EPFL

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MSE-422 – Advanced Metallurgy

4-Advanced steels

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Outline

- Fundamentals of steel metallurgy
- Overview of some selected high-performance steel classes
  - Stainless steels
  - Advanced high strength steels (AHSS)/TRIP/TWIP steels
  - Steels for elevated temperature applications

- Fundamentals of steel metallurgy
- Overview of some selected high-performance steel classes
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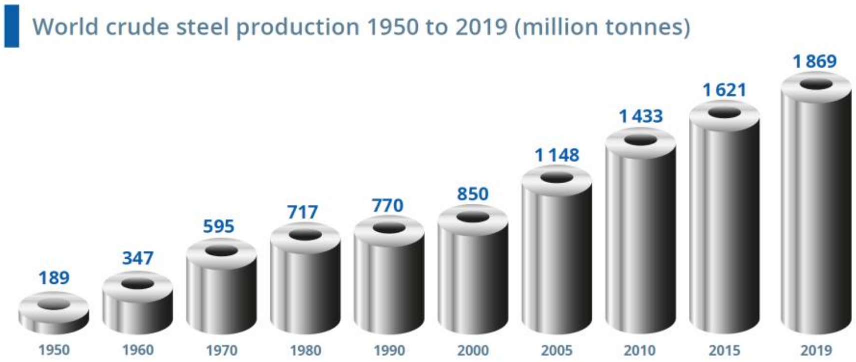
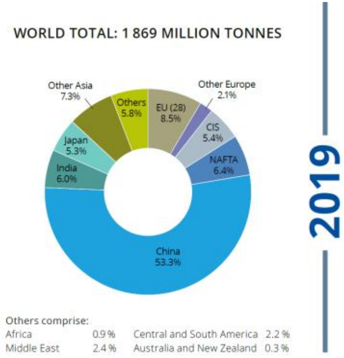
  - Steels for elevated temperature applications

Importance of steels – some facts

- Steels are the most widely used metallic materials in the world (world crude steel production 2019: 1.87 x 10^9 t)
- Steel = Fe + C (<2 wt.%) (+ other alloying elements)
- The first industrial process that allowed converting cast iron into steel was invented in the UK in 1850 (H. Bessemer)
- Alloying with various elements in combination with thermal or thermo-mechanical treatments allows varying the properties of steel in a very wide range





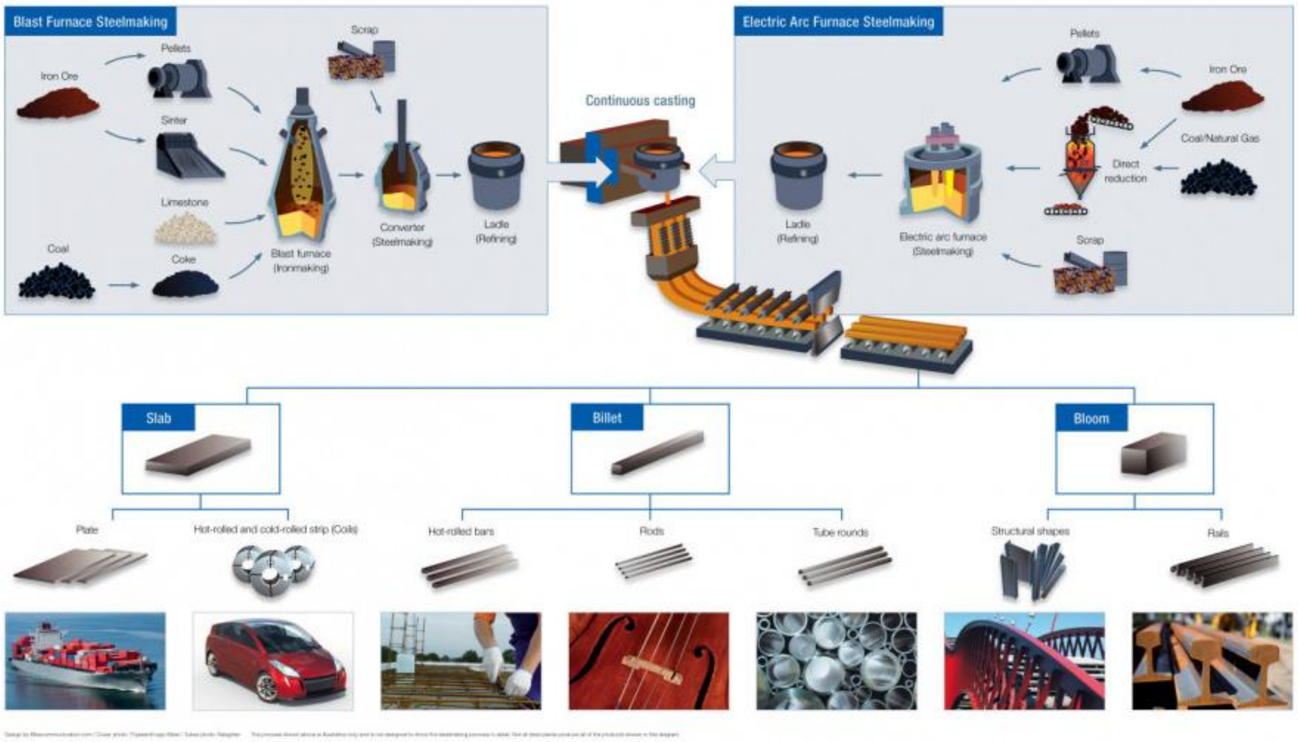
/www.worldsteel.org/

Importance of steels – some facts

- There are more than 3’500 different grades of steel with many different physical, chemical, and environmental properties
- Approximately 90% of all steels are carbon steels (Fe+C), most of them are used in construction
- Approximately 75% of the modern steels have been developed in the past 25 years
- Steel can be easily recycled; new steel products contain 37% recycled steel on average
- Globally, more than 6 million people work directly in the steel industry and >49 million people indirectly

/www.worldsteel.org/

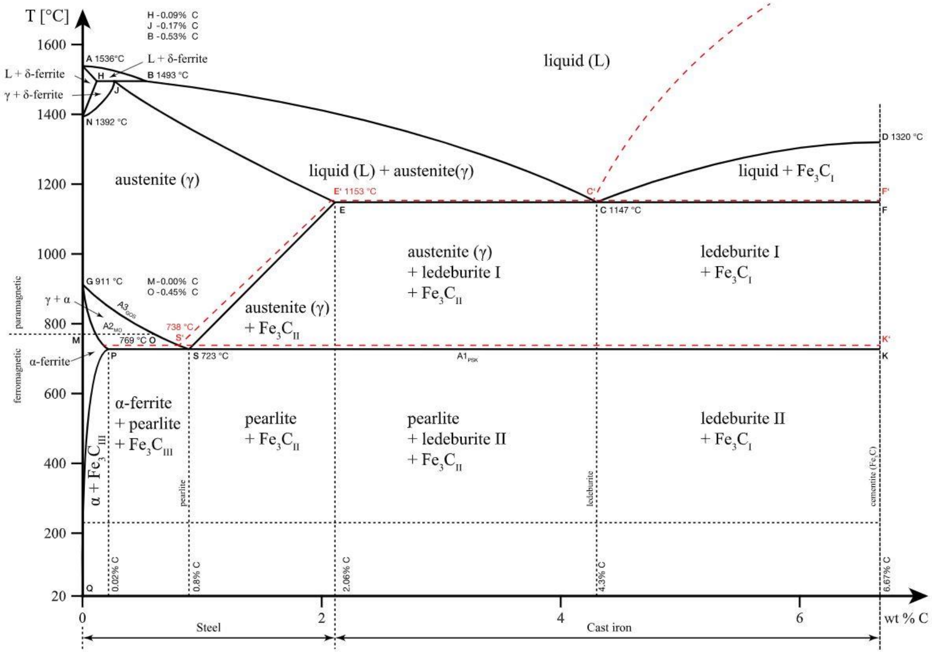
Overview of the steelmaking processs



/www.worldsteel.org/

The Fe-C diagram

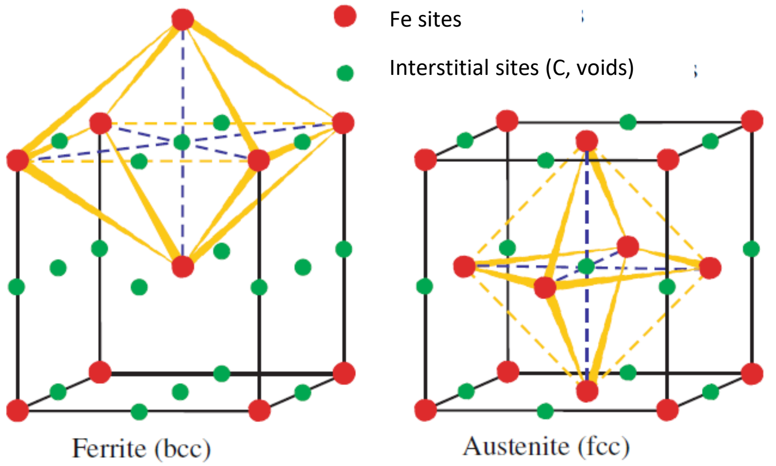
- <2.06 wt.% C: steel, >2.06 wt.% C: cast iron
- The main phases are
  - α-ferrite (bcc)
  - γ-austenite (fcc)
  - δ-ferrite (bcc)
  - Fe_3C-cementite (primary, secondary , tertiary)
- Other constituents
  - Pearlite = eutectoid α + Fe_3C
  - Ledeburite I = eutectic γ + Fe_3C
  - Ledeburite II = pearlite + Fe_3C
- Metastable phases/constituents
  - α'-martensite (bct)
  - Bainite = α + Fe_3C (similar to Pearlite but different morphologies and compositions)



Phases in steel

- α-ferrite
  - Body-centered cubic
  - Brittle-to-ductile transition
  - Stacking fault energy: 300 mJ/m^2
  - Ferromagnetic at RT

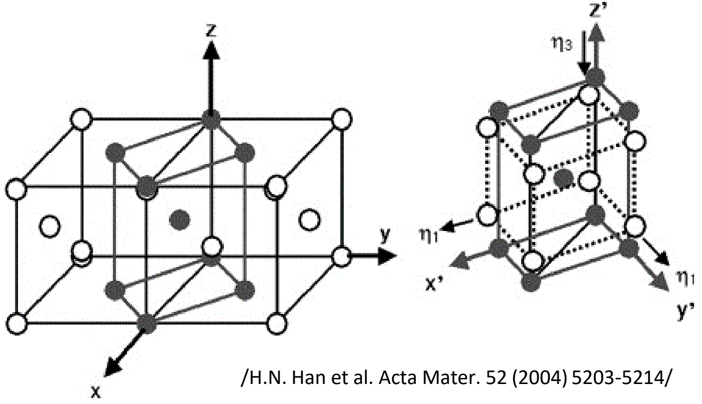
- γ-austenite
  - Face-centered cubic
  - No brittle-to-ductile transition
  - Stacking fault energy: <50 mJ/m^2
  - Diffusion coefficients only about 1/350 of that in α-ferrite
  - Paramagnetic



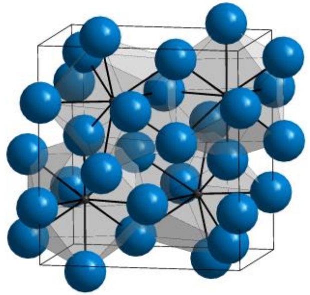
/R. Rana (ed.) High performance ferrous alloys, 2020/

Phases in steel

- α'-martensite
  - Body-centered tetragonal
  - Hard and brittle
  - Forms upon rapid cooling from austentite (exceeding critical cooling rate)
  - Meta-stable; decomposes after heat treatment
- Fe_3C-cementite
  - Orthorhombic
  - Hard and brittle
  - Ferromagnetic at RT
- δ-ferrite
  - Body-centered cubic
  - High temperature phase



/H.N. Han et al. Acta Mater. 52 (2004) 5203-5214/



Fe_3C
Fe – blue
C - black

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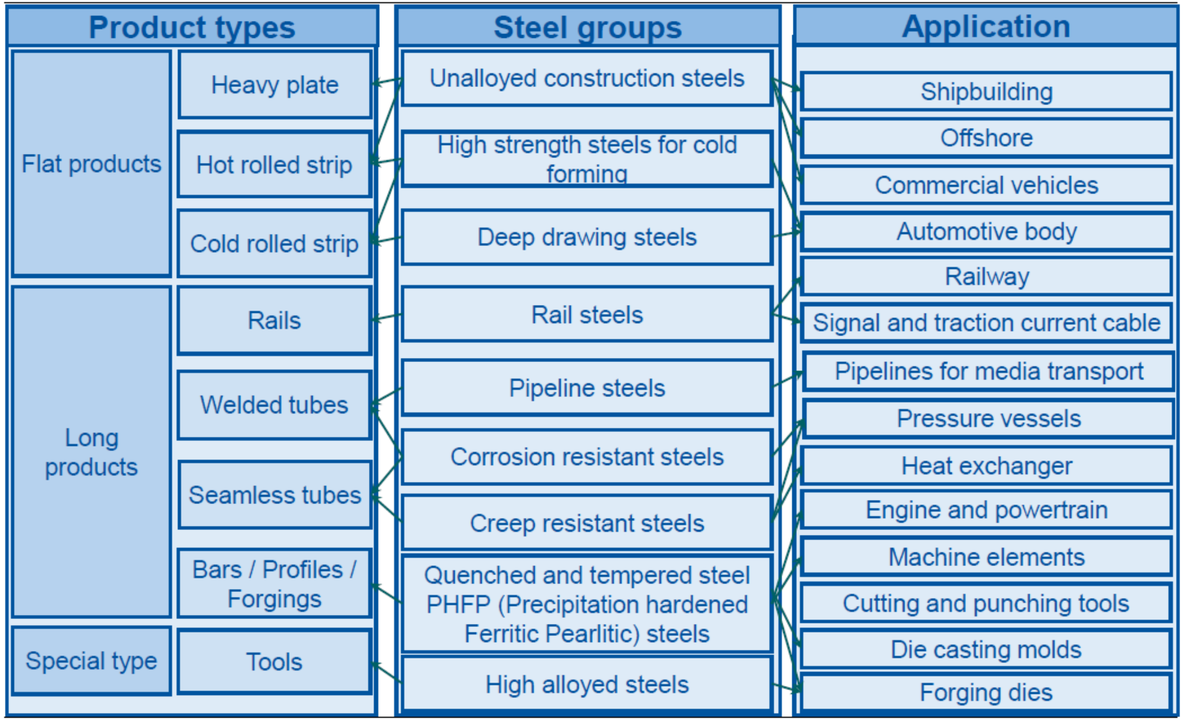
Classification of steels – steel groups

- *Carbon Steels* only contain trace amounts of elements besides carbon and iron. This group is the most common, accounting for 90% of steel production.
  - Low Carbon Steels/Mild Steels (up to 0.3% carbon),
  - Medium Carbon Steels (0.3–0.6% carbon),
  - High Carbon Steels (more than 0.6% carbon).
- *Alloy Steels* contain alloying elements like Ni, Cr, Cu, V, Mn, Al etc. These additional elements are used to influence the metal's strength, ductility, corrosion resistance, and machinability
  - Low Alloy Steels (∑ alloying elements <4 wt.%)
  - High Alloy Steels (∑ alloying elements >4 wt.%)
- *Stainless Steels* contain 10–20% chromium as their alloying element and are valued for their high corrosion resistance.
- *Tool Steels* make excellent cutting and drilling equipment as they contain tungsten, molybdenum, cobalt, and vanadium to increase heat resistance and durability.

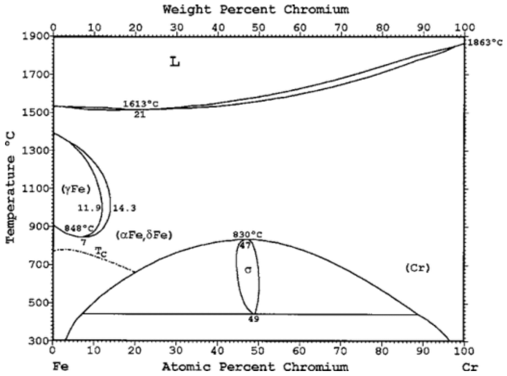
Classification of steels – product types

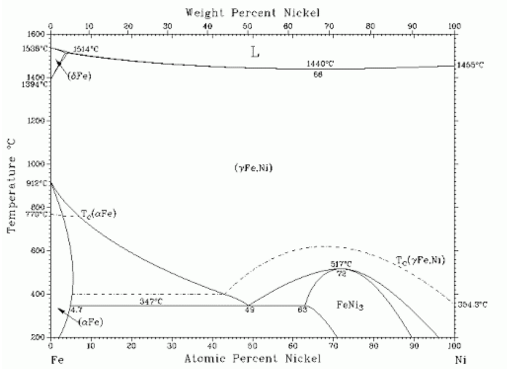


/Courtesy Prof. W. Bleck, course material "Steel Design, RWTH Aachen/

Alloying elements in steel – Cr and Ni

- To major alloying elements in steel are Cr and Ni
- Chromium (up to 30 wt.%)
  - Stabilizes α-ferrite
  - Forms carbides (→ particle strengthening)
  - Forms an oxide layer at >9 wt.% Cr (→ corrosion protection)
  - Reduces critical cooling rate for martensite formation
  - At higher contents formation of σ-phase (brittle)
- Nickel (up to 35 wt.%)
  - Stabilizes γ-austenite
  - Forms Ni_3M intermetallics (→ particle strengthening)



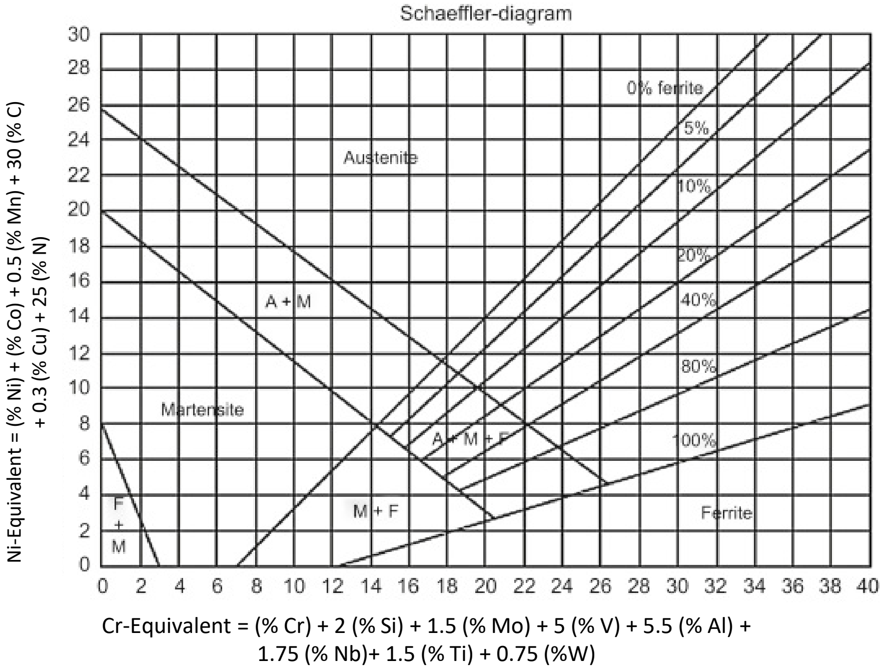


Alloying elements in steel

- Alloying elements in steel are distinguished between
  - Ferrite stabilizers: Cr, Si, Mo, V, Al, Nb, Ti, W
  - Austenite stabilizers: Ni, Co, Mn, Cu, C, N
- Ferrite stabilizing elements are summarized corresponding to an equivalent amount of Cr according their potency to stabilize ferrite
  - Cr-Equivalent = (% Cr) + 2 (% Si) + 1.5 (% Mo) + 5 (% V) + 5.5 (% Al) + 1.75 (% Nb)+ 1.5 (% Ti) + 0.75 (%W)
- Austenite stabilizing elements are summarized corresponding to an equivalent amount of Ni according their potency to stabilize austenite
  - Ni-Equivalent = (% Ni) + (% Co) + 0.5 (% Mn) + 30 (% C) + 0.3 (% Cu) + 25 (% N)

Phases in steel

- The phase microstructure in steels can be varied over a wide range depending on the ratio Cr_{eq}/Ni_{eq}
- The Schaeffler-diagram provides a map of the expected phases in alloys steels cooled from high T to RT



Role of main alloying elements in steel

Element	Effect	Max. wt.%
Mn	+ stabilizes fcc + reduces SFE + scavenges S	30
Co	+ solid solution strengthener + reduces SFE	20
Mo	+ solid solution strengthener + carbide former + supports martensite formation - supports σ-phase formation	5
W, V, Nb	Similar to Mo but - increase density - reduce HT corrosion resistance	4
Al	+ solid solution strengthener + reduces density + forms Ni_3M precipitates + forms stable Al_2O_3 layer at HT	6

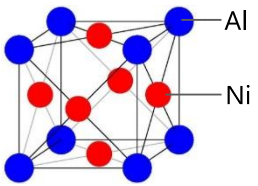
Element	Effect	Max. wt.%
Ti	+ carbide and nitride former + forms Ni_3M precipitates	2
Si	+ improves HT oxidation resistance - supports σ-phase	3
C	+ stabilizes fcc + carbide former	1
N	+ stabilizes fcc + nitride former	1
B	+ grain boundary strengthener - GB embrittlement if too much	0.01
Y, Ce, La	+ form HT-resistant dispersoids + improve HT oxidation resistance + hinder grain coarsening - Can have detrimental effects if too much	0.3

Other phases in steel

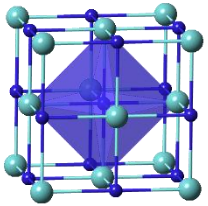
- Intermetallic compounds can have advantageous (e.g. Ni_3Al, Fe_2Mo → particle strengthening) or disadvantegeous (e.g. FeCr σ-phase → brittle)
- Transition metals form carbides, nitrides, oxides, borides, which can be used for particle strengthening (note: MC forms as blocky primary carbides upon solidification)
- Since carbon is usually abundant in steels, carbides are of particular importance
- The metallic components are usually interchangeable
- When sufficient N and B is available, mixed phases such as carbo-nitrides $M_n(C,N)_m$ or boro-nitrides $M_n(B,N)_m$ can also form

Phase	Structure	Example
M_3C	Orthorombic	$(Fe,Cr)_3C$
M_2C	Hexagonal	$(Mo,W)_2C$
M_7C_3	Hexagonal	$(Cr,Fe)_7C_3$
$M_{23}C_6$	Cubic	$(Mo,Fe)_{23}C_6$
M_6C	Cubic	$(Mo,W)_6C$
MC	Cubic	(Ti,W)C

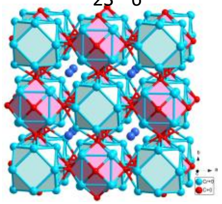
Ni_3Al



TiC



$Cr_{23}C_6$



Characteristic properties of different microstructure components

Phase	$\sigma_{Y0.2}$ [MPa]	σ_{UTS} [MPa]	A [%]	Hardness [HV]
Ferrite (interstitial free) Ferrite (~0.15% C)	100-150 ~220	~280 ~300	~50 ~45	~100
Austenite	~300	~600	~40	~240
Martensite (~0.1% C) Martensite (~0.4% C)	~800 ~2400	~1200 -	≤5 -	~380 ~700
Pearlite	~900	~1000	~10	
Bainite (~0.1% C)	400-800	500-1200	≤25	~320
Cementite	~3000	-	-	-
Nb Carbonitrides	-	-	-	2500-3000

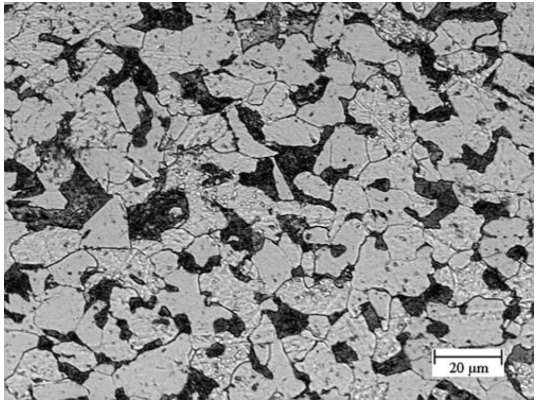
Single phase and multi-phase microstructures

- Steels are designated ‘single phase, ‘dual phase’, ‘multi-phase’
- These terms are used with regard to light optical microstructure descriptions, i.e. the phases than can be resolved in a light microscope
- Smaller consitutents like precipitates are not considered to be isolated phases in this respect
- While single phase microstructures can be simply described by grain size and grain shape, dual phase and multi-phase microstructures need additional features for quantification
    - Volume fraction of different phases
    - Grain sizes of each phase
    - Local chemical composition
    - Hardness ration of the hard and the sof phase
    - Mechanical stability of teh metastable phase
- Additionally, in two phase microstructures with higher volume fraction of the second phase, the a description of the geometrical distribution of both phases might be important

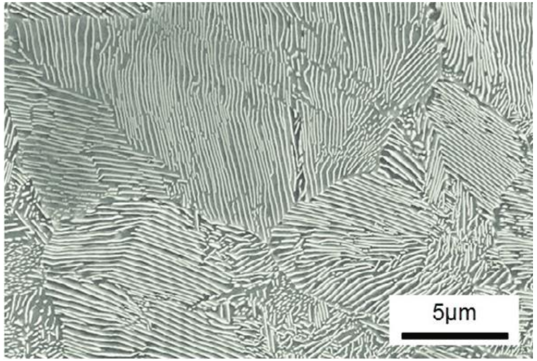
Microstructures of carbon steels

Examples

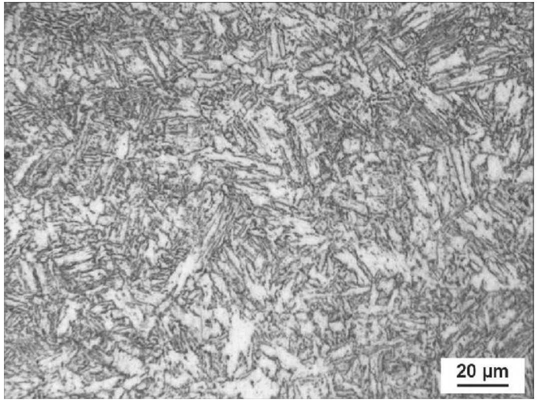
Carbon steel – ferritic-pearlitic microstructure



Carbon steel - pearlite

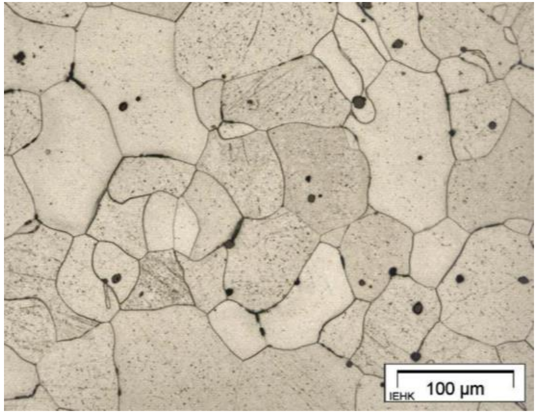


Carbon steel - tempered martensite

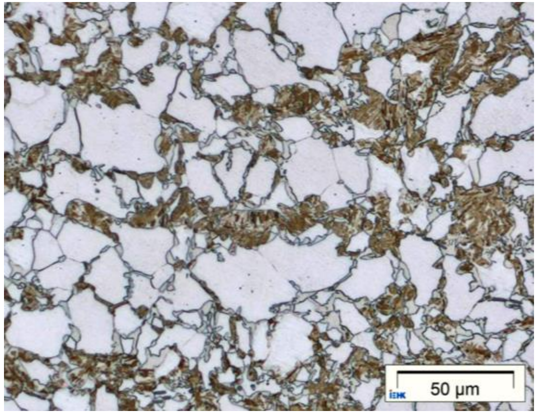


Single phase and multi-phase microstructures
Examples

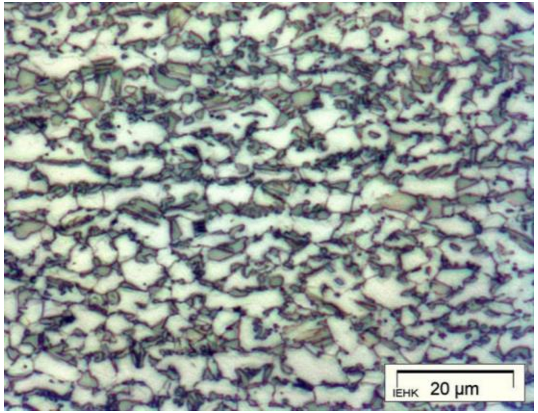
Single phase
Pure iron - ferritic microstructure, oxides and nitrides



Dual phase (DP) steel - ferritic-martensitic microstructure



Two-phase TRIP steel - ferrite + retained austenite



/www.muwi.rwth-aachen.de/IEHK_Metallography/

Steel nomenclature – alloy steel

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- The nomenclature of steels can be very confusing
- Example: <u>low alloy steel</u>

EN steel number (Europe)	EN steel name (Europe)	AISI/SAE grade (USA)	UNS (USA)
1.7225	42CrMo4	4140	G41400

42Cr Mo 4

Amount of C/100

Alloying elements

Amount of alloying elements
in wt.%/4 for Cr, Si, Mn, Ni, W
in wt.%/10 for Al, Mo, Nb, V, Ta, Ti, Zr, Cu
in wt.%/100 for P, S, N, C, Ce
in wt.%/1000 for B

Steel nomenclature – alloy steel

EPFL

- The nomenclature of steels can be very confusing
- Example: high alloyed/stainless steel

EN steel number (Europe)	EN steel name (Europe)	AISI/SAE grade (USA)	UNS (USA)
1.4301	X2CrNi18-10	304	S30400

High alloyed (stainless) steel

X2 Cr Ni 18-10

Amount of alloying elements in wt.%

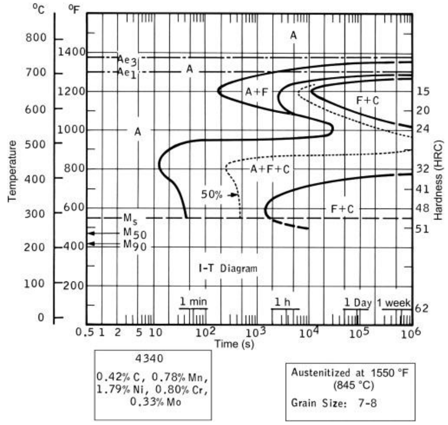
Amount of C/100

Alloying elements

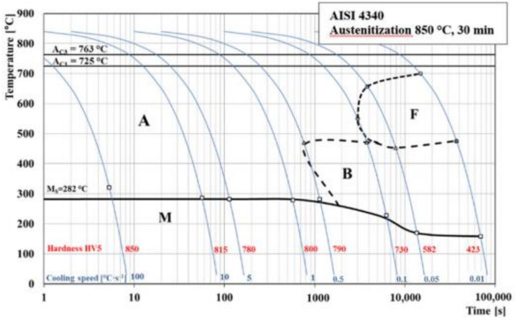
Heat treatment of steels

- The microstructures and mechanical properties (i.e. strength, ductility, toughness) of steels are strongly influenced by their thermo-mechanical history
- The properties can be adjusted over a wide range with specific heat treatments
- The main parameters are the temperature, time and cooling rate
- The constituents of a given steel after isothermal heat treatments are presented in Time Temperature Transformation (TTT)
- The constituents of a given steel after cooling from elevated temperatures are presented in Continuous Cooling Transformation (CCT diagrams)

TTT diagram AISI4340 – 36CrNiMo4



CCT diagram AISI4340 – 36CrNiMo4



Heat treatment of steels

- Solutionizing/normalizing:
  - Annealing at high temperatures (1000-1100°C/2-5h)
  - Goal: dissolution of precipitates, provide uniformity in grain size and composition
- Austenitizing
  - Annealing above upper critical temperature in austenite field (usually >800°C/2-5h)
  - Goal: austenitization for subsequent martensitic/bainitic transformation after quenching
- Tempering
  - Heating below the lower critical temperature (200-600°C)
  - Goal: partial transformation of martensite to reduce brittleness
- Ageing
  - Annealing at intermediate temperatures (500-900°C) after quenching of solutionized steel
  - Goal: formation of precipitates (carbides, nitrides, intermetallic phases) from super-saturated matrix

- Fundamentals of steel metallurgy
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Stainless (corrosion resistant) steels

- Stainless steels are characterized by a high resistance against electrochemical (‘rust’) and chemical corrosion
- The first stainless steel was developed in 1912 (Krupp, Germany)
- Because of their properties, stainless steels have found applications in the chemical industry, civil engineering, biomedical technology, consumer goods etc.

Chemical technology

/www.basf.com/

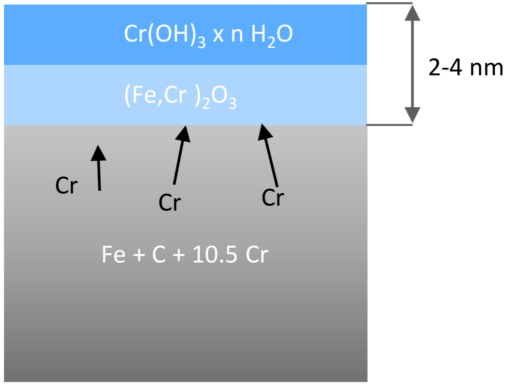
Civil engineering

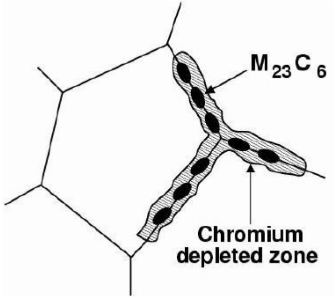
/www.architecturaldigest.com/

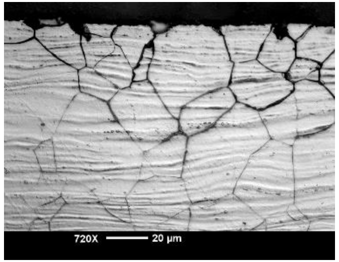
Biomedical technology

Stainless steels

- Steels become stainless when they contain at least 10.5 wt.% Cr
- The high amount of Cr leads to the formation of a thin (2-4 nm) but dense Cr-rich oxide-hydroxide layer at the surface (passivation)
- The presence of Cr-containing carbides in particular on grain boundaries can lead to local loss of passivation and inter-granular corrosion
- This can be avoided by the addition of alternative carbide formers with higher affinity to C (e.g. Ti, Nb)







/www.Wikipedia.com/

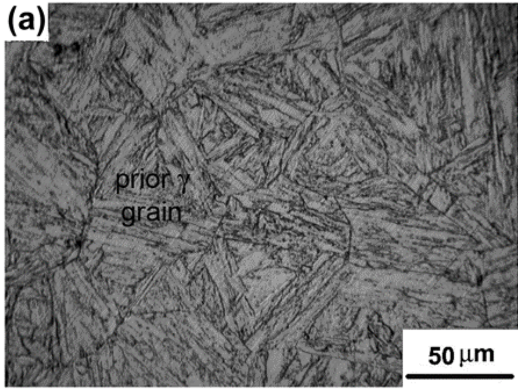
Stainless steels

Ferritic and martensitic steels

- Ferritic stainless steels
  - Composition: >12 wt.% Cr, <0.1 wt.% C, <2 wt.% Mo
  - Average mechanical and corrosion properties
  - Applications:
  - Example: X6CrTi12

- Martensitic stainless steel
  - Composition: 12-18 wt.% Cr, 0.1-1.2 wt.% C
  - The mechanical properties are strongly dependent on the heat treatment
  - Applications: cutting tools, knives, valves
  - Example: X20Cr13, X17CrNi 16-2, X39CrMo 17-1

X12Cr13 – OM microstructure



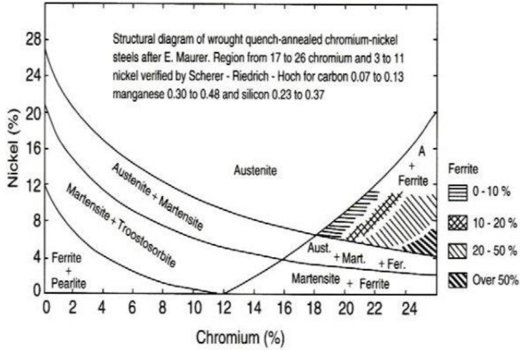
/M. Mirzaee et al, J. Mater. Res 32(3) (2017) 687-696/

Alloy	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
X20Cr13	450-550	650-950	<15
X17CrNi 16-2	>550	750-950	<15
X39CrMo 17-1	>600	800-950	<15

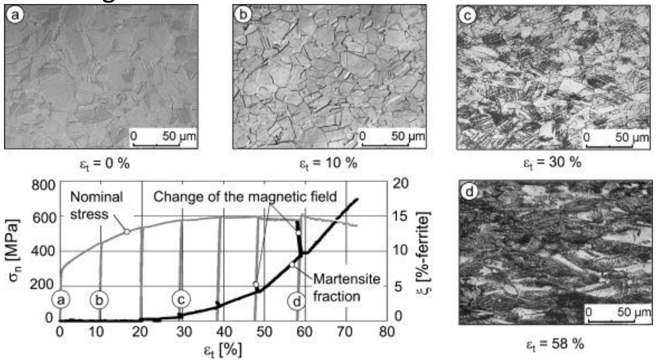
Stainless steels

Austenitic steels

- Composition: >12 wt.% Cr, >8 wt.% Ni, <0.1 wt.% C
- The amounts of Cr and Ni are adjusted so that the steel is fully austenitic upon quenching
- At lower Ni contents (<10 wt.%), the austenite is meta-stable, i.e. it can transform into martensite upon plastic deformation or rapid cooling to very low temperatures (< -190°C)
- Applications: household, food processing, pharmaceutical, chemical, automotive industry
- Example: X5CrNi 18-10 (1.4301/AISI 304)
  X2CrNiMo 17-12-2 (1.4404/316L)



Light micrographs related to stress–strain and magnetic fraction-strain curves of AISI 304



/M. Smaga et al, MSEA 483/484 (2008) 394-397/

Stainless steels

Austenitic steels – mechanical properties

- Strengthening mechanisms in austenitic steels
  - Grain boundary strengthening not very efficient due to low H-P coefficient compared to ferritic steels
  - Precipitation strengthening possible by carbides, nitrides, but amounts of C,N usually low
  - Solid solution strengthening mainly by interstitial C and N, substitutional atoms less efficient
  - Dislocation strengthening very pronounced and main strengthening mechanism
- As the microstructure is only fcc, only little effect of heat treatments

Table 2.11 Mechanical properties of steels for implant surgery (minimum values at room temperature) (DIN, 1997b)

	Condition	Ultimate tensile strength (MPa)	Tensile yield strength (MPa)	Elongation at fracture (%)
X2CrNiMoN18133	Solution treated	600–800	300	40
X2CrNiMo18153		490–690	190	40
X2CrNiMoN18154		590–800	285	40
X2CrNiMnMoN22136		850–1050	500	35

Table 2.12 Mechanical properties of wire for implant surgery (DIN, 1997b)

	Condition	Ultimate tensile strength (MPa)	Elongation at fracture[a] (%)
X2CrNiMoN18133	Solution treated	800–1000	30
X2CrNiMoNi18154	Solution treated	800–1000	40
X2CrNiMoNi18133	Cold worked	1350–1850	–
X2CrNiMoN18154	Cold worked	1350–1850	–

[a]Minimum values.
The values depend on the diameter of the wire (decrease in diameter and increase in degree of deformation = increase in value).

Table 2.13 Mechanical properties of X2CrNiMo17133 stainless steel as a function of the degree of cold working (Cigada *et al.*, 1983)

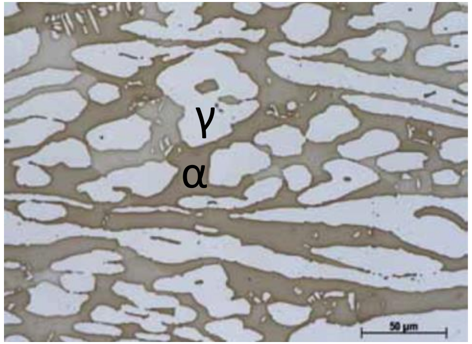
Degree of cold working (%)	Ultimate tensile strength (MPa)	Tensile yield strength (MPa)
0	584	255
31	912	831
50	1138	1036
63	1255	1169
70	1344	1204
76	1421	1252

/Breme, Helsen, 1998/

Stainless steels

Duplex steels

- Composition: 22-25 wt.% Cr, 3-8 wt.% Ni, <0.05 wt.% C
- Stabilization of both ferrite and austenite (~50/50)
- Combination of the properties of ferritic and austenitic steels (high strenght, high toughness)
- High Cr amount can lead to formation of FeCr σ-phase after annealing at 300°C < T < 800°C
- Applications: Pipes for production/transportation of oil and gas, sea water desalination
- Examples: X3CrNiMo 22-5-3, X3CrNiMo 25-7-4
  X2CrNiMoCoN 28-8-5-1



/www.outokumpu.com/

Alloy	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
X3CrNiMo 22-5-3	>450	650-830	>25
X3CrNiMo 25-7-4	>530	730-930	>25
X2CrNiMoCoN 28-8-5-1	>650	800-1000	>25

- Fundamentals of steel metallurgy
- Overview of some selected high-performance steel classes
  - Stainless steels
  - Advanced high strength steels (AHSS) / TRIP/TWIP steels
  - Steels for elevated temperature applications

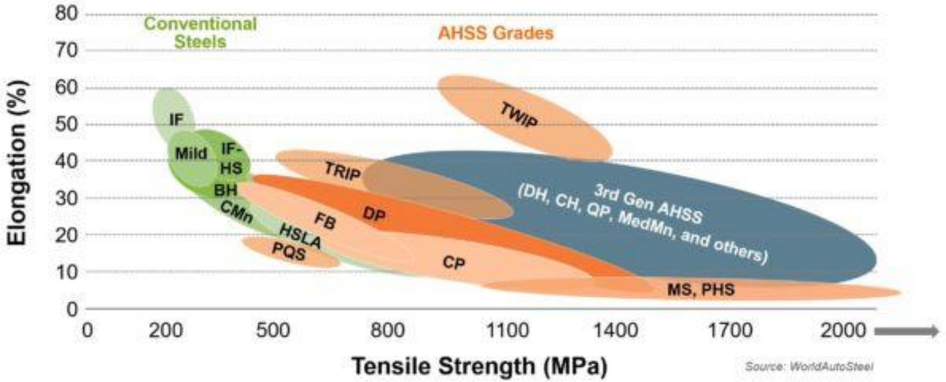
Advanced high strength steels

- Requirements for steels in a modern car body structure
  - Light weight due to high strength for increased energy efficiency
  - Safety due pronounced deformation abilities upon impact loads
  - Freedom of design due to pronounced sheet forming capabilities
  - Sustainability by recycling at the end of car life-time
  - Low Costs

Advanced high strength steels

History and properties

Steel class	Alloy content	Since approx.
HSS	<3 wt.%	1980
AHSS 1st gen.	<5 wt.%	1990
AHSS 2nd gen.	15-40 wt.%	2000
AHSS 3rd gen.	< ca. 10 wt.%	2010



Advanced high strength steels

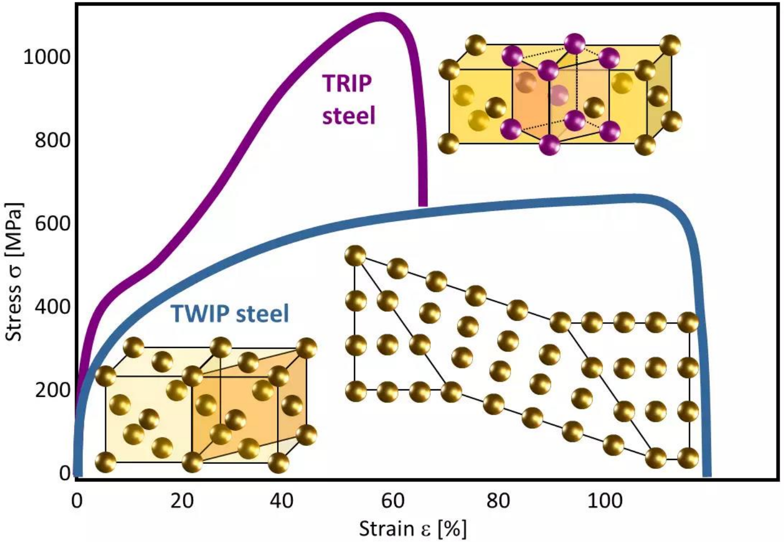
Microstructures and characteristics

Steels	Microstructure	Characteristics
HSS	α	**BH**: bake hardening steel grades, which show additional strengthening during paint bake treatment by controlled C aging **IF-HS:** high strength interstitial free steels, strengthened by Mn and P addition **P**: P alloyed high strength steels **IS:** steels with medium yield strength and isotropic flow behaviour, microalloyed with Ti or Nb **CMn:** high strength steels with increased C, Mn and Si contents for solid solution strengthening **HSLA:** high strength low alloy steels, strengthened by microalloying with Nb or Ti
AHSS 1st gen.	$\alpha+\alpha'$ $\alpha+\alpha_B+\gamma_R$ $\alpha+\alpha'$ $\alpha+\alpha_B+\alpha'$	**DP:** dual phase steels with a microstructure of ferrite and 5-30 vol.% martensite islands **TRIP:** transformation induced plasticity steels containing ferrite, bainite and retained austenite **PM:** partly or fully martensitic steels **CP:** complex phase steels with a mixture of strengthened ferrite, bainite and martensite
AHSS 2nd gen.	γ or high fractions of γ	**HMS-TRIP:** steels with an alloying concept that strain induced $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ transformation occurs **HMS-TWIP:** steels with an alloying concept that mechanical twinning occurs during straining

Advanced high strength steels

TRIP and TWIP steels

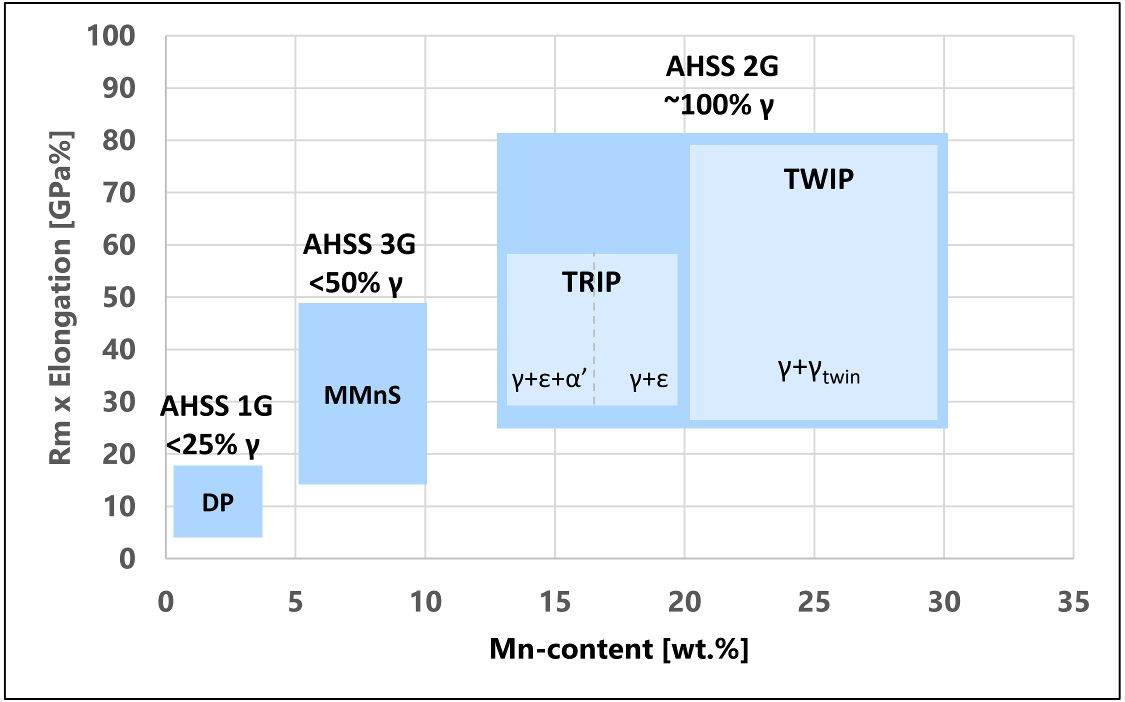
- **TRansformation-Induced Plasticity (TRIP)** steel is a class of austenitic steels which undergoes a mechanically induced martensitic transformation upon deformation
- **TWinning-Induced Plasticity (TWIP)** steel is a class of austenitic steels which can deform by both glide of individual dislocations and mechanical twinning



/Courtesy T. Hickel, MPIE Düsseldorf/

Advanced high strength steels

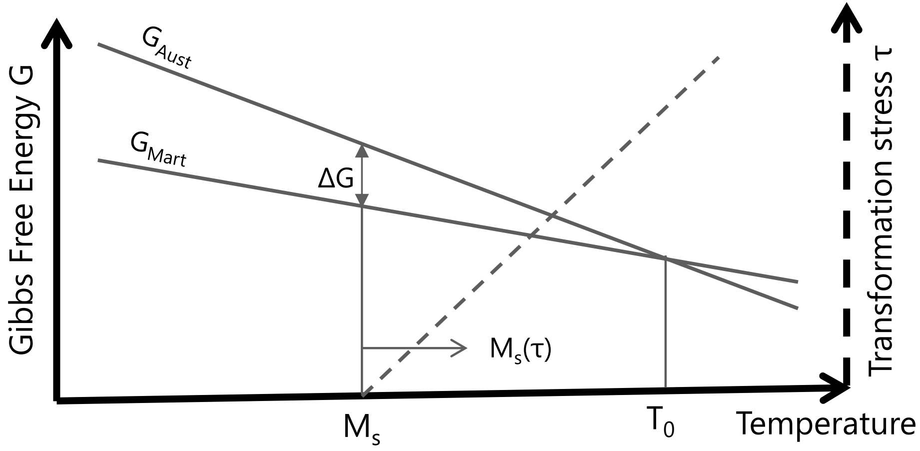
Influence of Mn content



TRansformation Induced Plasticity Steels

Mechanically induced martensite

- The austenite in TRIP steels is meta-stable
- Thermodynamic driving force for the austenite ↔ martensite transformation is the Gibbs free energy difference ΔG
- Martensite more stable below T_0
- Transformation occurs at Ms, at which ΔG exceeds a critical value for nucleation and growth



TRansformation Induced Plasticity Steels

Mechanically induced martensite

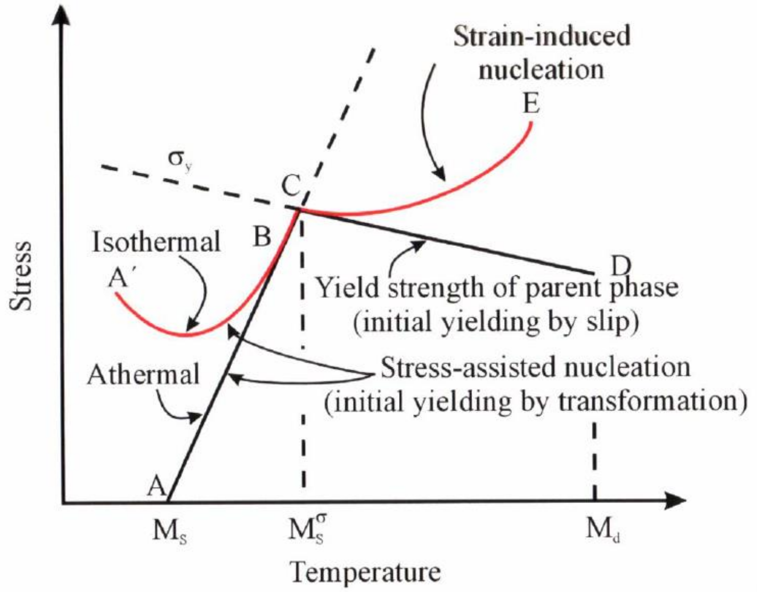
- A key feature to exploit the TRIP effect is to control the transformation behavior of austenite to martensite during deformation
- The three temperatures M_s, M_s^σ and M_{d30} are often used to describe the austenite stability:
  - M_s: temperature at which the athermal martensite transformation begins
  - M_s^σ: temperature at which the first time strain-induced martensite is formed
  - M_{d30}: temperature at which 30% tensile deformation induces a transformation of 50 % of the austenite to martensite

athermal transformation = transformation that does not require thermal activation

TRansformation Induced Plasticity Steels

Mechanically induced martensite

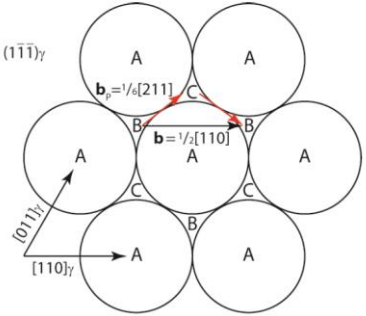
- Above M_s, austenite can transform to martensite under deformation.
- At M_s^σ, the mode of the transformation of retained austenite to martensite changes from stress assisted to strain induced
  → stress needed to initiate martensitic transformation = yield strength of the austenite.
- Above M_s^σ, the austenite is strained and the martensite nucleation is supported by plastic strain.
- Above M_d, the austenite is stable even when plastic strain is applied and no martensite transformation occurs.

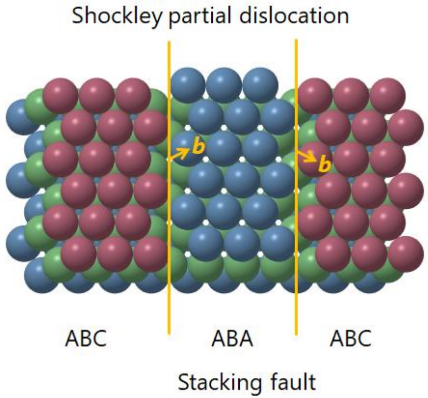


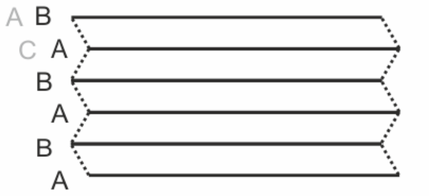
TRansformation Induced Plasticity Steels

The fcc-γ → hcp-ε transformation

- The formation of hcp ε-martensite can be related the generation of stacking faults (SF), which is an interruption of the normal stacking sequence of atomic planes in the crystal structure
- In fcc alloys, the SF is associated with a slip {111}<112> of partial dislocation produced during shear by 1/6<112>
- A SF on every **second plane** changes the stacking sequence of the {111} plane from ABCABCAB to ABCABABABC



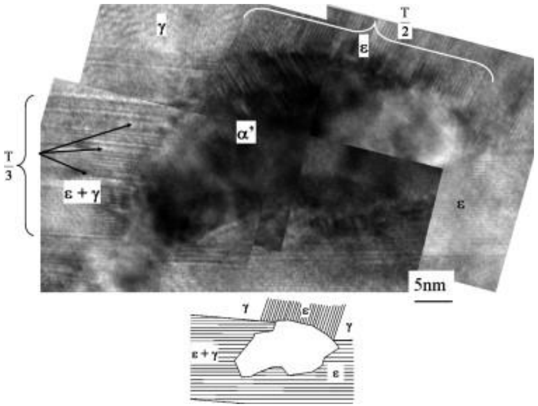


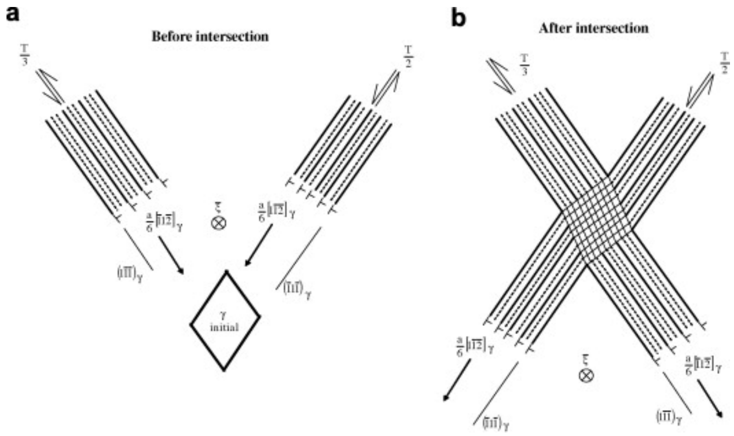


TRansformation Induced Plasticity Steels

The hcp-ε → bct-α’ transformation

- At higher strains, α’-martensite can nucleate at interesections of ε-martensite bands
- The partial dislocations forming the ABAB stacking faults in the ε-martensite bands interact in such a way that the lattice is locally transformed into a bcc/bct structure



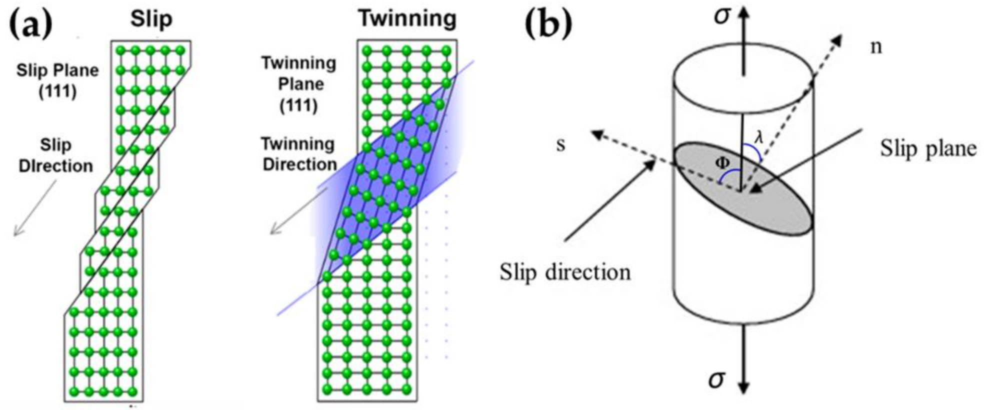


/L. Bracke et al, Scripta Mater 57(5) (2007) 385-388/

TWinning Induced Plasticity Steels

Twinning vs. dislocation glide

- Slip occurs when dislocations glide through the material, causing crystal planes to slide along each other.
- Twinning occurs via a concerted shift of atomic positions in the twinning direction. The twin crystal's structure is a mirror image of the parent structure about the twinning plane.

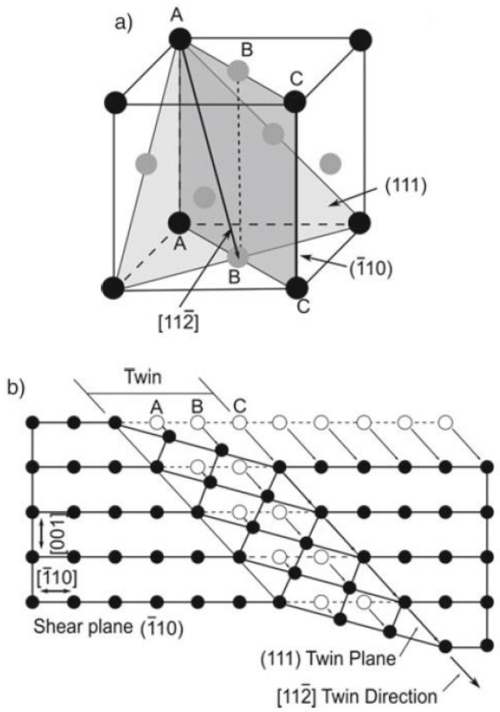


/G. Yang, S.J. Park, Materials 12(12) (2019) 2003/

TWinning Induced Plasticity Steels

Twinning mechanism

- In the fcc crystal lattice, mechanical twinning occurs on the {111} plane
- It results from homogeneous shearing of the matrix by the highly coordinated glide of {111}<112> Shockley partial dislocations on **successive** {111} twinning planes
- A SF on **every consecutive plane** changes the stacking sequence of the {111} plane from ABCABCAB to ABCACBABC
- This corresponds to a local mirror image of the original fcc lattice
- The TWIP effect is similar to the TRIP effect in the sense that partial dislocations and SFs play an important role



/G. Yang, S.J. Park, Materials 12(12) (2019) 2003/

TRIP and TWIP steels

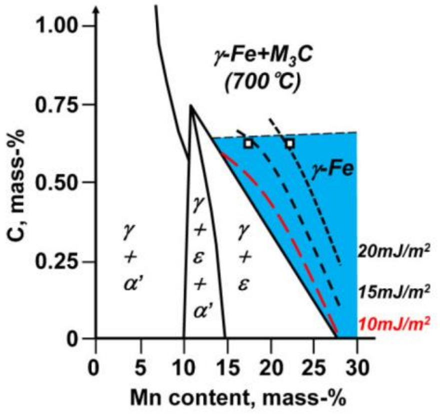
Role of the stacking fault energy on deformation mechanism

- The stability of the hcp ε-martensite can be related to the intrinsic stacking fault energy

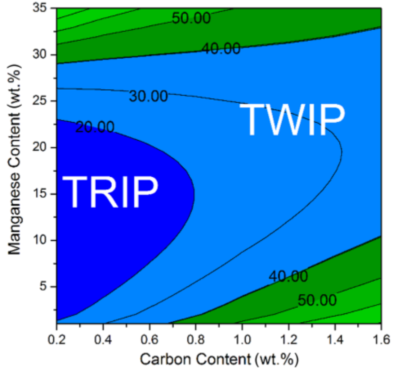
  $SFE = n\rho\Delta G^{\gamma\rightarrow\varepsilon} + 2\sigma^{\gamma/\varepsilon}$ [mJ/m²]

  ρ: planar atomic density of {111}γ (2.95x10^{-5} mol/m²)
  $\Delta G^{\gamma\rightarrow\varepsilon}$: Gibbs free energy difference between γ and ε
  $\sigma^{\gamma/\varepsilon}$: interfacial energy between γ and ε (15 mJ/m²)

- The SFE is strongly influenced by the amount of Mn and C
- The SFE determines the predominant deformation mechanism
  - Strain-induced γ→ε transformation occurs in steels with SFEs <20 mJ/m²
  - Deformation twinning occurs in steels with SFEs between ~20 mJ/m²and 50 mJ/m²
  - Partial and/or perfect dislocation gliding above ~50 mJ/m²



/B.C. De Cooman et al., Mat. Sci. Technol. 28(5) (2011) 513-527/

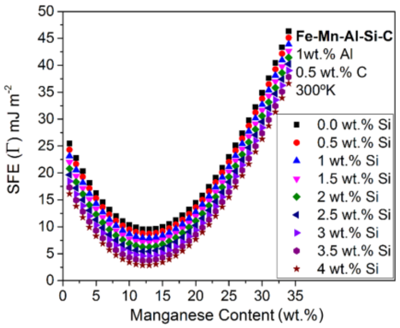


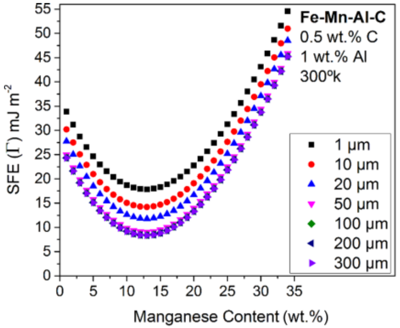
/O.A. Zambrano, J. Eng. Mater. Technol. 138(4) (2016) 041010/

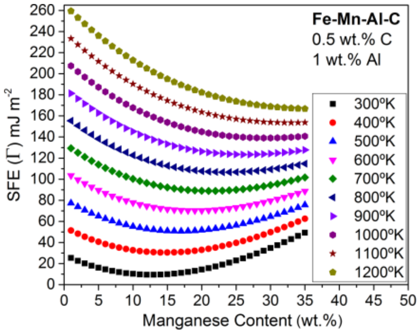
TRIP and TWIP steels

Role of the stacking fault energy on deformation mechanism

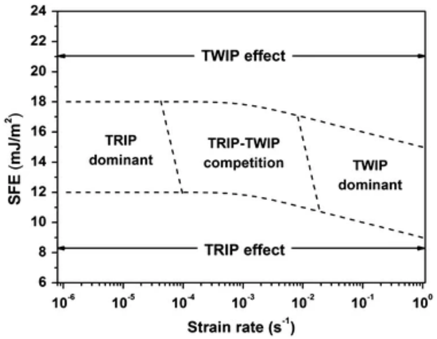
- Other factors influencing the stacking fault energy
  - Austenite grain size: smaller grains are more stable
  - Chemical composition: Besideds Mn and C changes in SFE are seen when adding Si, Cu, Cr, N
  - Temperature: SFE is lower at lower T
  - Strain rate: adiabatic heating increases SFE and reduces the driving force for transformation
  - Stress state: hydrostatic compressive stresses suppress the transformation







/O.A. Zambrano, J. Eng. Mater. Technol. 138(4) (2016) 041010/



/S. Lee et al., Metall. Mater. Trans. A 45 (2014) 717–730/

TRIP/TWIP steels

Chemical composition

- In commercial TRIP/TWIP steels, the mechanism is mainly adjusted by the amount of Mn
  - TRIP: 6-15 wt.% Mn
  - TRIP/TWIP: 15-20 wt.%
  - TWIP: >20 wt.%
- The the carbon content is varied between 0.1-0.6 wt.% C and is controlled during processing to retain a significant amount of metastable austenite at room temperature and for solid solution strengthening.
- In order to suppress carbide formation and local depletion of C in the matrix during quenching as well as for solid solution strengthening, additions Si (0-3 wt.%) and Al (1-3.5 wt.%) are employed
- Precipitation strengthening is achieved by adding minor amounts of Ti, V or Nb and the formation of carbides

Mechanical properties of TRIP/TWIP steels

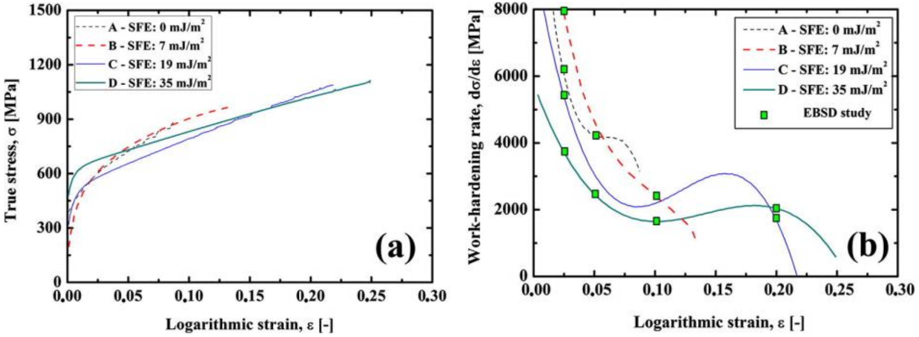
Influence of SFE on deformation mechanism

- The role of stacking fault energy on defining the work-hardening behavior of manganese-rich steels was studied by the tensile deformation of four high-manganese steels
- The flow behavior and work-hardening rate diagrams, together with the activity of different deformation mechanisms (TRIP, TWIP), were studied and correlated with the microstructural investigations

Table 1. The chemical composition, microstructure, processing route, and the SFE value of the materials investigated.

Material	Chemical composition			Microstructure		Process	SFE at 300 K (mJ m^{-2})
	Fe	Mn (wt.%)	C (wt.%)	Before deformation	After deformation		
A	Bal.	13	0.3	γ	$\gamma + \varepsilon_D + \alpha'_D$	HR	~0
B	Bal.	22	0.1	$\gamma + \varepsilon$	$\gamma + \varepsilon + \varepsilon_D$	HR	7
C	Bal.	18	0.6	γ	$\gamma + \gamma_T$	HR	19
D	Bal.	24	0.7	γ	$\gamma + \gamma_T$	HR	35

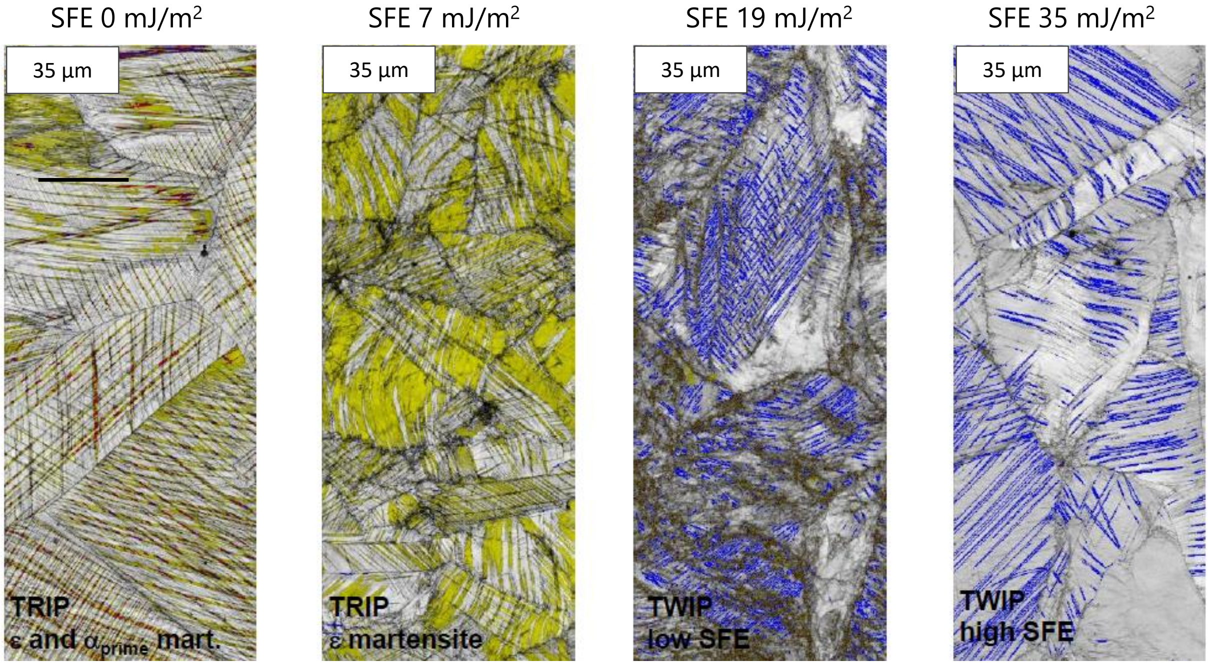
γ, γ_T, ε, ε_D, and α'_D are austenite, twinned austenite, $\varepsilon^{Ms}_{h.c.p.}$ martensite, deformation-induced $\varepsilon^{Ms}_{h.c.p.}$ martensite and deformation-induced $\alpha^{Ms}_{b.c.t.}$ martensite, respectively. HR stands for the hot-rolled state. The HR sheets had the thickness of 3 mm.



/A. Saeed-Akbari et al., Scripta Materialia 66 (2012) 1024–1029/

Mechanical properties of TRIP/TWIP steels

Influence of SFE on deformation mechanism



EBSD, yellow: ε-martensite, red: α'-martensite, blue: twins

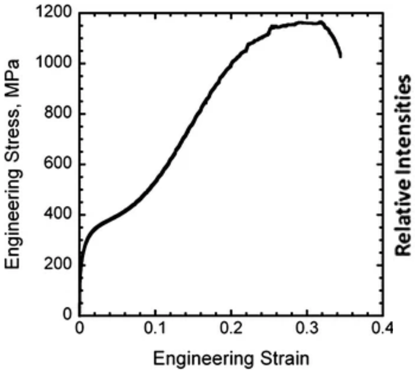
/A. Saeed-Akbari et al., Scripta Materialia 66 (2012) 1024–1029/

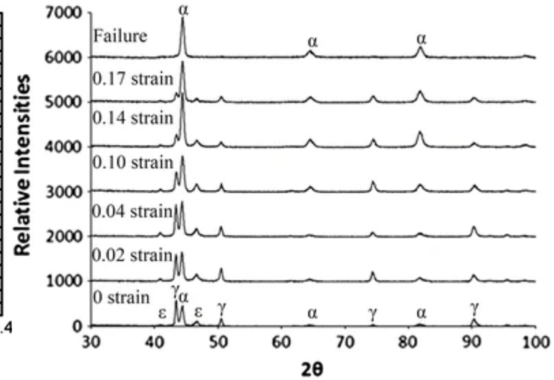
Mechanical properties of TRIP/TWIP steels

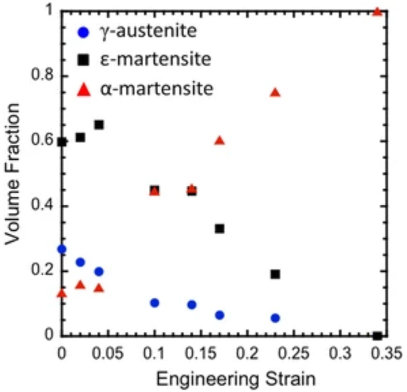
Work hardening behavior with multiple TRIP mechanisms

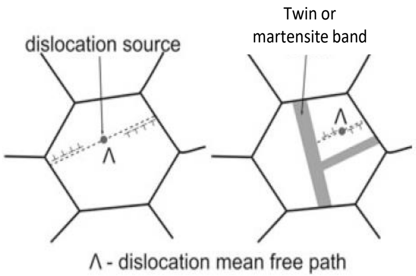
- TRIP steels can achieve high strength (Rm > 1100) at elongations up to 35%
- The predominant strengthening mechanism is a two-stage TRIP phenomenon characterized by γ→ε and ε→α'
- High work hardening rates attributed to the TRIP mechanism's segmentation of the austenite into new and smaller phases → dynamic Hall-Petch effect

Fe-15.3Mn-2.85Si-2.38Al-0.07C-0.017N/solutionized, water quenched









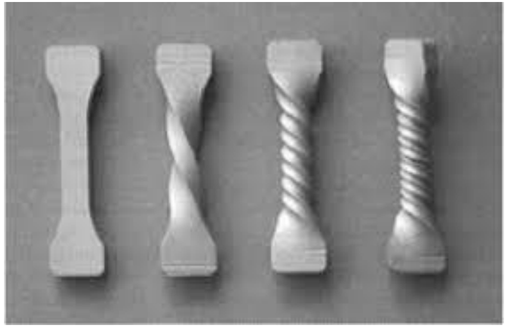
/M.C. McGrath et al, Metall. Mater. Trans. A, 44 (2013) 4634-4643/

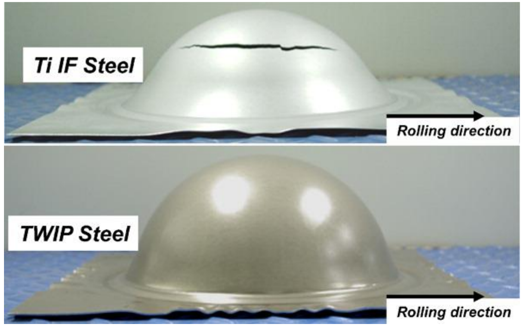
/B.C. De Cooman et al., Mat. Sci. Technol. 28(5) (2011) 513-527/

Mechanical properties of TRIP/TWIP steels

Work hardening behavior with multiple TRIP mechanisms

- TWIP steels have an outstanding ductility and can achive elongations at fracture >100%





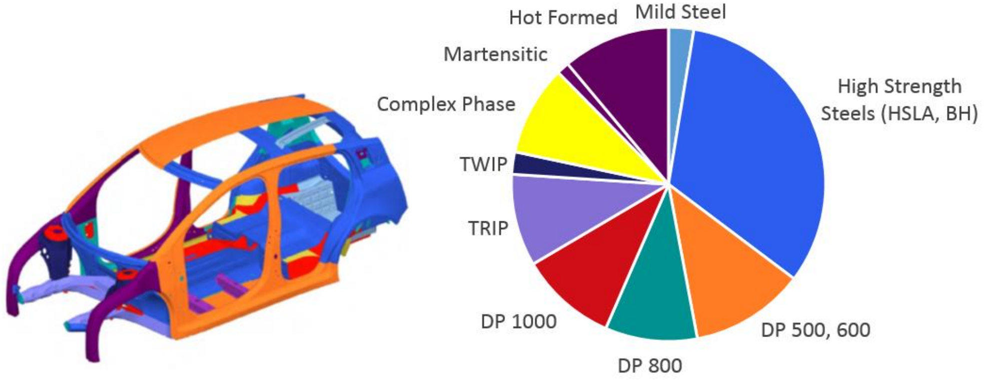
/MPI für Eisenforschung, www.mpg.de/

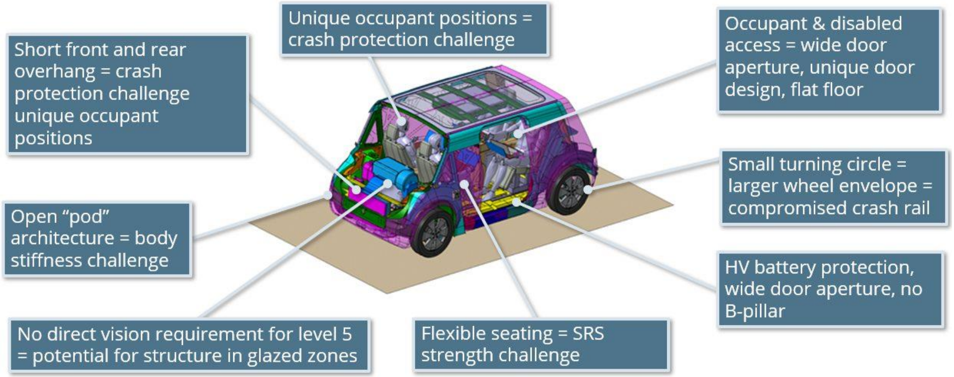
/B.C. De Cooman et al., Mat. Sci. Technol. 28(5) (2011) 513-527/

Advanced High Strength Steels

Applications of AHSS

Current applications in car body structures





Challenges for future autonomous vehicle applications

/ahssinsights.org/

Advanced High Strength Steels – 3rd generation

Current trends in AHSS research

- The current research efforts on AHSS focus on
  - Medium Mn TRIP steels (MMnS)
  - Quenched and partioned steels
  - Maraging TRIP steels
  - High modulus steels
  - Low density steels
- Literature
  - D. Raabe et al., Current Challenges and Opportunities in Microstructure-Related Properties of Advanced High-Strength Steels, Metall. Mater. Trans. A **51** (2020) 5517–5586
  - W. Bleck et al., The TRIP Effect and Its Application in Cold Formable Sheet Steels, steel research int. 88 (2017) No. 10
  - R. Rana (Ed.), High performance ferrous alloys, Springer Nature Switzerland AG 2021

Advanced High Strength Steels – 3rd generation

	Typical chemical composition, wt% (Fe balanced)										
Steel designation	C	Si	Mn	Cr	Mo	Ni	Al	Co	Ti	Special process	Microstructure
Meta-stable ASS	0.02–0.15	n/a	0–6	17–20	n/a	3–7	n/a	n/a	n/a	no	$\gamma(100\%)$
LC TRIP	0.1–0.3	1–2	1–2	n/a	n/a	n/a	1–2	n/a	n/a	Intercritical annealing	$\alpha(40\text{–}60\%) + \alpha_B(35\text{–}45\%) + \gamma_R(5\text{–}15\%)$
HMnS TRIP	0.1–0.6	0–3	14–23	n/a	n/a	n/a	0–3	n/a	n/a	no	$\gamma(100\%)$
Q&P TRIP	0.1–0.3	1–2	1.5–3	n/a	n/a	n/a	n/a	n/a	n/a	Q&P treatment	$\alpha' + \gamma(5\text{–}10\%) + (\alpha)$
MMnS TRIP	0.05–0.4	0–3	4–12	n/a	n/a	n/a	0–2	n/a	n/a	ART annealing	$\alpha + \gamma(20\text{–}40\%)$
Maraging TRIP	0.01	0.06	12	n/a	1	2	0.1	n/a	1	Aging treatment	$\alpha' + \gamma(\approx 15\%)$

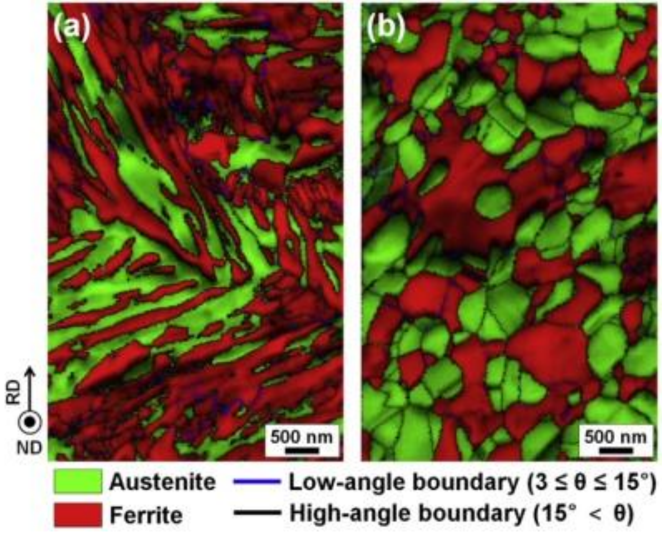
ASS: Austenitic Stainless Steels; LC: Low Carbon; TRIP: Transformation-Induced Plasticity; HMnS: High-Manganese Steels; MMnS: Medium-Manganese Steels; Q&P: Quenching and Partitioning; Maraging: Martensite Aging; HEA: High Entropy Alloy; ART: Austenite Reverted Transformation.

/W. Bleck et al, steel research int. 88(10) (2017) 1700218/

Advanced High Strength Steels – 3rd generation

Medium Mn TRIP steels

- Medium Mn steels consist of 3-12 wt.% Mn, 0.1-0.4 wt.% C, 0-3 wt.% Si, and 0-2 wt.% Al
- Microalloying is not that common in the MMnS because the formation of carbide consumes carbon, which may deteriorate the stability of austenite
- They show and excellent strength-ductility combination (product of tensile strength and total elongation up to ~70 GPa%), simple heat treatment process and low-cost alloy ingredients
- They often consist of multiple phases such as different types of austenite (retained, partition stabilized, reverted), martensite, ferrite and sometimes also delta ferrite



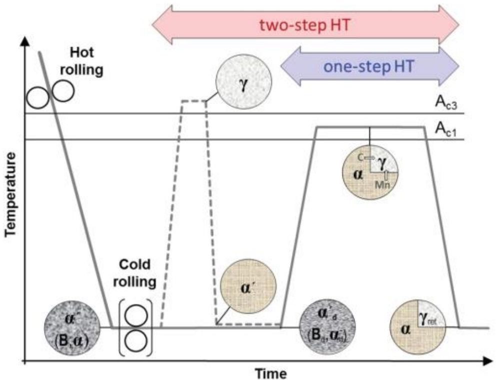
EBSD IQ-phase maps taken from the normal direction of (a) a hot-rolled and annealed specimen and (b) a cold-rolled and annealed specimen.

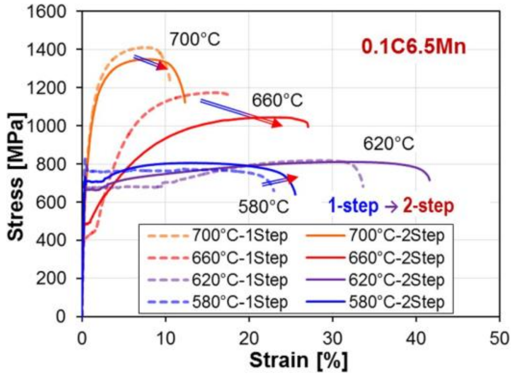
/J.H. Han et al., Acta Mater 121 (2017) 199-206/

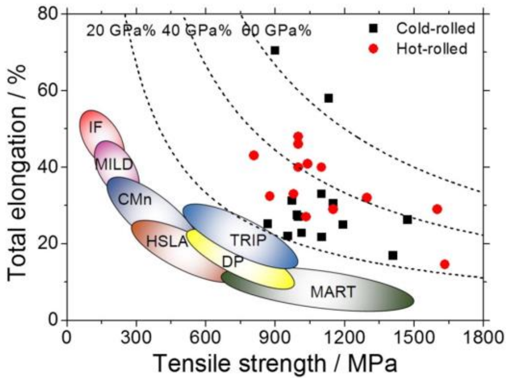
Advanced High Strength Steels – 3rd generation

Medium Mn TRIP steels

- Outstanding combination of tensile strength x elongation compared to that of conventional AHSS
- Mechanical performance strongly influenced by the volume fractions of austenite, ferrite and martensite as well as the thermal pre-treatment







/R. Schneider et al., Mater Sci Tech 35(17) (2019) 2045-2053/

Advanced High Strength Steels – 3rd generation

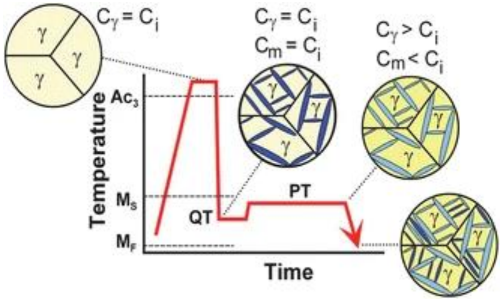
Quenched and Partitioned (Q&P) steels

- Quenched and Partitioned (Q&P) steels have a composition of 1-1.5 wt.% Mn, 0.1-0.3 wt.% C, and 0-1.5 wt.% Al
- They have their name from their particular Q&P heat treatment process
  - In the quenching step, fully austenitized or intercritically annealed steels are quenched to temperatures (referred to as the "quench temperature") below the martensite start (Ms) temperature but above the martensite finish (Mf) temperature in order to form a controlled volume fraction of martensite.
  - The quenched steels are then held at the same or higher temperatures than the quench temperature during the subsequent partitioning step.
- Austenite that prevails after quenching is considered to be stabilized through carbon partitioning from martensite into the austenite during the partitioning treatment.
- Carbon is pumped into austenite to stabilize retained austenite instead of forming Fe_3C or austenite decomposition into bainite.

Advanced High Strength Steels – 3rd generation

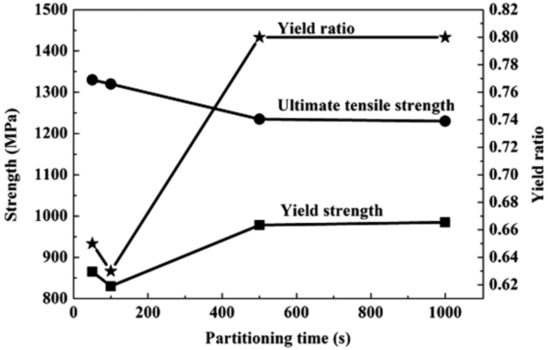
Quenched and Partitioned (Q&P) steels

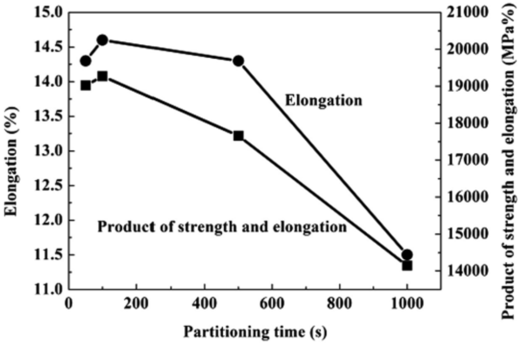
- The resultant microstructures of the steels mainly consist of tempered martensite and retained austenite so that a higher strength can be achieved as compared to conventional TRIP steels.
- Q&P steels show an ultrahigh strength of 1000–1400 MPa with adequate ductility of 10–20%



/L. Wang & J.G. Speer., Metallography, Microstructure, and Analysis 2 (2013) 268–281/

Fe–0.21C–1.67Si–1.65Mn–0.2V wt%





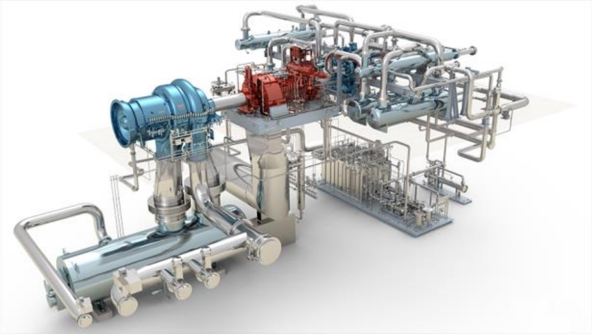
/X. Tan et al., MSEA 589 (2014) 101-111/

Outline

- Fundamentals of steel metallurgy
- Overview of some selected high-performance steel classes
  - Stainless steels
  - Advanced high strength steels (AHSS)/TRIP/TWIP steels
  - Steels for elevated temperature applications

Steels for elevated temperature applications

- Modern steam turbines
  - Steam inlet temperature: 560-620°C, up to 700°C in the future
  - Inlet pressure: up to 260 bar
  - Spinning: 14’000 rpm
  - Power output up to 2000 MW
  - Maintenance intervals: up to 100’000 service hours (>10 years)
- Requirements for steels used in power generation and turbo-machinery
  - Long-term creep resistance at T>500°C
  - Resistant against thermo-fatigue (start-stop cycles)
  - Resistant against high temperature oxidation and/or gas corrosion
  - Sufficient ductility and fracture toughness even after long-term use



/www.man-es.com/

Steels for elevated temperature applications

- General classification of steels for high temperature applications
  - High-strength steels
    - Service range <400°C
    - Low-C martensitic/austenitic
  - Creep resistant steels
    - Service range 400-550°C
    - Ferritic – ferritic/bainitic
    - Examples: X45CrSi 9-3, X10CrAl24, 10CrMo 9-10
  - High-temperature steels
    - Service range 550-750°C
    - Ferritic/martensitic (<620°C), austenitic (>620°C)
  - Heat-resistant steels
    - Service range up to 1000°C
    - Ferritic or austenitic

Main strengthening mechanism: particle strengthening with carbides and/or IM particles

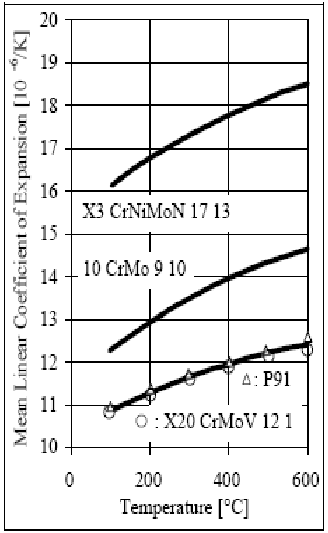
Comparison of physical properties

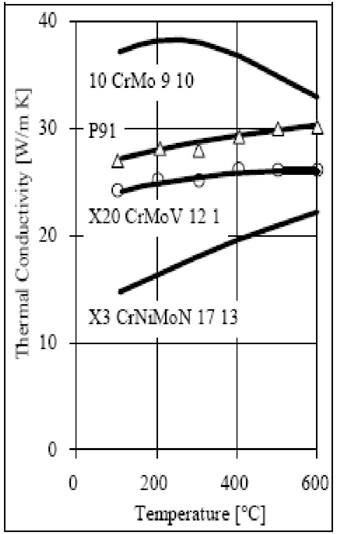
- Austenitic steels have a higher coefficient of thermal expansion (CTE) than ferritic/martensitic steels
- Austenitic steels have a lower thermal conductivity than ferritic/martensitic steels

→ Thermal cycling in a defined temperature range leads to larger strain amplitudes for austenitic steels

→ Local heating can lead to more pronounced thermal gradients in austenitic steels

→ Austenitic steels are in general more prone to thermal fatigue than ferritic/martensitic steels

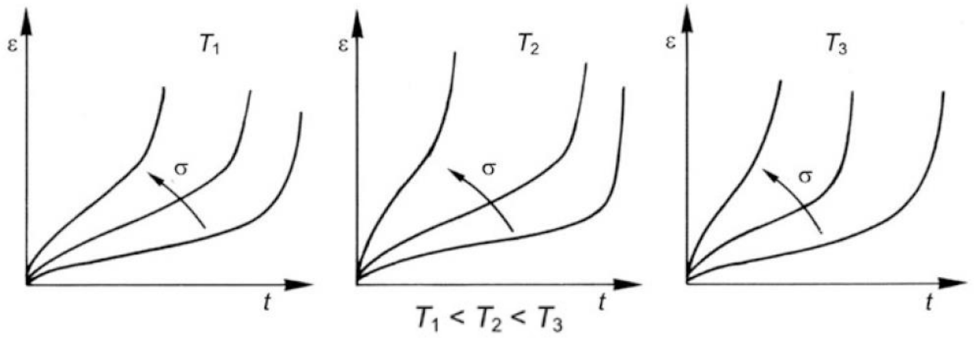


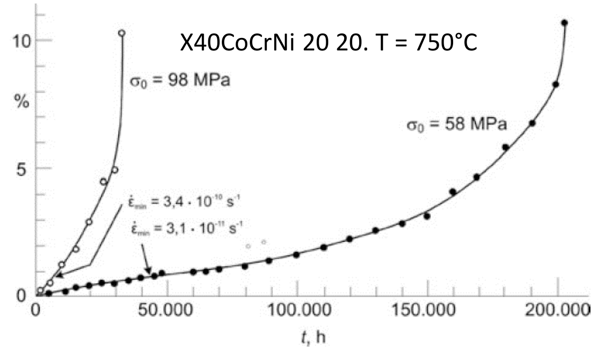


Physical properties of 10CrMo9 10, P91, X20CrMoV 12-1 and X3CrNiMoN 17 13

Reminder - time dependent plasticity - creep

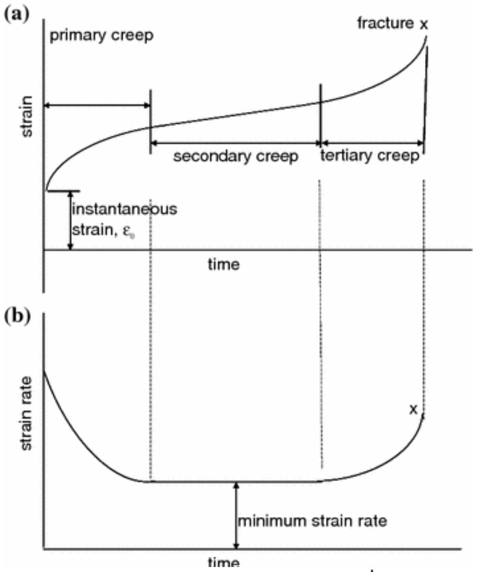
- Creep is the time-dependent plastic deformation under a constant stress at elevated temperatures, which can result in sudden catastrophic failure
- Creep can occur at even at very low mechanical loads significantly below the static yield stress (e.g. dead weight of the component, centrifugal forces in rotating parts)
- Creep is more pronounced with increasing loads and increasing temperature

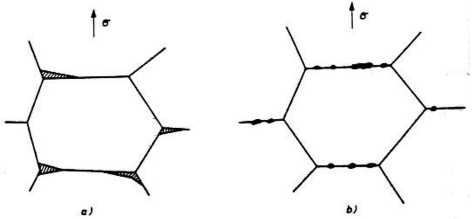




Reminder - time dependent plasticity - creep

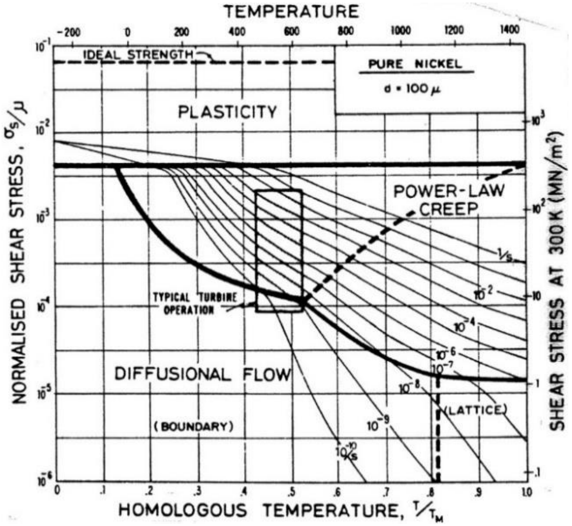
- Primary creep
  - decreasing creep rate $\dot{\varepsilon}$, hardening because of increasing dislocation density
- Secondary creep
  - $\dot{\varepsilon}$ minimal and constant, softening because of recovery processes (dislocation annihilation)
  - Cross slip and climb are activated
  - Diffusion of vacancies
  - Overall, equilibrium between hardening (formation of dislocations) and softening processes
- Tertiary creep
  - Increasing $\dot{\varepsilon}$, pronounced material damage
  - Cracks at grain boundary triple points (high σ, short t)
  - Pores on grain boundaries ⊥ loading direction (low σ, long t)





Reminder - time dependent plasticity - creep

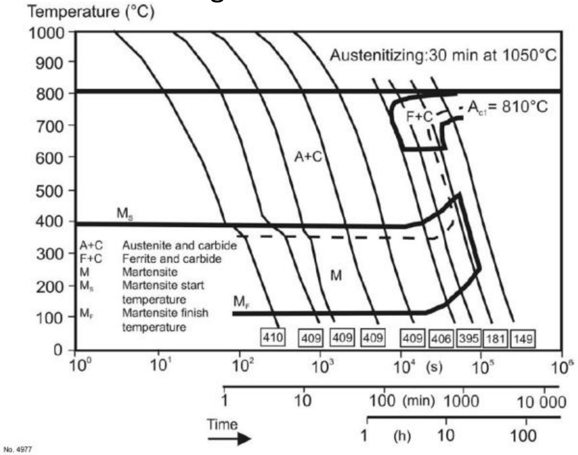
- At low/medium T and high σ (below YS)
  - Plastic deformation due to dislocation glide and twinning
- At low/medium T and medium σ (below YS)
  - Power law creep due to cross slip of screw dislocation and climb of edge dislocations $\dot{\varepsilon} = A\sigma^n$ (Norton)
- At medium T and low/medium σ
  - Diffusional creep, grain boundary diffusion (Coble)
- At high T and low/medium σ
  - Diffusional creep, bulk (lattice) diffusion (Nabarro-Herring)
  - Grain boundary sliding



Ferritic-martensitic 9-12% Cr steels

- Composition: 9-12 wt.% Cr, 0.1-0.2 wt.% C, carbide formers Mo, Nb, V, Ti
- The amount of Cr leads to formation of martensite upon air cooling between 300° and 100°C
- Austenitizing and tempering at T>650°C leads to
  - Formation of sub-µm sized carbides
  - Partial transformation of martensite into ferrite
  - Stabilization of retained martensite
- The amount of Cr leads to the formation of a Cr-rich oxide layer at the surface
- Applications: steam turbine rotor parts, pipes etc. with $T_{service}$<620°C
- Examples: X20CrMoV 12-1, X10CrMoVNb 9-1

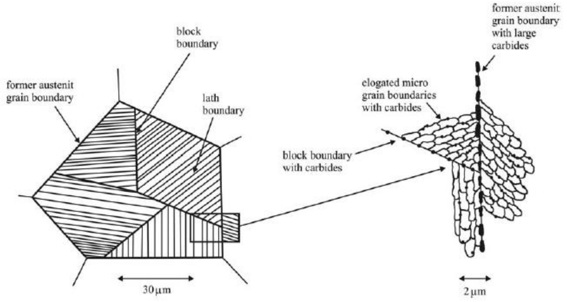
CCT diagram X20CrMoV12-1



Ferritic-martensitic 9-12% Cr steels

Microstructure

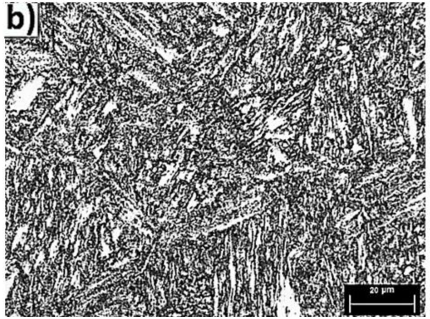
- Martensite laths grow from former austenite grain boundaries, forming a martensite block
- Carbides form a dense network due to precipitation on
  - Former austenite grains boundaries
  - Martensite block boundaries
  - Sub- or micro-grain boundaries (dislocation networks)



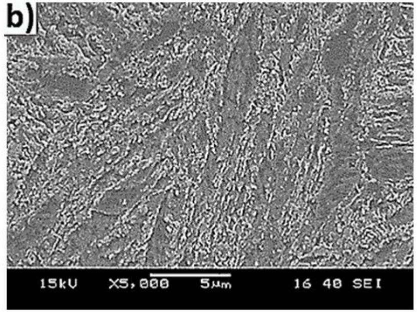
/A.A. Bazazi, PhD Thesis RU Bochum, 2009/

Microstructure of X20CrMoV12-1 after solutionizing 1030°C/0.5 h, quenching in oil and tempering at 690°C/2h

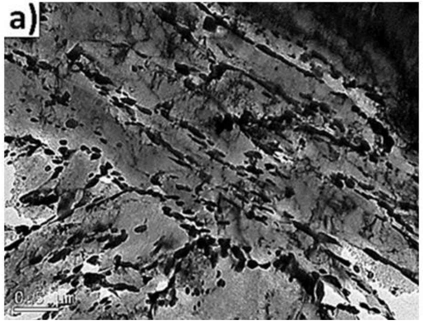
OM



SEM



TEM

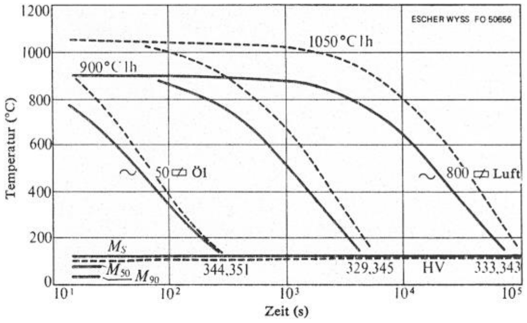


/F.W Comeli et al., Am. J. Mater. Sci. 8(4) (2018) 65-72/

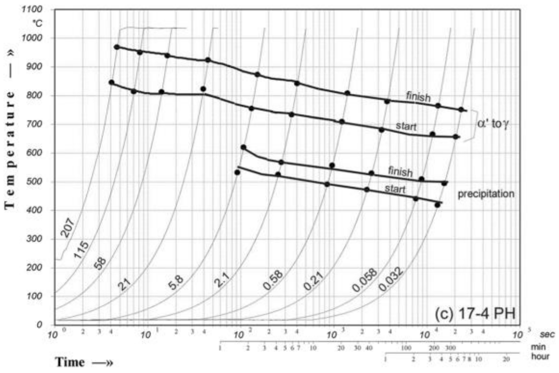
Nickel-martensitic precipitation hardened steels

- Composition: 12-17 wt.% Cr, 3-8 wt.% Ni, 0.05 wt.% C, small amounts of IM phase formers Mo, Cu, Nb, Al, Ti
- The amount of Cr leads to formation of martensite upon air cooling between 300° and 100°C
- 1st tempering at 700°C-900°C leads to partial transformation of martensite into austenite (15-45 vol%)
- 2nd tempering at 400°C-600°C leads to formation of sub-µm IM particles
- Because of the low C content, these steels exhibit a high strength with high ductility and toughness
- Applications: compressor impellers, pumps with $T_{service}$<300°C
- Examples: X3CrNiMo 13-4, X5CrNiMoCuNb 14-5-1-1 (14-5 PH, X5CrNiCuNb 16-4-3 (17-4 PH)

CCT diagram X5CrNiCuNb 16-4-3



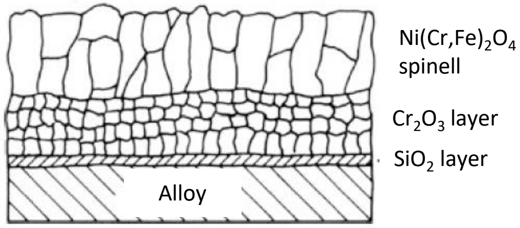
CHT diagram X5CrNiCuNb 16-4-3



Austenitic high-temperature steels

- Composition: 17-30 wt.% Cr, 13-25 wt.% Ni, up to 0.5 wt.% C, carbide and IM formers Mo, Nb, W, V, Ti, Al
- The amounts of Cr and Ni are adjusted so that the austenite is fully stabilized
- The high Cr amounts lead to the formation of a dense Cr-rich oxide layer at the surface, which is further stabilized by the addition of Si, Al, or Nb
- Higher amount of solid solution strengtheners (Mo, W) in fcc lattice than in bcc lattice
- Applications: heat exchangers, exhaust pipe systems for e.g. trucks
- Examples: X3CrNiMoN 17-13, X5NiCrAlTi 31-20, X12CrNiMoNb 20-15

Schematic, oxide layer on steel ccontaining Si



High temperature oxidation behaviour

- Oxidation behaviour is characterized by measuring the weight gain as a function of time due to oxide layer growth
- High alloy steels have a significantly better oxidation behaviour than low alloy or carbon steels due to dense Cr-rich oxide layer

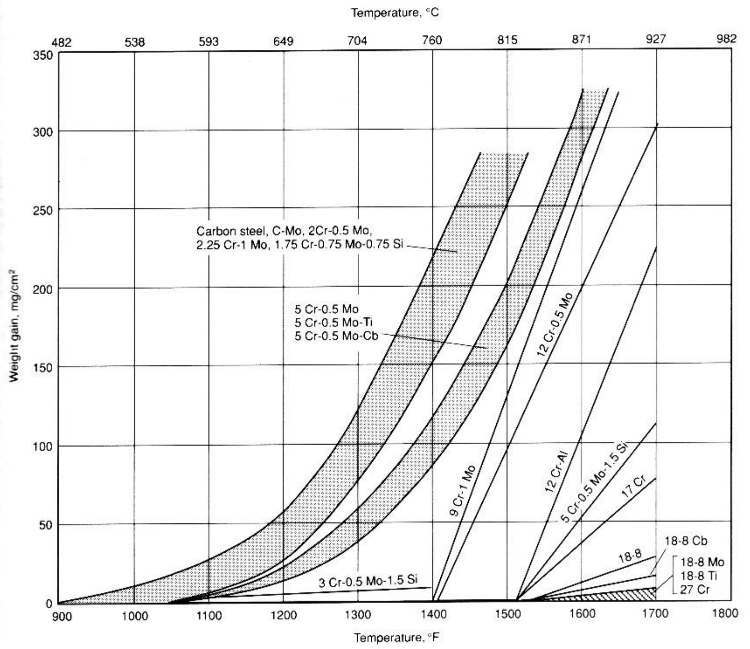


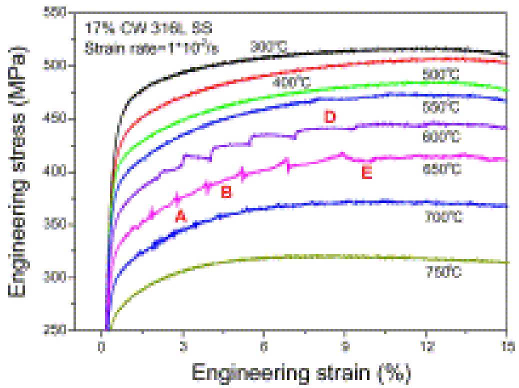
Fig. 3 Oxidation resistance of carbon, low-alloy, and stainless steels in air after 1000 h at temperatures from 590 to 930 °C (1100 to 1700 °F). Source: Ref 2

Steels for elevated temperature applications

Mechanical properties

Alloy	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
X20CrMoV 12-1 (martensitic)	500 (RT) 250 (550°C)	750-850	16
X3CrNiMoN 17-13 (austenitic)	260 (RT) 125 (550 °C)	550-750	35
X5NiCrAlTi 31-20 (austenitic)	200 (RT) 90 (550 °C)	500-750	35
X3CrNiMo 13-4 (nickel martensitic)	550 (RT) 460 (400 °C)	760-1000	16-18
X5CrNiMoCuNb 14-5 (nickel martensitic)	720-1000	930-1270	10-15

High temperature mechanical proprties of SS316L



/S.G. Hong,, J. Nuclear Mater. 328(2-3) (2004) 232-242/

Steels for elevated temperature applications

Creep properties

- Austenitic steels have a higher creep resistance than ferritic or ferritic/martensitic steels
- Reasons
  - Higher amount of solid solution strengtheners
  - Significantly lower diffusion coefficients of fcc lattice
  - Lower stacking fault energy → dislocations tend to produce stacking faults

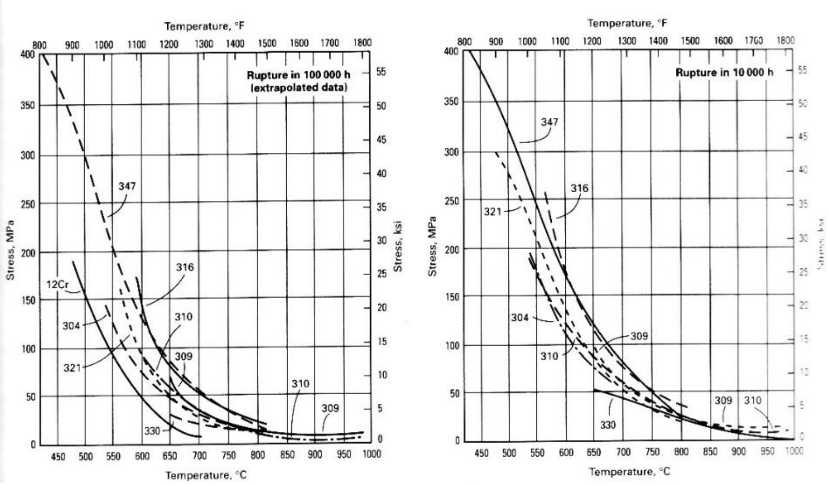


Table 5.2 **A Tabulation of Diffusion Data**

Diffusing Species	*Host Metal*	$D_0(m^2/s)$	*Activation Energy Q_d* *kJ/mol*	*eV/atom*
Fe	α-Fe (BCC)	2.8×10^{-4}	251	2.60
Fe	γ-Fe (FCC)	5.0×10^{-5}	284	2.94
C	α-Fe	6.2×10^{-7}	80	0.83
C	γ-Fe	2.3×10^{-5}	148	1.53

Learning objectives

- Fe-Fe_3C diagram; main phases in steel including their crystal structures
- Schaeffler diagram and its application; concept of Cr- and Ni-equivalents
- The most important alloying elements in steels and their main roles; the main ferrite and austenite stabilizers
- Understand and apply steel nomenclatures
- Some typical microstructures of steels and how to explain them.
- Heat treatment of steels
  - Understand how heat treatments affect the phases, microstructures and properties of steels
  - Read and understand TTT and CCT diagrams
  - Sketch simple temperature-time-profiles to obtain desired properties (e.g. high hardness, ductility etc.) of certain steels

Learning objectives

- Stainless steels
  - Sub-classifications of stainless steels
  - Main elements and rough compositional ranges of stainless steel
  - Understand why stainless steels are "stainless“
  - Typical applications
- AHSS/TRIP/TWIP steels
  - Sub-classification of AHSS/TRIP/TWIP steels
  - Main alloying elements and compositional ranges
  - Explanation of the TRIP/TWIP effect; what determines the TRIP/TWIP effect?
  - Formation of stacking faults; concept of stacking fault energy and role of Mn on SFE
  - Typical applications
- Steels for elevated temperature applications
  - Sub-classification of these steels
  - Main alloying elements and rough compositional ranges
  - Understand the high-temperature strengthening mechanisms in steels?
  - Typical applications