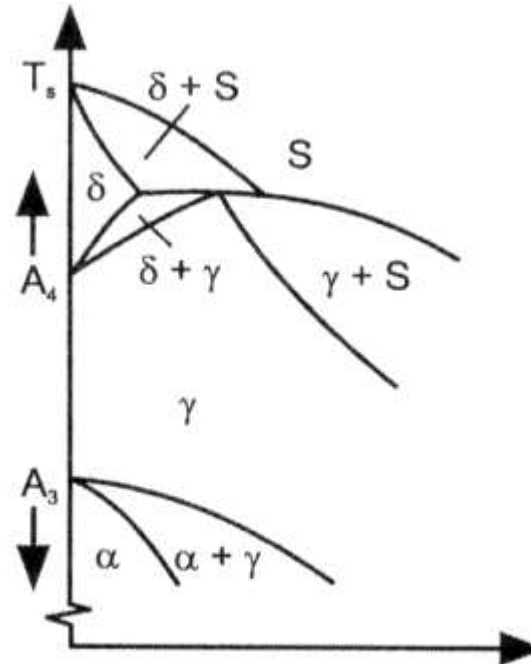


Abb. 6.18. γ -stabilisierende Elemente: C, Mn, Ni, Cu, N, Co, Zn

Ferrite and Austenite Formers

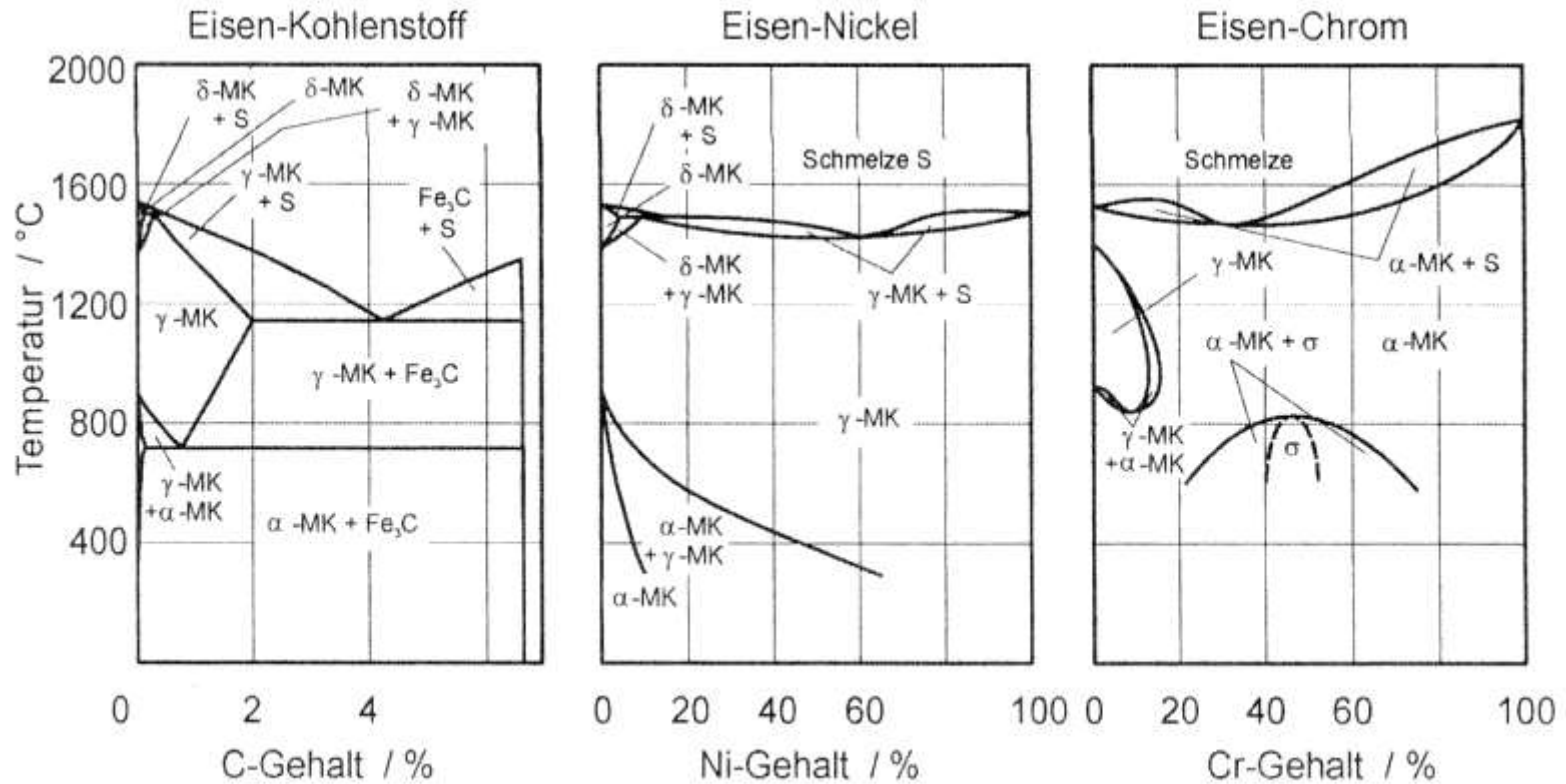
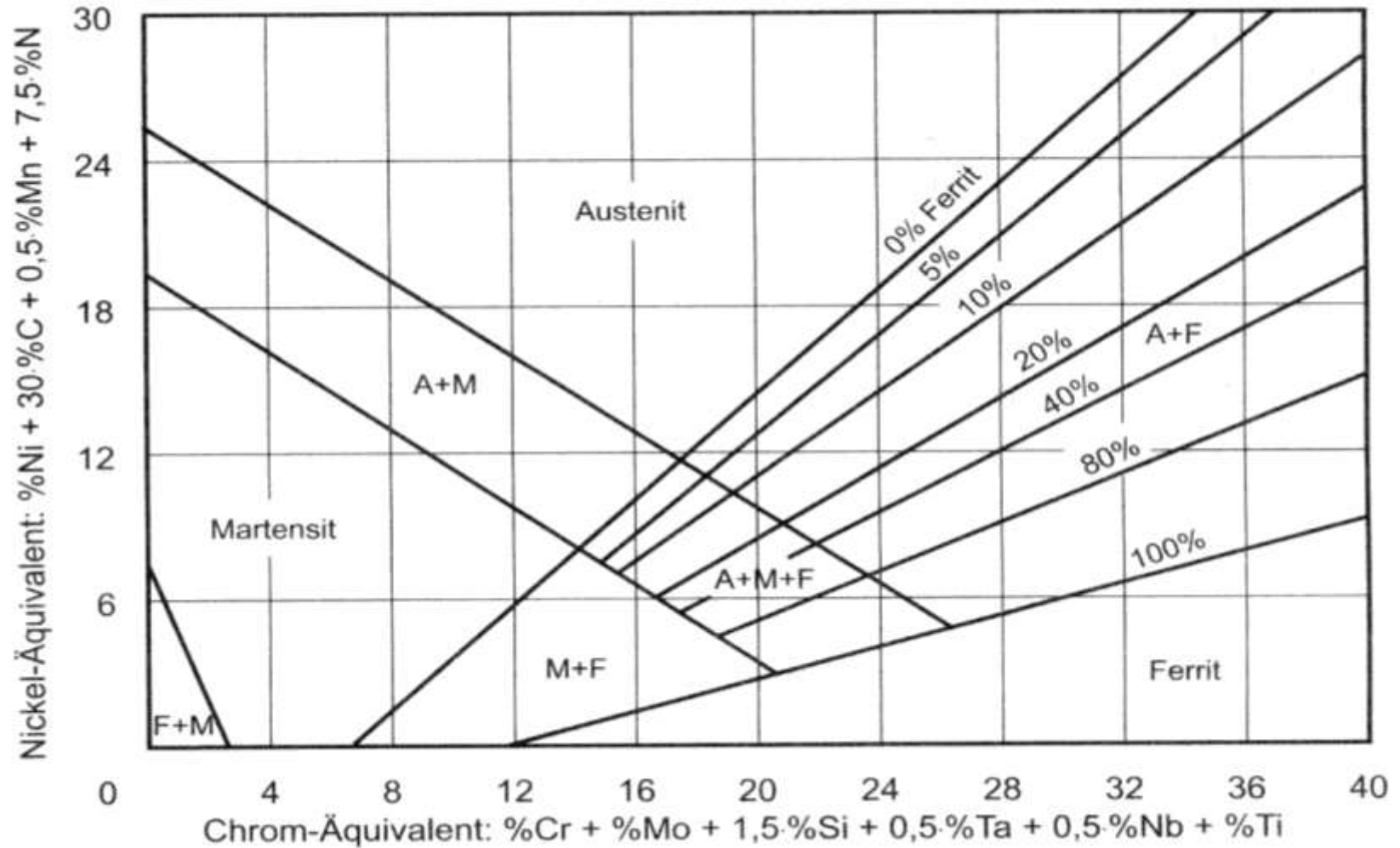


Abb. 6.19. Einfluss der Elemente Nickel und Chrom auf das Eisen-Kohlenstoff-Diagramm

Schaeffler Diagram



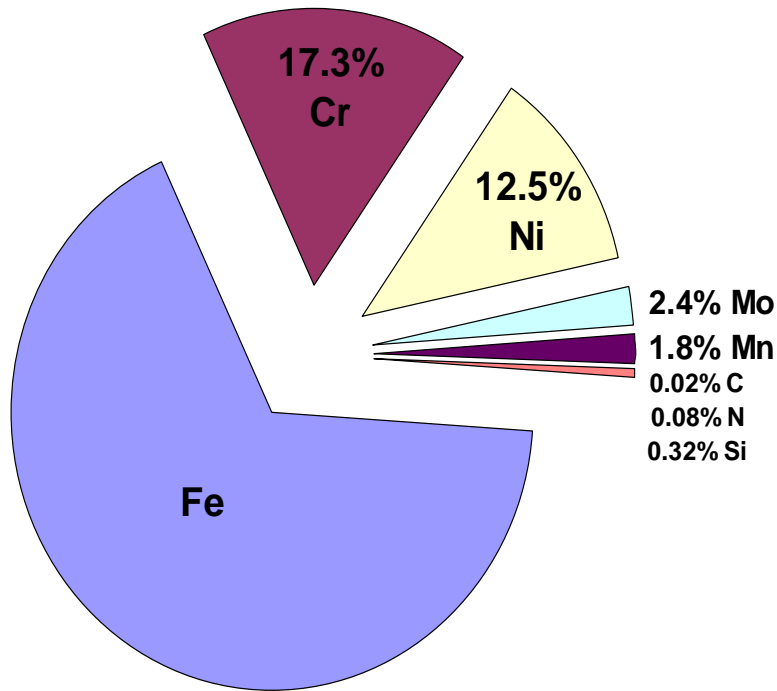


APPLICATIONS

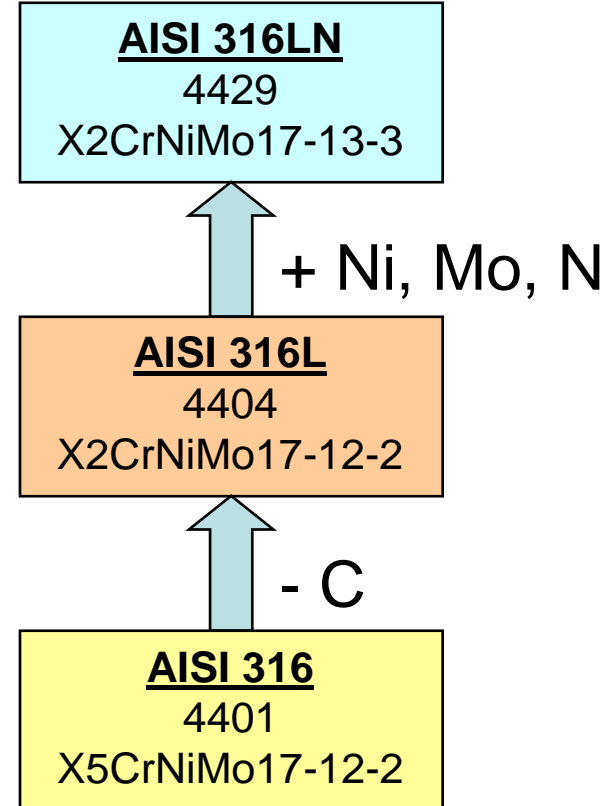
Fusion Materials

316 Stainless Steel

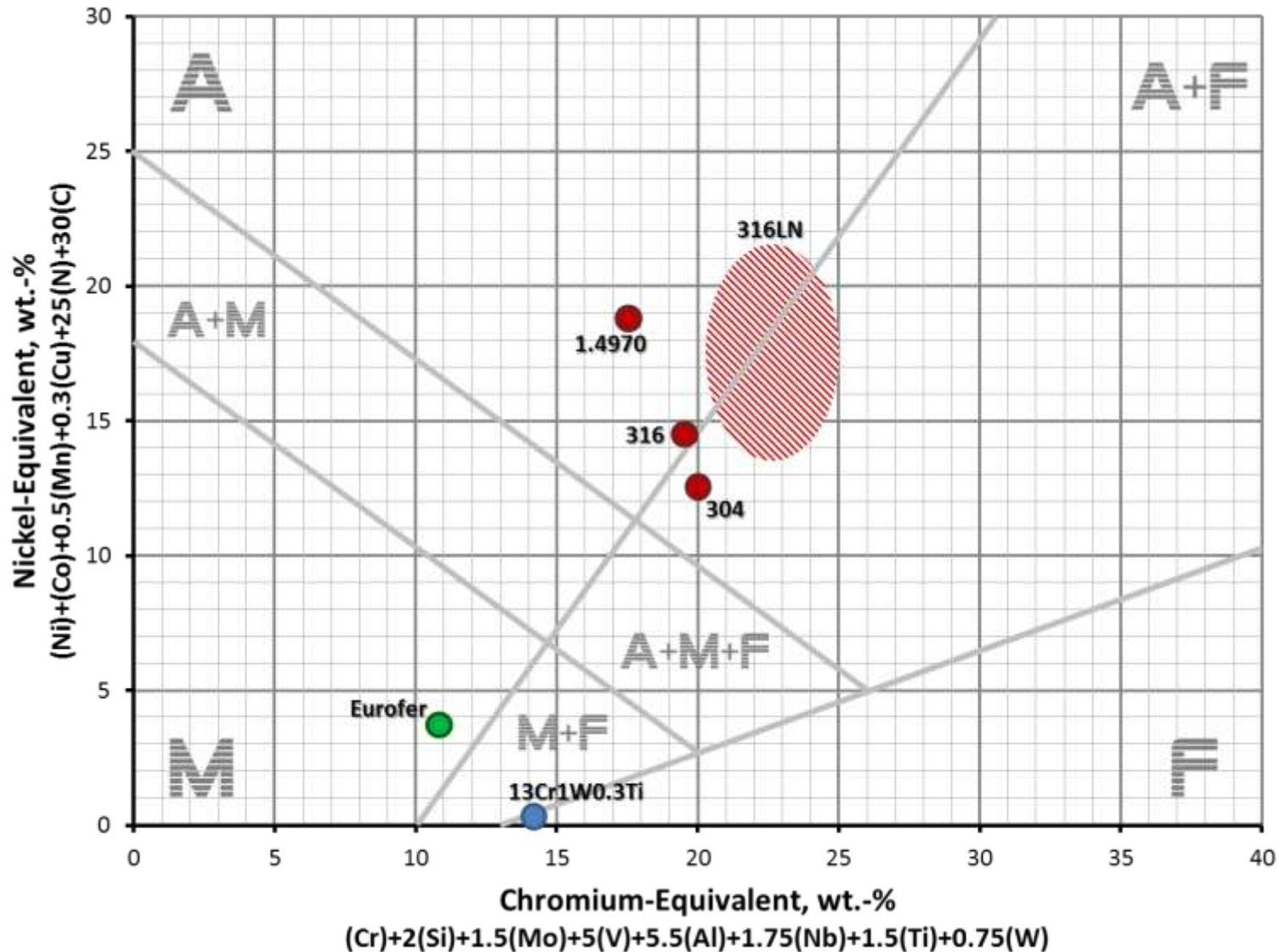
AISI 316L(N)
NIROSTA® 4429



Cr-Ni-Mo Steels: V4A-Series

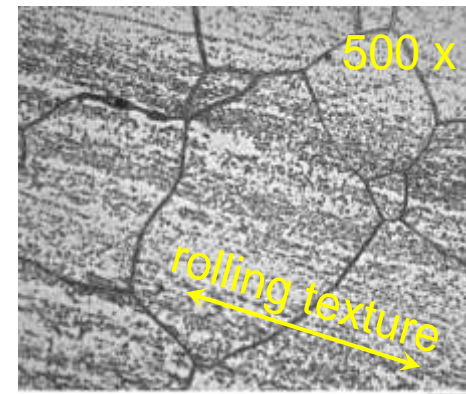
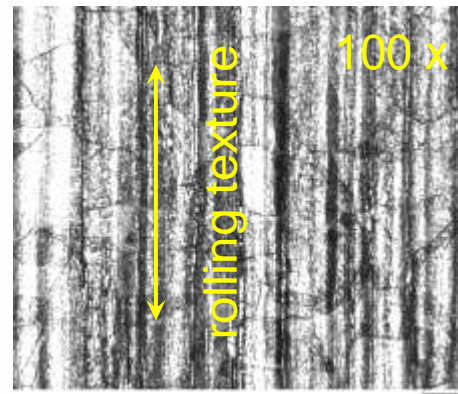
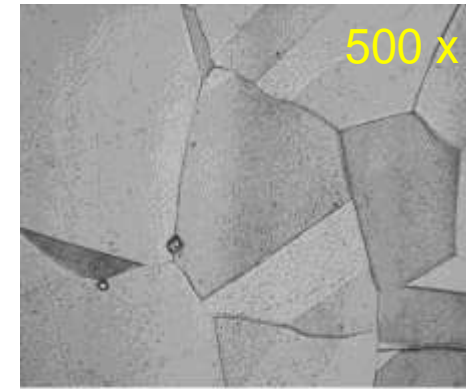
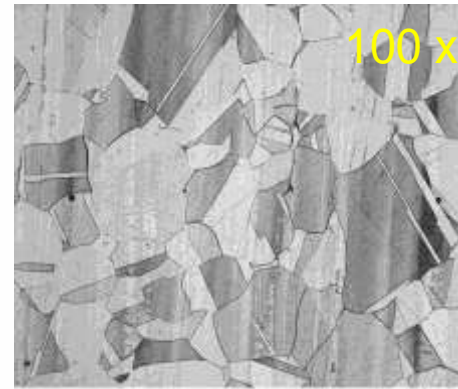


Overview: Steels for Nuclear Applications

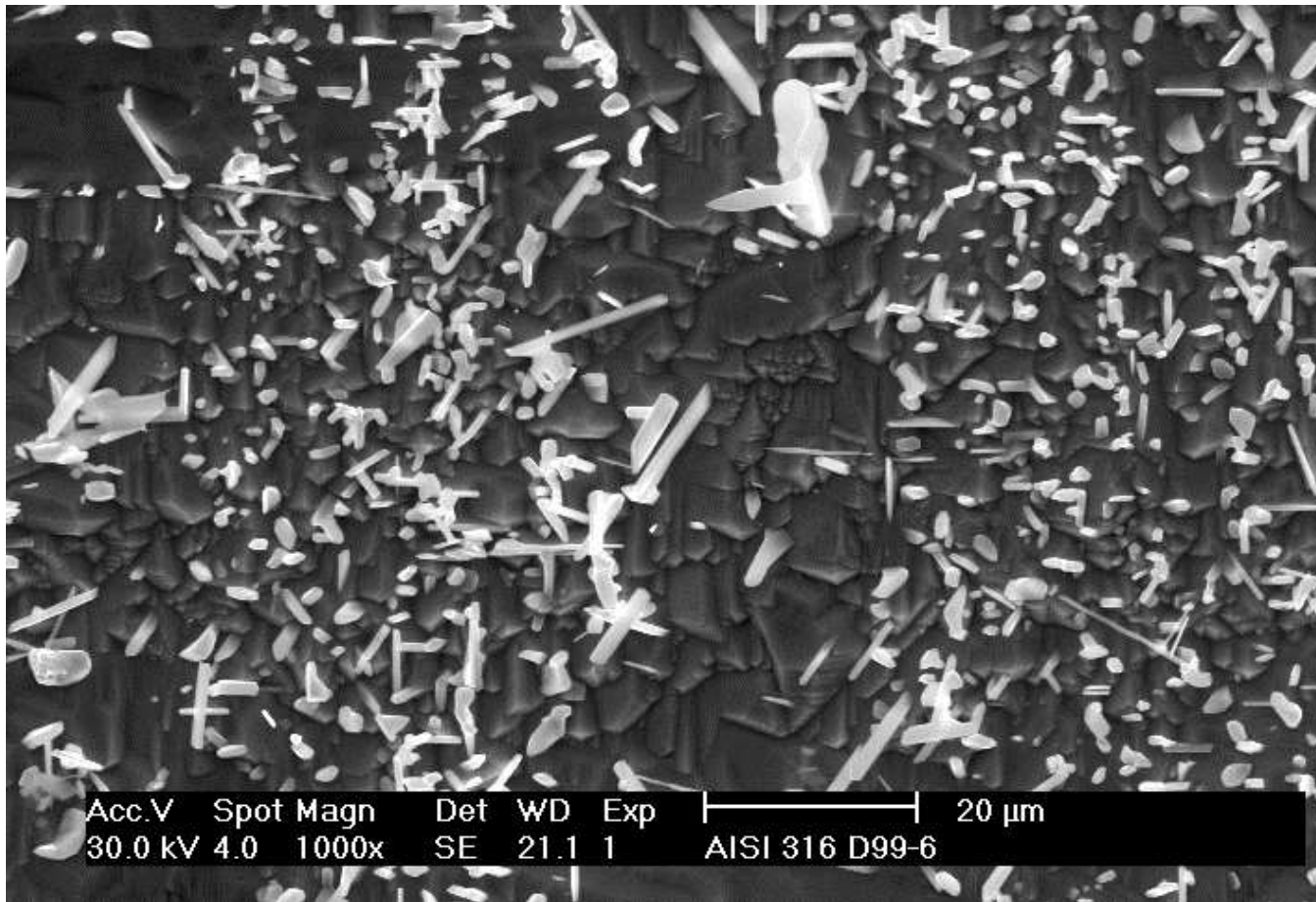


316 Stainless Steel

- austenitic steel
- fcc lattice
- corrosion resistant
- non-magnetic
- cost-effective
- strengthening only by cold work
- recrystallisation only after cold work
- grain size adjustable by heat treatment only by small amount
- operation temperature up to about 600°C
- No DBTT
- High thermal expansion
- Low thermal conductivity

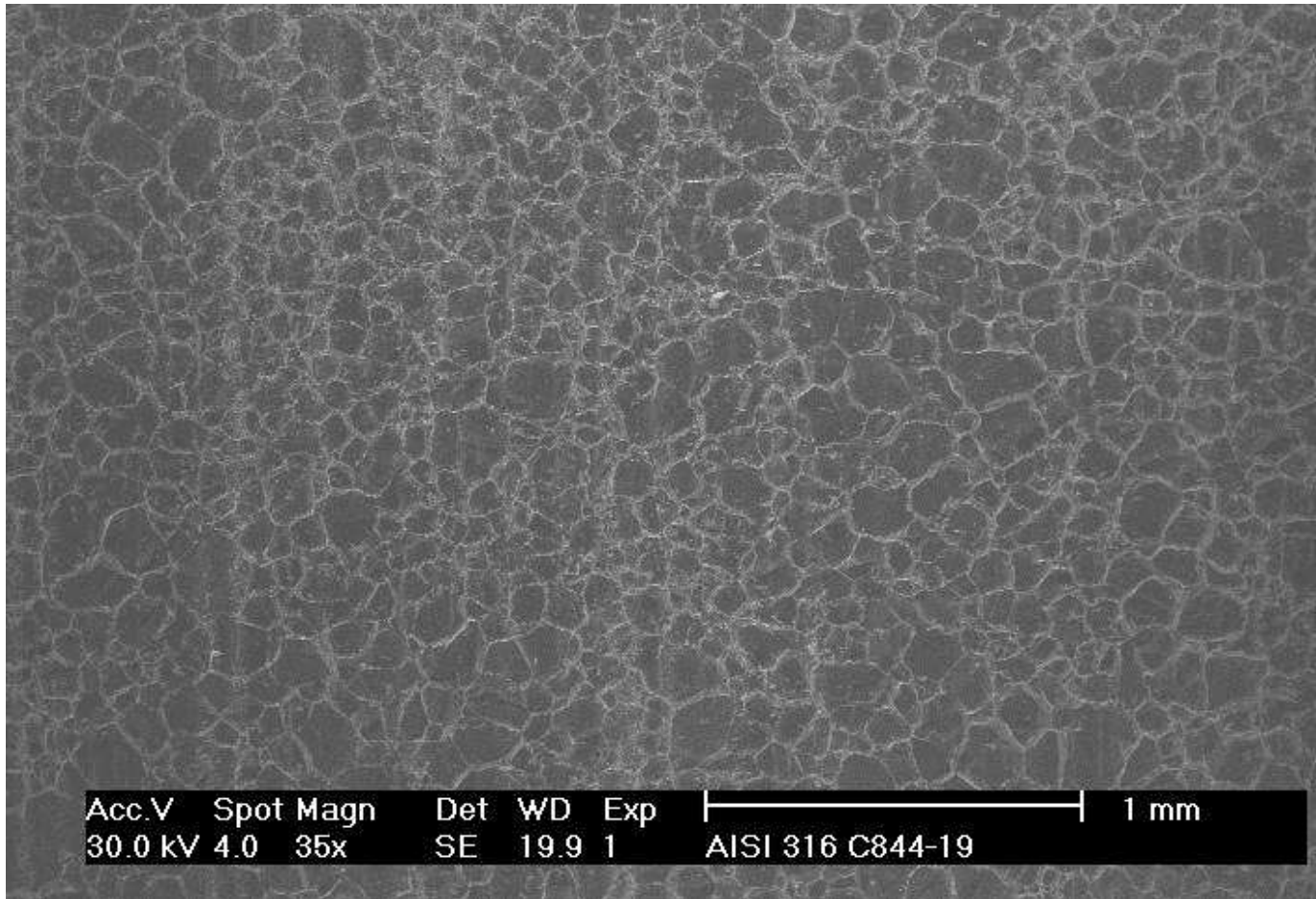


316 Steels are prone to thermal aging



Carbide (as well as sigma- and laves phase) formation in 316 steel (after 10 years at 600 °C).

316 Steels are prone to thermal aging



Carbide (as well as sigma and laves phase) formation in 316 steel at grain boundaries (after 10 years at 600 °C).

EUROFER , P91, P92, F82H, ...

9% CrWVTa Ferritic/Martensitic Steel with Reduced Activation

Basic composition of EUROFER

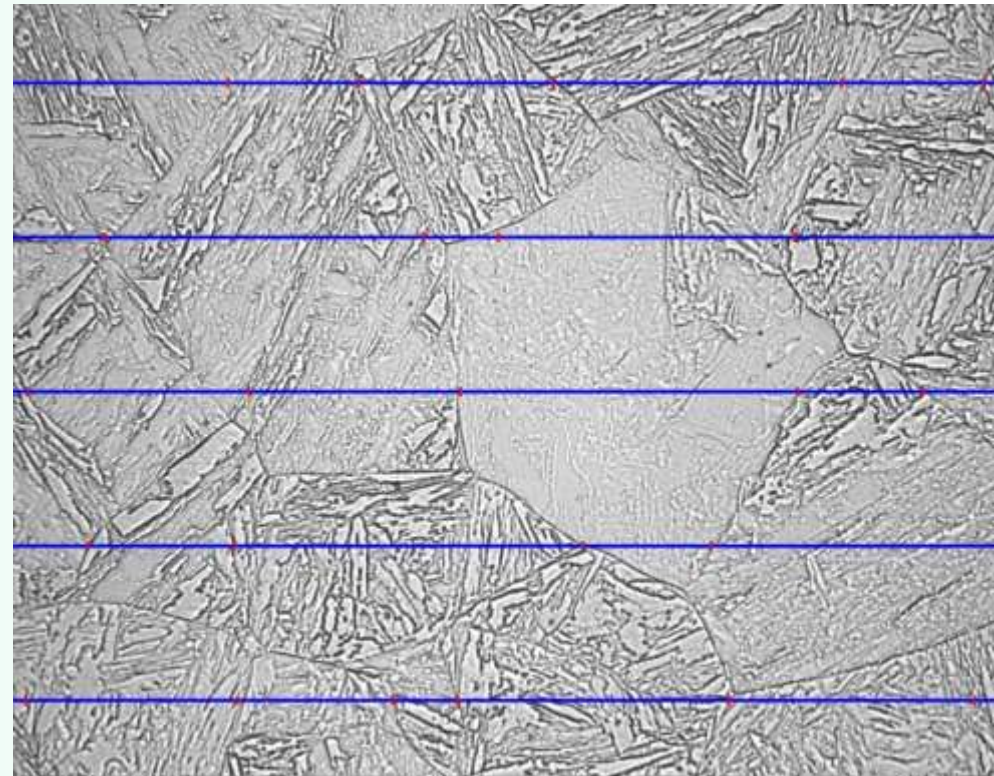
	Specification (wt.-%)	EUROFER 97 FZK-Analysis (wt.-%)
Cr	8,5-9,5	9,2
C	0,09-0,12	0,1
Mn	0,2-0,6	0,5
V	0,15-0,25	0,2
W	1,0-1,2	1,15
Ta	0,05-0,09	0,14
N	0,015-0,045	0,023
O	<0,01	<0,001
S	<0,005	0,004
Si	<0,05	0,043
Al	<0,01	0,0051
P	<0,005	<0,04
Cu	<0,005	0,0035

All values in wt.%

Nb, Mo, Ni, Cu, Al, Co restricted to ppm-values

EUROFER

- martensitic steel
- bcc lattice
- magnetic
- low activation
- aging resistant
- microstructure can be controlled by heat treatment (annealing and quenching)
- hardness can be controlled by heat treatment (tempering)
- operation temperature up to about 550 °C



ASTM-Korngröße: 6,6
Mittlere Sehnenlänge: 32 μm
Mittlerer Korndurchmesser: 39 μm

20 μm

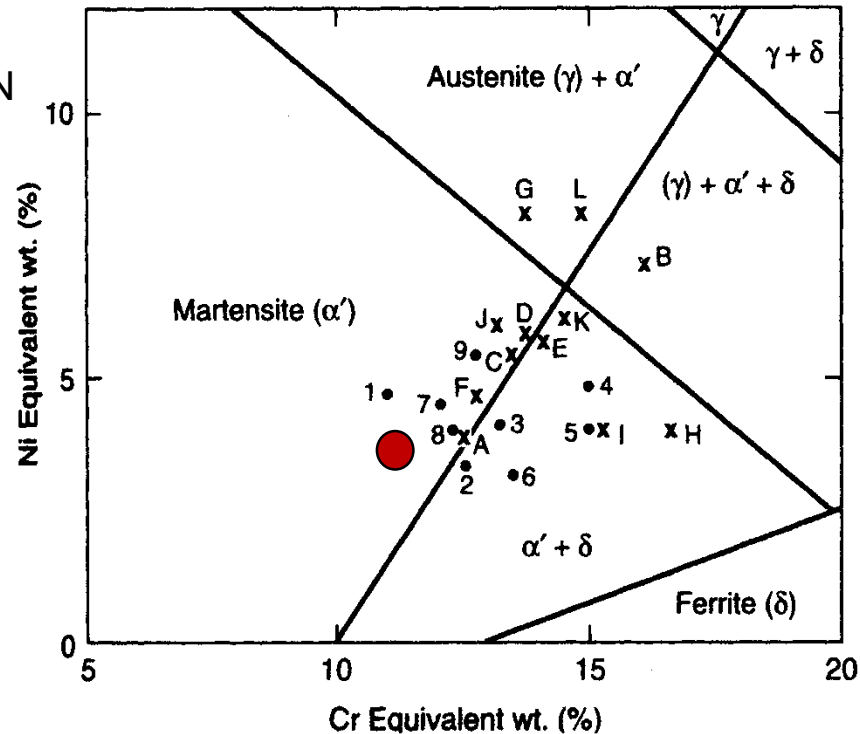
Physical Metallurgy

Ni equivalent (wt%) =
 $Ni + Co + 0.5 Mn + 0.3 Cu + 30 C + 25 N$
(Eurofer: $0.25 + 3 + 0.5 = 3.75$)

Cr equivalent (wt%) =
 $Cr + 2 Si + 1.5 Mo + 5 V + 1.75 Nb + 0.75 W + 1.5 Ti + 5.5 Al + 1.2 Ta + 1.2 Hf + 1 Ce + 0.8 Zr + 1.2 Ge$
(Eurofer: $9.2 + 1 + 0.8 + 0.2 = 11.2$)

Rule for avoiding δ -ferrite by
Cr equivalent (wt%) = $Cr + 6 Si + 4 Mo + 11 V + 5 Nb + 1.5 W + 8 Ti + 12 Al - 4 Ni - 2 Co - 2 Mn - Cu - 40 C - 30 N$
 < 9

(Eurofer: $9.2 + 2.2 + 1.7 - 1 - 4 - 0.7 = 7.4$)



9% Cr Steels (●)

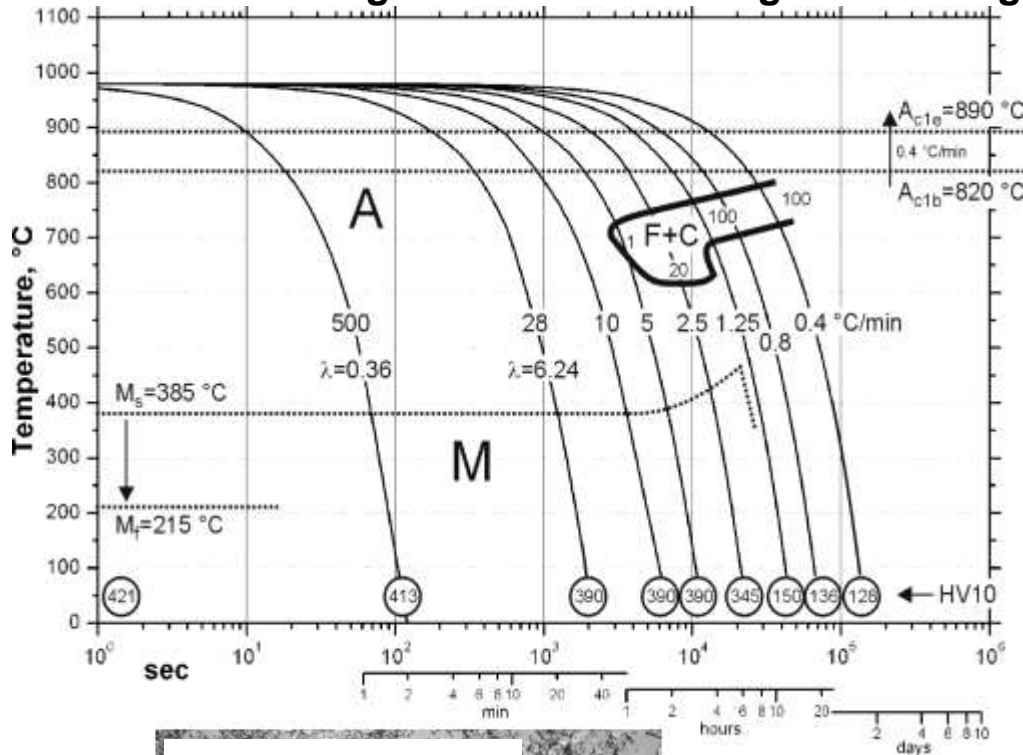
1. EM10
2. HCM9M
3. NSCR9
4. EM12
5. JFMS
6. TEMPALOY F-9
7. T91
8. TB9 (NF616)
9. E911

12% Cr Steels (x)

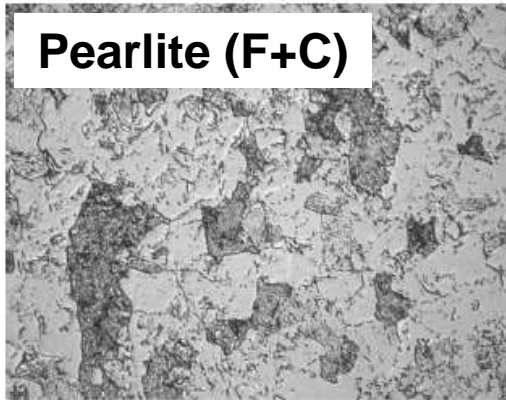
- | | |
|-------------|-----------|
| A. FI | G. GE |
| B. HT9 | H. HCM12 |
| C. FV448 | I. TB12 |
| D. 1.4914 | J. TR1150 |
| E. MANET I | K. HCM12A |
| F. MANET II | L. HR1200 |

Structure & Transformation

Transition during Continuous Cooling and Heating



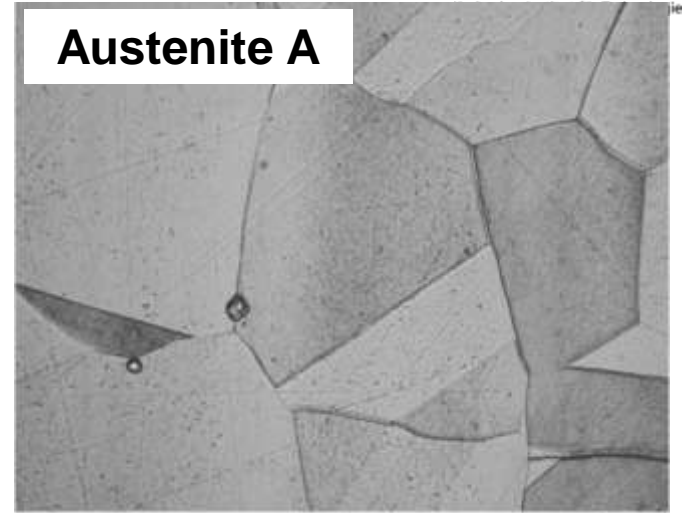
Pearlite (F+C)



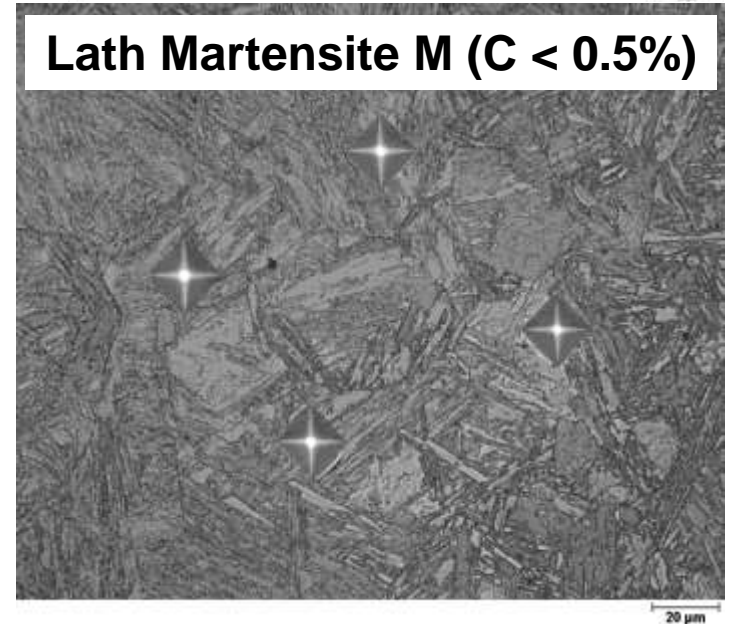
0601A00117

50 μ m

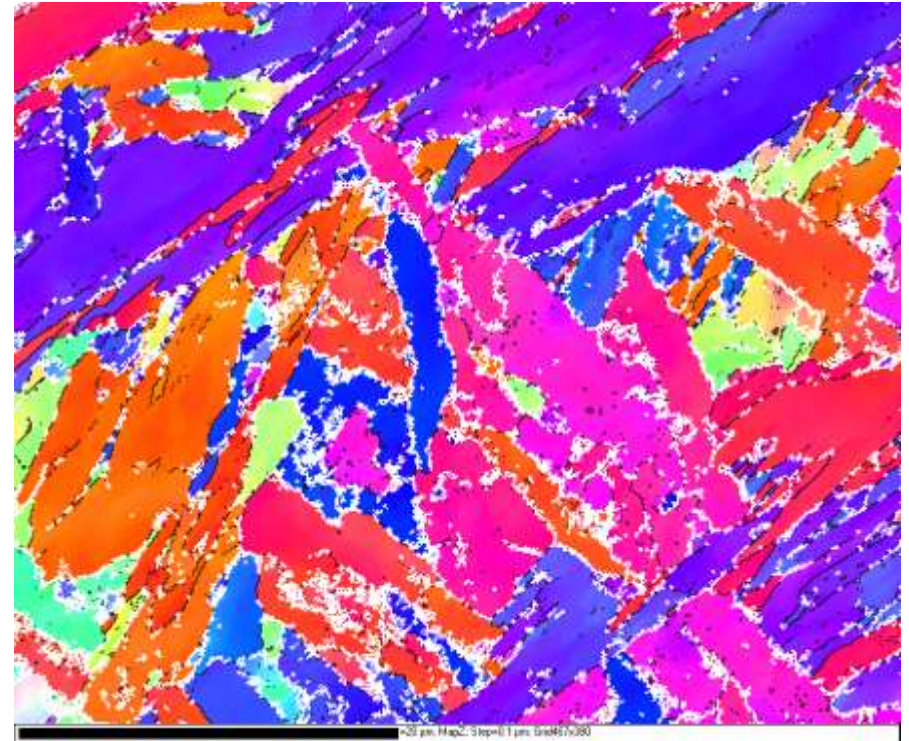
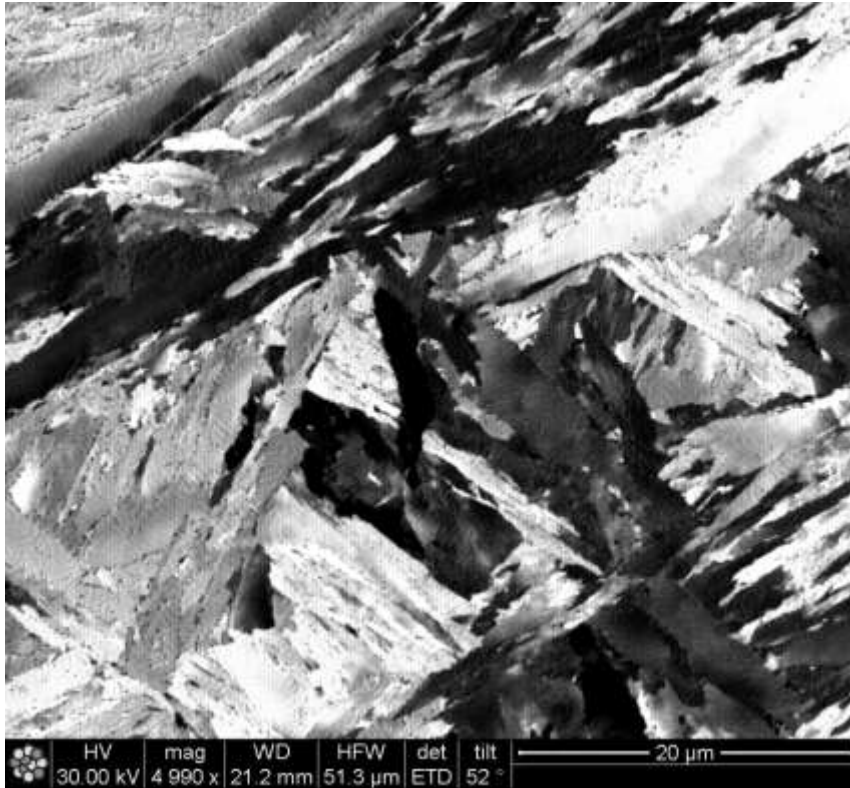
Austenite A



Lath Martensite M (C < 0.5%)



EUROFER: Martensite Microstructure



Structure & Transformation

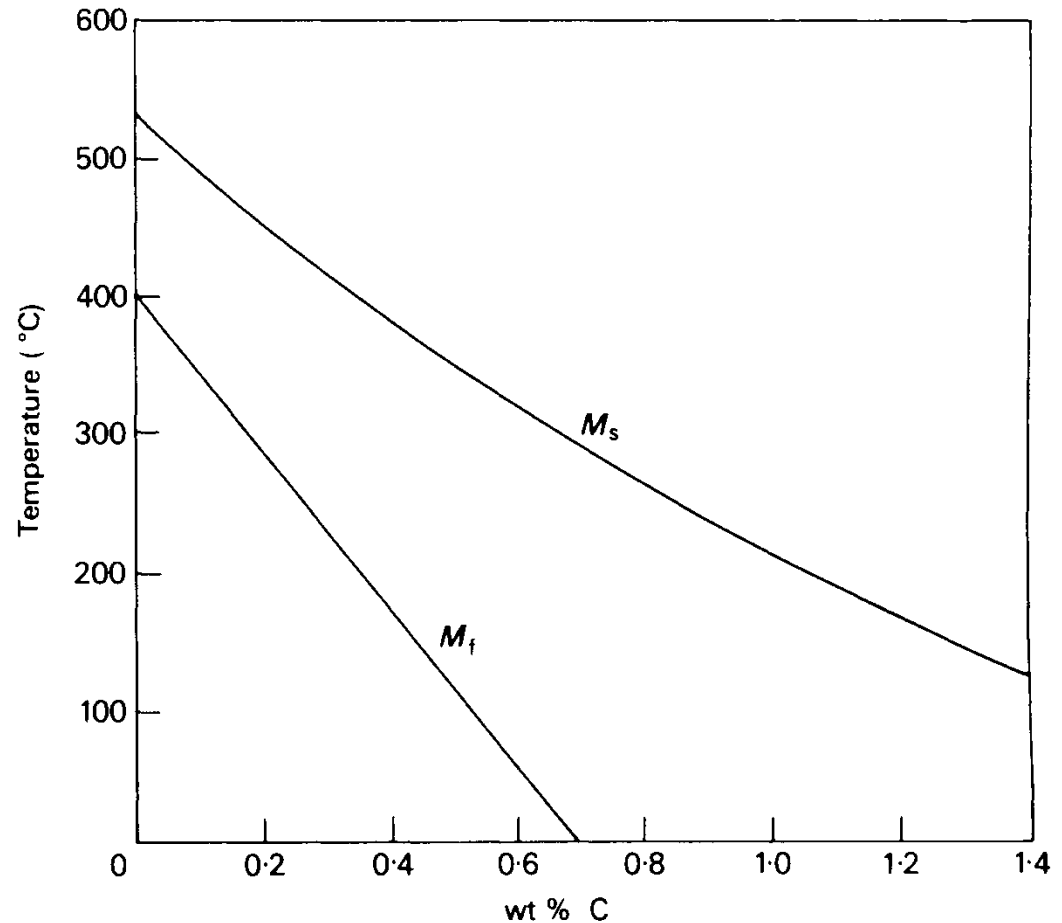
Effect on M_s Temperature

$$M_s (\text{°C}) = 635 - 474 [C + 0.86 N - 0.15 (Nb + Zr) - 0.066 (Ta + Hf)] - [17 Cr + 33 Mn + 21 Mo + 17 Ni + 39 V + 11 W]$$

(Eurofer: $635 - 474[0.1+0.02-0.1] - [155+17+8+12]=635-9.5-192=433$)

Effect on A_{C1} Temperature (change per wt%)

Ni	-30
Mn	-25
Co	-5
Si	+25
Mo	+25
Al	+30
V	+50



Structure & Transformation

Solubility of C and N in wt%

C in γ -iron	1150°C	2.04
	723°C	0.80
C in α -iron	723°C	0.02
	20°C	$<5 \times 10^{-5}$
N in γ -iron	650°C	2.8
	590°C	2.35
N in α -iron	590°C	0.10
	20°C	$<10^{-4}$

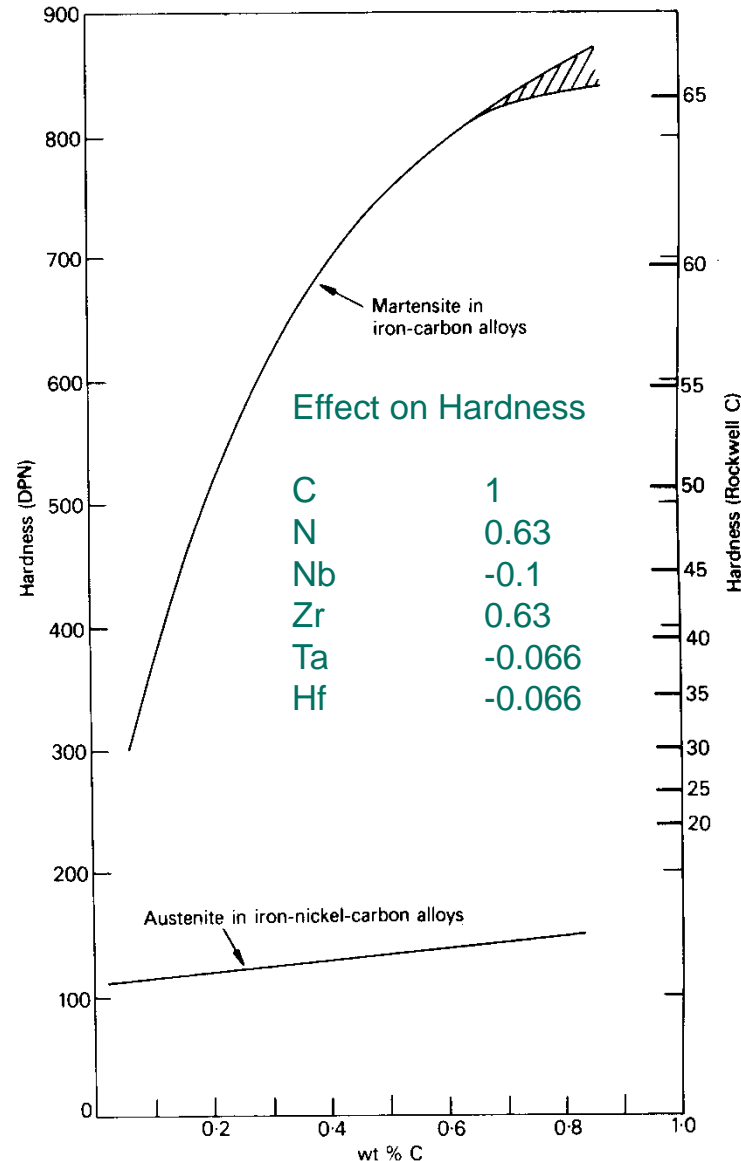
Excess C and N is precipitated

Strong Carbide Formers: Hf, Zr, Ti
 Medium Carbide Formers: Ta, Nb, V
 Low Carbide Formers: W, Mo, Cr

Stronger Nitride Formers: Hf, Zr, Ti, B
 Strong Nitride Formers: Ta, Nb, V, Al

Ni, Co, P, Si do NOT form Carbides.
 They are in solution with the ferrite phase only.

Mn does also not form Carbides, but is in solid solution only in Fe_3C .



Types of Heat-Treatments

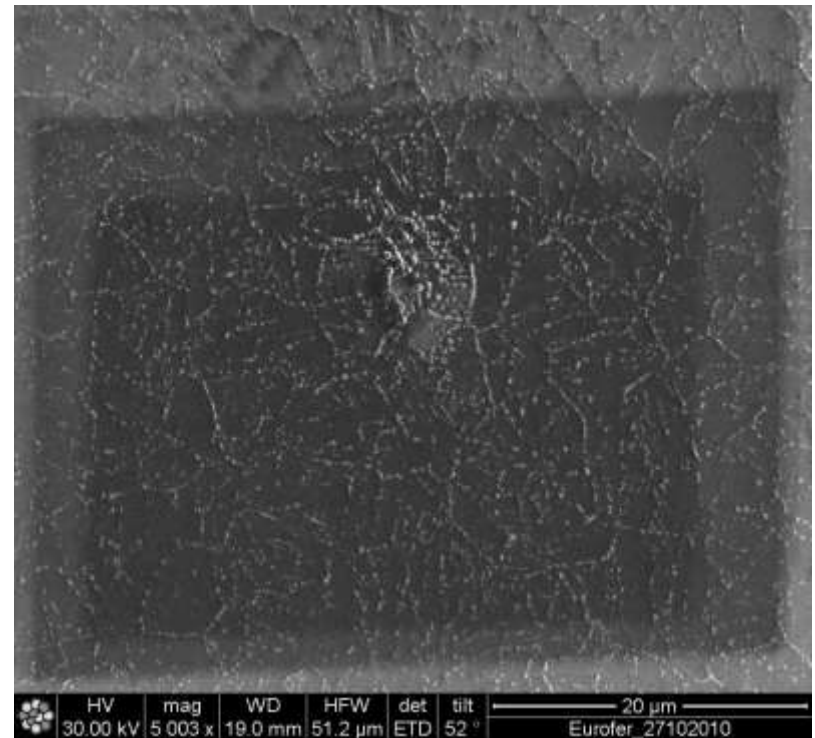
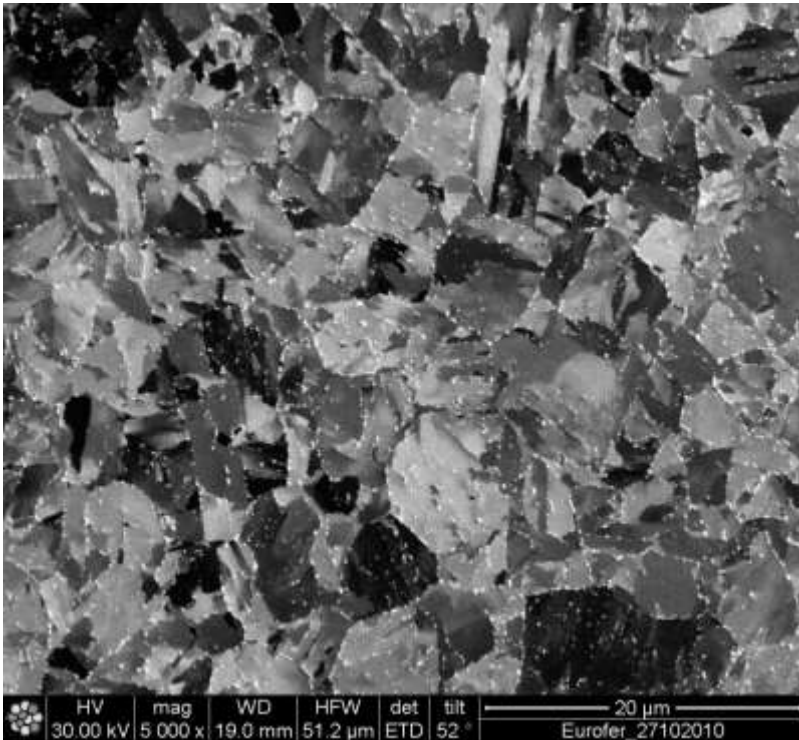
- Austenitization, Hardening, Solution Treatment, or Annealing: $T > A_{c1e}$ (typically $T > 900\text{ °C}$)
- Tempering: typically $650\text{ °C} < T < 800\text{ °C}$
- Stress Relieving: typically $T < 400\text{ °C}$

Influence on Microstructure

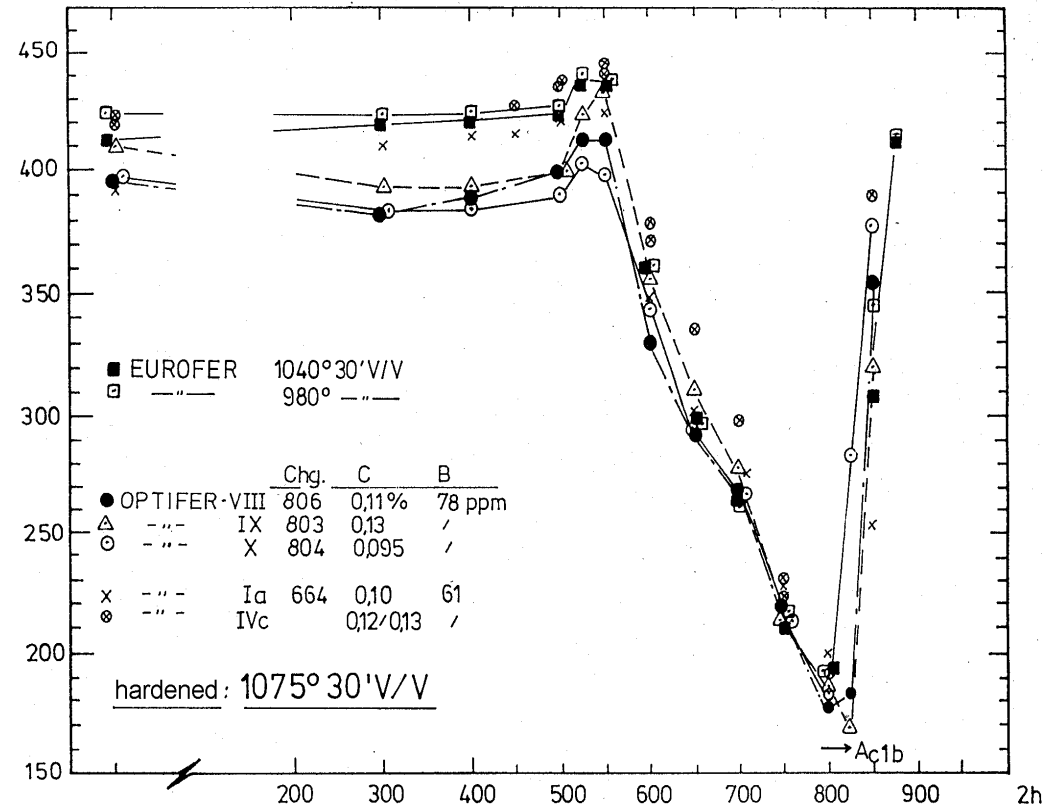
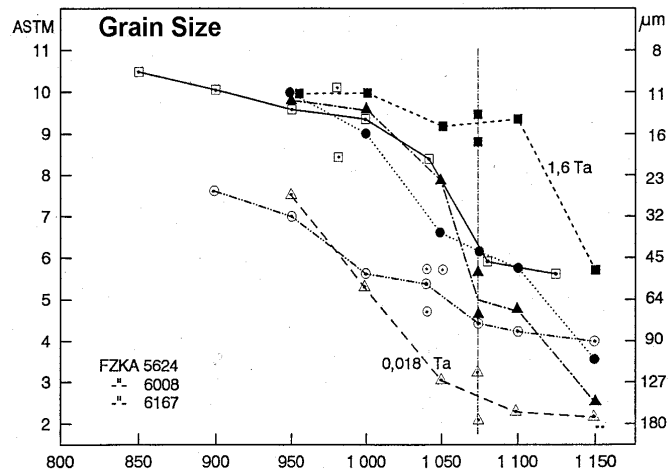
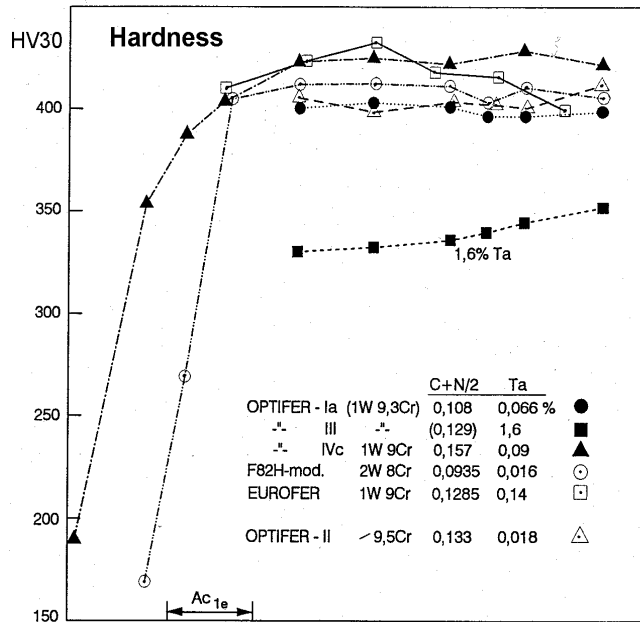
Austenitization → Austenite grain size depends on temperature, BUT NOT on annealing time

Tempering → Degree of precipitations depends on temperature AND on tempering time. Due to tempering, a bcc lattice is restored since carbon precipitates at grain and lath boundaries.

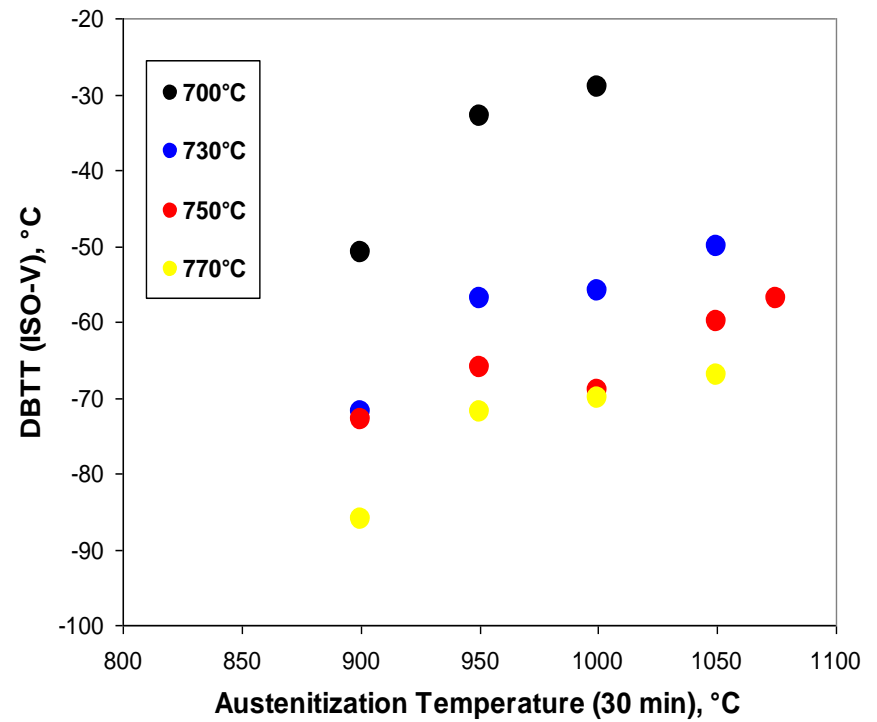
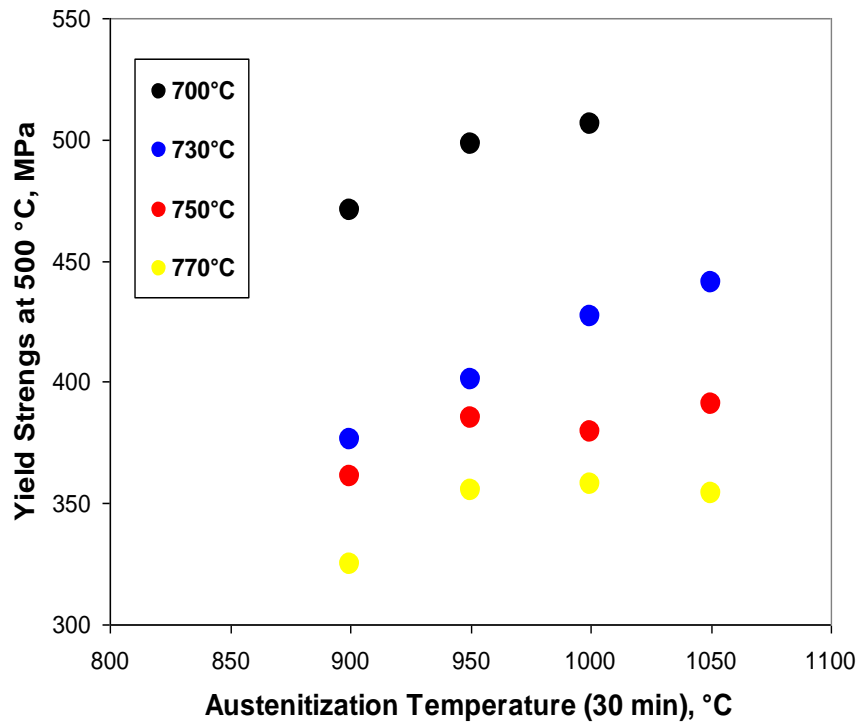
EUROFER: Carbide Formation



Influence on Mechanical Properties



Influence on Mechanical Properties

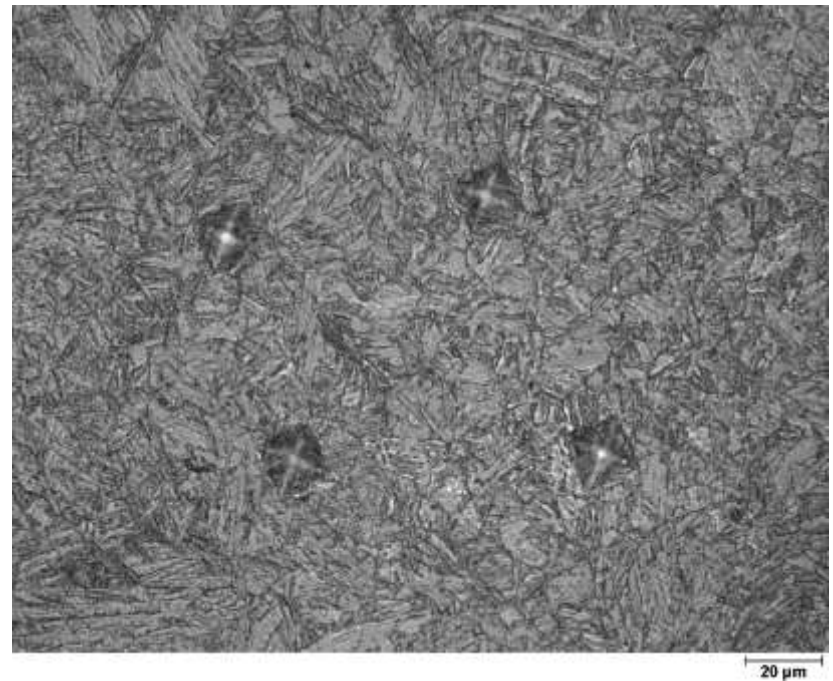


Ctrl + Alt + Del (Strg + Alt + Entf) or Reset

1.: 1050 °C/30 min + 780 °C/2 h



2.: 1050 °C/30 min + 780 °C/2 h



Annealing restores the microstructure completely!