I. Physical metallurgy

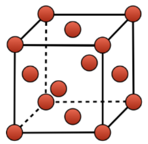
1. Classes and properties

Class	Typical properties
Metal Alloys	1) Thermal + electric conductivity 2) Ductility 3) Castable 4) Reflective
Ceramics	1) High T resistance (High E, low α) 2) High compression strength 3) Thermal + electric insulator 4) Wear resistance
Polymers	1) Cheap 2) Thermal + electric insulator 3) Corrosion resistance 4) Moldable

1.1 Structural model of metals

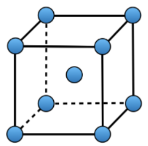
$$\phi = \frac{\text{Volume occupied by atoms in unit cell}}{\text{Total volume of unit cell}}$$

1.1.1 FCC (Face-centered cubic)



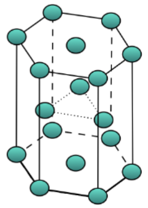
- Packing efficiency: $\phi \approx 74\%$
- Many slip systems (12)
- Closest pack direction

1.1.2 BCC (Body-centered cubic)



- Packing efficiency: $\phi \approx 68\%$
- Many slip systems (6)
- Not closest pack direction
- Cottrell atmosphere

1.1.3 HCP (Hexagonal close-packed)



- Packing efficiency: $\phi \approx 74\%$
- Very few slip systems (3)
- Closest pack direction

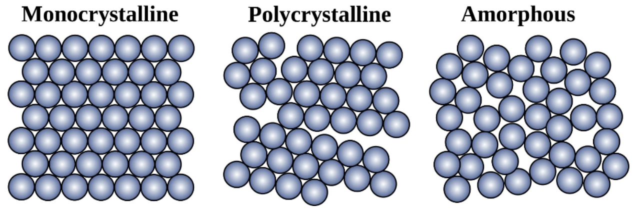
1.2 Structural model of ceramics

- Ionic bonding, complex crystal structures (ceramics), amorphous (glasses)
- Brittle, but high chemical and thermal resistance
- Insulators
- Wear-resistant (e.g. ferro-/piezoelectricity)

1.3 Structural model of polymers

- Macromolecules (10^3 to 10^5 C atoms)
- Weaker intermolecular bonds but strong atomic bond in molecular chain
- Electrically and thermally insulating
- Cheap, moldable, massive waste problem, pollutant
- Matrix for many composite materials (no recycling)

1.4 Amorphous and crystalline materials



1.4.1 Amorphous materials

- No crystal lattice (e.g. quartz glass, polymers)
- Atomic distances defined by chemical bonds
- Bond angles are variable

Field: inorganic classes (also Gorilla glass), metallic glasses (ferrous transformer sheet metal), amorphous plastics (PMMA - plexiglass, COC, ...)

1.4.2 Crystalline materials

- Crystal lattice (e.g. metals, ceramics, quartz)
- Atomic distances and bonding angles are defined

1.4.3 Monocrystalline materials

Only for special applications, expensive.
Field: single-crystal turbine blades (T $>$ 1000°C, creep-resistant), semiconductors, MEMS components made of silicon (gyroscopes in smartphones, accelerometers), optical elements (laser crystals, $\lambda/4$ plates, crystals for frequency doubling of lasers).

1.4.4 Polycrystalline materials

Most metal components are polycr. (made of many grains/crystals).

1.5 Directional dependence

1.5.1 Anisotropy and Isotropy

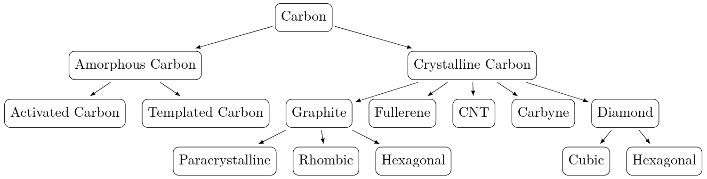
- **Anisotropic**: properties depend on the direction (eg. single crystals, wood, composites)
- **Isotropic**: properties do not depend on direction (eg. polycr. metals, amorphous materials)
- **Quasi-isotropic**: properties microscopically depend on the direction but not macroscopically

1.6 Polymorphism (Allotropy)

1.6.1 Iron

- α-Fe (ferrite, BCC) $\rightarrow$ below 911°C
- γ-Fe (austenite, FCC) $\rightarrow$ 911°C to 1392°C
- δ-Fe (ferrite, BCC) $\rightarrow$ 1932°C to 1536°C

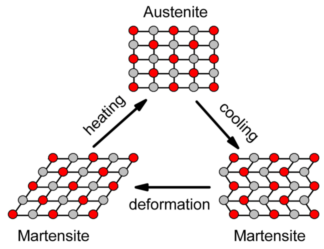
1.6.2 Carbon



1.6.3 Other materials

- Titanium: HCP $<$ 880°C , BCC $>$ 880°C
- Shape memory allory (eg. NiTi)
- Zirconia (high crack resistance due to phase transformation toughening)
- Ferro- and piezoelectric materials (eg. PZT, quartz, ...)

1.6.4 Shape memory alloy (SMA)



NiTi is a SMA used for screen lock of tablet notebooks, medtech and spectacle frames.

1.7 Microstructure and phases

1.7.1 Homogeneous microstructure

They have only one phase and crystal structure. A phase can be either crystalline or amorphous (eg. only iron crystals).

1.7.2 Heterogeneous microstructure

They have multiple phases and many types of crystal structures (eg. graphite and iron).

1.8 Alloys

An alloy is a metallic material of at least 2 types of atoms:

- Metal + metal (iron-nickel, gold-silver, tin-lead, aluminum-copper)
- Metal + non-metal (iron-carbon, nickel-phosphorus)

1.8.1 Microstructure of alloys

- **Solid solution crystal**: homogeneous, single-phase, only one type of crystal
- **Mix of different crystal types**: heterogeneous, multi-phase

2. Metal structures and crystal lattice defects

2.1 Lattice defects

2.1.1 0-dimensional defects

Point defects due to vacancies and impurity atoms.

2.1.2 1-dimensional defects

Line defects due to dislocations. Edge dislocations insert an extra half-plane of atoms in the crystal, distorting the nearby planes of atoms.

2.1.3 2-dimensional defects

Surface defects due to grain boundaries. Crystal growth starts at multiple locations within the molten metal

Crystallization from a melt: (1) homogeneous melt, (2) nucleation of crystals, (3) crystal growth surrounded by residual melt, (4) fully solidified polycrystalline structure with grain boundaries.

2.1.4 3-dimensional defects

Volume defects due to precipitations, inclusions, voids, cracks in the crystal structure.

3. Elastic and plastic deformation

3.1 Elastic deformation

The coefficient of thermal expansion α is inversely proportional to: Young's Modulus E, Bonding energy, Melting temp.

3.2 Elastic constants of isotropic materials

3.2.1 Elastic stress, strain, and Young's modulus

$$\varepsilon_x = \frac{\sigma_x}{E} \iff \sigma_x = \frac{E}{\varepsilon_x}$$

3.2.2 Poisson's ratio ν

When a material is stretched in x, it tends to contract in y, z:

$$\nu = -\frac{\varepsilon_{y,z}}{\varepsilon_x}$$

3.2.3 Relation between 3 isotropic elastic constants G

$$G = \frac{E}{2(1+\nu)} = \frac{\sigma}{2\varepsilon_x(1+\nu)}$$

3.3 Plastic deformation in metals

The plastic deformation is permanent and non-reversible

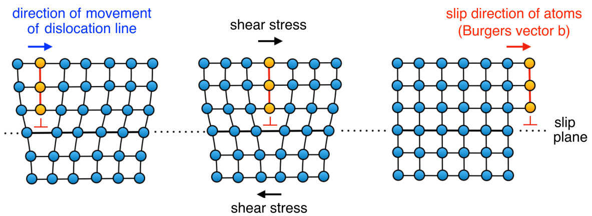
3.3.1 At room temp T_R

- Dislocations move on densely packed slip planes in densely packed directions
- Smaller slip distances require less external force or energy

3.3.2 At high temps

The metal creeps, leading to diffusion of atoms, especially at grain boundaries.

3.4 Simplified dislocation slip model



3.5 Slip systems

3.5.1 Slip systems in FCC metals

FCC metals have 12 close packed systems, making them **soft and highly ductile** (eg. Au, Ag, Cu, Al, α-Fe).

3.5.2 Slip systems in HCP metals

HCP metals are closely packed but deform on only one slip plane with 3 slip systems, resulting in **limited ductility** (eg. Ti, Zn, Mg).

3.5.3 Slip systems in BCC metals

BCC metals have 48 slip systems but are less closely packed, leading to **higher strength and lower ductility** (eg. α-Fe, Cr, W, Mo, Ta, Nb).

3.6 Metals crystal structure vs Ductility

Metal	Ductility	Packing structure	Slip systems	Slip system orientation
FCC	Highest ductility among metals	Closest-packed (74%)	4 slip planes $\rightarrow$ 12 slip systems	Very high probability of favorable orientation (Schmid's law)
BCC	Lower ductility than FCC, but still generally good	Less closely packed (68%)	Many slip planes and slip systems	Strength often higher than FCC metals
HCP	Limited ductility under normal conditions	Closest-packed (74%)	Only 1 slip plane $\rightarrow$ 3 slip systems	Low probability of favorable orientation ($-45°$ to load axis)

3.7 Cottrell atmospheres and Dislocation pinning

- In α-Fe with a BCC structure (ferrite), the sites for interstitial atoms are much smaller than γ-Fe (austenite)
- Carbon atmos in ferrite diffuse into the distortion fields near dislocation lines, forming Cottrell atmospheres
- Causes upper yield point (R_{eH}) in tensile tests and brittle fracture at low temps
- During plastic deformation, dislocations must first break freefrom the Cottrell atmosphere.

4. Strenghtening mechanisms

Dim	Lattice Defect	Strengthening Mechanism	Increase in 0.2% Yield Strength
0-D	**Substitution / Interstitial atoms** with concentration of c in the solid solution crystal	Solid solution hardening	$\Delta R_{p0.2} \sim c^{1/2}$
1-D	**Dislocations** (dislocation density N)	Strain (cold-work) hardening	$\Delta R_{p0.2} \sim N^{1/2}$
2-D	**Grain boundaries** defining an average grain size of d	Grain boundary hardening strength and ductility still good	$\Delta R_{p0.2} \sim d^{-1/2}$
3-D	**Coherent precepitates** with a size of D (also: semi-coherent and incoherent precipitates and dispersion particles)	Precipitation hardening	$\Delta R_{p0.2} \sim D^{1/2}$

4.1 Solid-solution hardening

- Impurity atoms in a solid solution create lattice distortion fields that impede dislocation motion
- Interstitial atoms cause stronger lattice distortions than substitutional atoms, leading to a greared strengthening effect
- A larger atomic radius mismatch and higher impurity concentration both increase the stremgthening effect
- **Result**: increased strength but reduced ductility

4.1.1 0-d: SSH application field

Al-Mb and Al-Mg alloys (5000 and 3000) for automotive sheet metal, airplane outer skin, beverage cans; Structural and stainless steels; Gold jewerly (Au with Ag, Cu, Ni, Pt, Pd, ...)

4.2 1-d: Strain hardening (Work hardening)

- Cold work increases dislocation density $\rightarrow$ dislocation entanglement
- Cold working / cold forming: below the recrystallization temp
- Hot forming: above the recrystallization temp
- Recrystallization temp: $(T_{\text{recr}} \approx 0.4, T_m\ [\text{K}])$
- **Result**: strength increases but ductility decreases

4.2.1 SH application field

Any cold-formed parts: cold rolled sheet metal, neckline holes in sheet metal of a washing machine drum, cold pressed steels.

4.3 2-d: Grain boundary hardening

- Smaller grains increase strength: grain boundaries hinder dislocation slip
- Not suitable at high temp: grain growth reduces strength and ductility
- **Result**: strength and ductility both increased (statistical grain orientation, Schmid's law)

4.3.1 GBH application field

High-strength fine-grain or even Q+T structural steels: cranes, oil platforms, bridges, shipbuilding.

4.4 3-d: Precipitation hardening

- Increase in strength by coherence of the precipitates and size and number of the precipitates
- **Result**: increase in strength but decrease in ductility

4.4.1 Effect of precipitate coherence on strength

Coherent: lattice planes match, strong strain fields in the matrix $\rightarrow$ large strength increase.

Semi-coherent: misfit dislocations at the interface reduce lattice strain $\rightarrow$ strength decreases.

Incoherent: lattice planes mismatch; little matrix distortion $\rightarrow$ small strength increase.

4.4.2 PH application field

High-strength aluminum alloys for aerospace, maraging steels, stainless PH steels, highly temp-resistant Ni base superalloys for turbine blades.

II. Strength and Ductility

5. Properties of material

Property	Context	Characteristic values
Mechanical	Withstanding static or dynamic loads/forces/stress	Young's modulus, static strength, hardness, fatigue strength, creep strength, toughness, ductility
Technological	Material processing	Formability, welding suitability, castability, hardenability
Physical	Various functional properties	Electrical and thermal conductivity, transparency, magnetizability, refraction index, ...
Chemical	Resistance to normal or harsh environments	Resistance against corrsion, UV light or oxidizing agents, food safety, biocompatibility, toxicity

5.1 Failure hypotesis and Material testing methods

Failure hypothesis	Material testing methods
Failure of metals due the plastic deformation (dislocation slip) under static stress	Tensile test, compression test, bending test, torsion test
Failure due the crack formation and crack growth under dynamic oscillating stress	Fatigue tests (HCG, LCF)
Failure due the crack growth under sudden impact (crack growth under constant load)	Impact notch toughness test (Fractures mechanics)
Failure due the plastic deformation at high temperatures (diffusion, especially along the grain boundaries) under static stress	Creep test (or relaxation test)

6. Tensile test

6.1 Engineering stress and stress conditions

6.1.1 Normal vs Engineering vs Shear stress

Engineering stress is the force F acting on the original cross-sectional area S_0. Normal stress is the normal force F_N that acts perpendicularly to S_0. The shear stress τ is the force F_Q parallel to S_0.

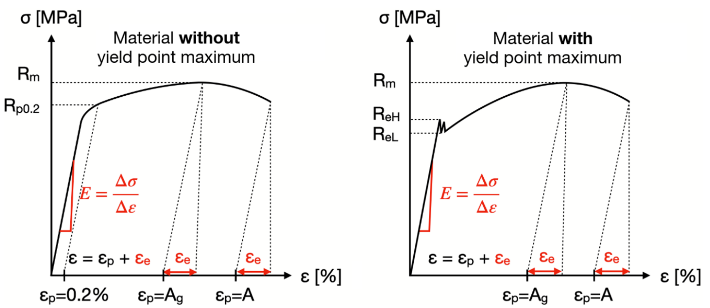
$$\sigma = \frac{F}{S_0} \quad ; \quad \sigma_N = \frac{F_N}{S_0} \quad ; \quad \tau = \frac{F_Q}{S_0} \quad ; \quad \sigma = E \cdot \varepsilon$$

6.1.2 Engineering strain ε

Engineering strain is the ratio of the change in length to the original length of the material under load:

$$\varepsilon = \frac{\Delta L}{L_0}$$

6.2 Stress-strain behavior of metals



6.2.1 Yield stress R

- **R_{eH}**: Upper Yield point
- **$R_{p0.2}$**: 0.2% Yield Stress
- Without max yield point: $\sigma_{max} = R_{p0.2}$

6.2.2 Yound's modulus

Slope of the linear-elastic region:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

6.2.3 Tensile strength R_m

It correspondes to the stress at the max of the stress-strain curve. With max yield point: $\sigma_{max} = R_m$; upper yield point R_{eH}.

6.3 Fracture strain A

Plastic strain at fracture is defined with respect to the initial specimen length L_0. (eg. $L_0 = 50\text{mm} \to A_{50\text{mm}}$)

6.3.1 Uniform strain A_g

It corresponds to the plastic strain at maximum load before necking begins.

6.3.2 Contraction at fracture Z

$$Z = \frac{\Delta S}{S_0}$$

7. Other quasi-static mechanical tests

7.1 Bending test

A specimen is placed on two supports, loaded in bending (typically at midspan) until failure, and the maximum bending stress is calculated.

7.2 Torsion test

A cylindrical specimen is clamped and twisted by applying torque until yielding or fracture, and the torsion strength is taken from the peripheral shear stress.

7.3 Creep and relaxation tests (High temps)

- Creep: time-dependent deformation under constant stress
- Relaxation: decreasing stress under constant strain
- At high T, strength becomes time- and strain-rate-dependent
- Strain changes with time under constant load
- Creep/relaxation tests assess heat-resistant materials for high-T applications (eg. steels and Ni alloys above 400°C)

III. Steel - technology and applications

Stees is a Carbon-iron alloy. Has very good properties: strength, ductility, toughness, formability, machining, weldability. Can be heat-treated due its polymorphism.

8. Steel Technology

8.1 Blast furnace and Pig iron

- **Process**: reduction of iron oxide with coke
  $Fe_2O_3 + 3C \to 2Fe + 3CO$
- **Product**: pig iron (3-5% C, also Mn, Si, S, P)

8.2 Crude steel production

- Pig iron refined to crude steel by reducing carbon content
- Oxygen-Blown Converter (OBC): refining with oxygen
- Electric Furnace (EF): melts scrap steel or direct-reduced iron (sponge iron) to crude steel

8.3 Secondary metallurgy

- Crude steel further purified and adjusted to final composition in a ladle furnace
- Process:
  - Deoxidation (chemical or vacuum)
  - Advanced purification (electroslag remelting (ESR), vacuum arc remelting (VAR), powder metallurgy (PM))
  - Alloying additions

8.4 Semi-finished products

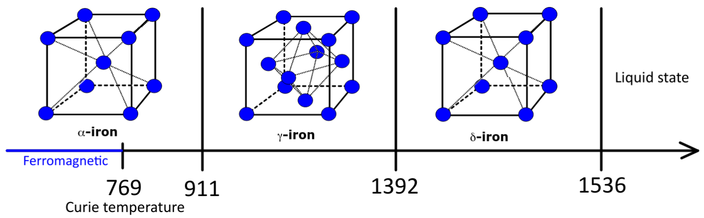
- Produced mainly by continuous casting (slabs, billets)
- Formed into sheets, plates, wires, rods, pipes, and profiles by hot or cold rolling/drawing

8.5 Important alloying elements

Function	Alloying elements
Hardenability	Mn, Cr, Ni, Mo, V, Si
Grain refinement	Al, V, Ti, Nb
Corrosion resistance	Cr (>12%), Cu, Ni, Si, Mn, Mo, N
Wear/heat resistance	Cr (>1%), Mo, V, Al, Ti, Nb, Mo
Scale resistance	Cr, Al, Si

9. Microstructure formation

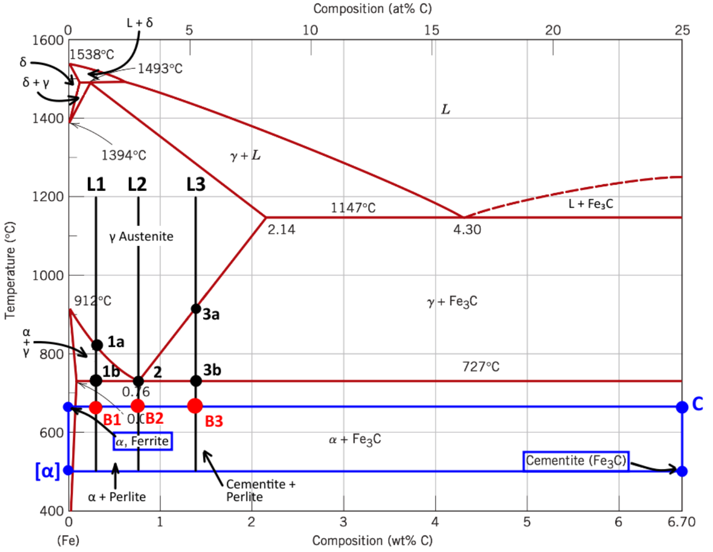
9.1 Polymorphism of iron



9.2 Metastable iron-iron carbide phase diagram

9.2.1 Phase diagram

Symbol	Phase	Description
α	Ferrite	BCC structure, very low carbon solubility ($\leq$ 0.022 wt% C at 727°C), soft and ductile
γ	Austenite	FCC structure, higher carbon solubility ($\leq$ 2.14 wt% C at 1147°C), though and formable
δ	Delta ferrite	BCC form stable only at high temperatures (> 1394°C)
Fe_3C	Cementite	Hard, brittle iron carbide with 6.70 wt%
L	Liquid phase	Molten iron-carbon alloy



9.3 Microstructure formation of Steel (Slow Cooling)

Type	Composition range wt% C	Resulting microstructure	Properties
Hypoeutectic	< 4.3	Primary austenite +ledeburite	toughness ↑ brittleness ↓ machinability ↑
Eutectic	4.3	Ledeburite (austenite +cementite)	castability ↑↑ hardness ↑ ductility ↓
Hypereutectic	> 4.3	Primary cementite +ledeburite	hardness ↑↑ wear ↑↑ machinability ↓ toughness ↓
Hypoeutectoid	< 0.8	Primary ferrite +pearlite	ductility ↑↑ weldability ↑↑ formability ↑↑ hardness ↓
Eutectoid	0.8	Pearlite (ferrite +cementite)	hardness ↑ toughness ↑ ductility ↓
Hypereutectoid	> 0.8	Primary cementite +pearlite	hardness ↑↑ wear ↑↑ toughness ↓

9.3.1 Eutectoid steel final microstructure at T_R

The microstructure is 100% pearlite, consisting of ferrite lamellae (soft, ductile phase forming the light layers), and cementite lamellae (hard, brittle phase forming the dark layers).

9.3.2 Hypereutectoid steel final microstructure at T_R

Final components are grain boundary cementite (hard and brittle, formed before eutectoid reaction) and pearlite (lamellar mixture of ferrite and cementite).

9.4 Faster cooling / Quenching

Fast cooling of steels changes the transformation behavior compared to equilibrium cooling.

9.4.1 Fast cooling

- Transformation temps shift to lower values
- Pearlite become finer and forms over a wider Temp range
- Martensite and bainite can form

9.5 Ferrite

- α-iron (BCC), stable at low temps
- Very low carbon solubility $\to$ carbon tends to form cementite
- Soft and ductile $\to$ good formability and toughness

9.6 Austenite

- γ-iron (FCC), stable at higher temps
- High carbon solubility $\to$ carbon dissolves readily
- Parent phase for transf. to pearlite, bainite, and martensite

9.7 Pearlite

- Forms from austenite during slow cooling (eutectoid trans.)
- Lamellar mixture of ferrite (α) and cementite (Fe_3C)
- Higher strength and hardness than ferrite, but lower ductility; finer lamellae give higher strength

9.8 Martensite

- Very fast cooling of austenite produces martensite
- Diffusion does not occur, so no ferrite or pearlite
- Lattice shear of FCC austenite produces BCT

9.9 Bainite

- Produced by a rapid cooling (250-500°C)
- Combined shear and limited diffusion; cementite precipitate
- Higher strength than pearlite, more ductile than martensite
- Good for high-performance components and tools

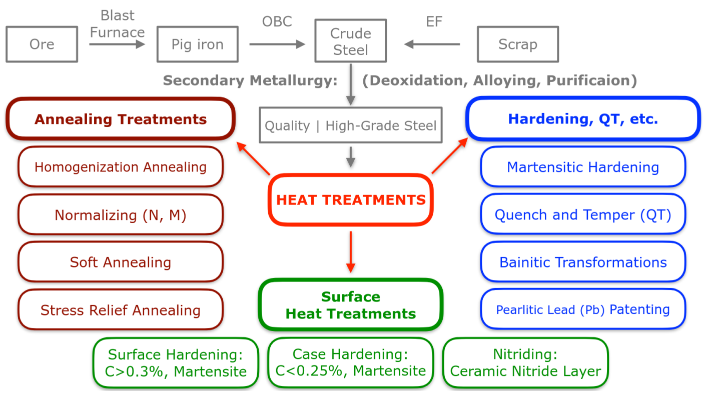
9.9.1 Upper bainite

- Forms at higher bainitic T (350-500°C)
- Ferrite needles with cementite lamellae at ferrite boundaries

9.9.2 Lower bainite

- Forms at lower bainitic T (250-350°C)
- Ferrite needles with fine cementite particles inside the ferrite

10. Heat treatments



IV. Hardness and Toughness

11. Hardness

It measures resistance against localized plastic deformation.

11.1 Hardness testing

11.1.1 Common testing methods

Testing method	Application
Vickers (HV)	Universal application
Rockwell (HCR)	For hard steels
Brinell (HB)	For soft steels and aluminum
Berkovich	For nanoindentation
Shore A, D	For rubber and plastic

Approximate relation: $R_m \approx 3\times$ HB or HV

11.2 Hardness Testing procedures

11.2.1 Indentation depth

Hardness is measured based on how deep the indenter penetrates the material.

11.2.2 Indentation area

Hardness is determined by the surface area of the indentation left in the material.

12. Notch Impact Toughness

12.1 Impact Notch Toughness test (Charpy)

- Applied mainly to structural steel (BCC)
- Shows the transition temp from ductile to brittle fracture
- Determines the absorbed impact energy (“notch toughness”)
- Failure hypotesis: crack propagation under sudden loads

12.2 Toughness

12.2.1 Material behavior

- **Tough material**: absorb high energy before fracture
- **Brittle material**: fracture with little energy absorbtion

12.2.2 Energy criterion

- **Ductile fracture**: if absorbes > 27 J of the impact energy
- **Brittle fracture**: if absorbes < 27 J of the impact energy