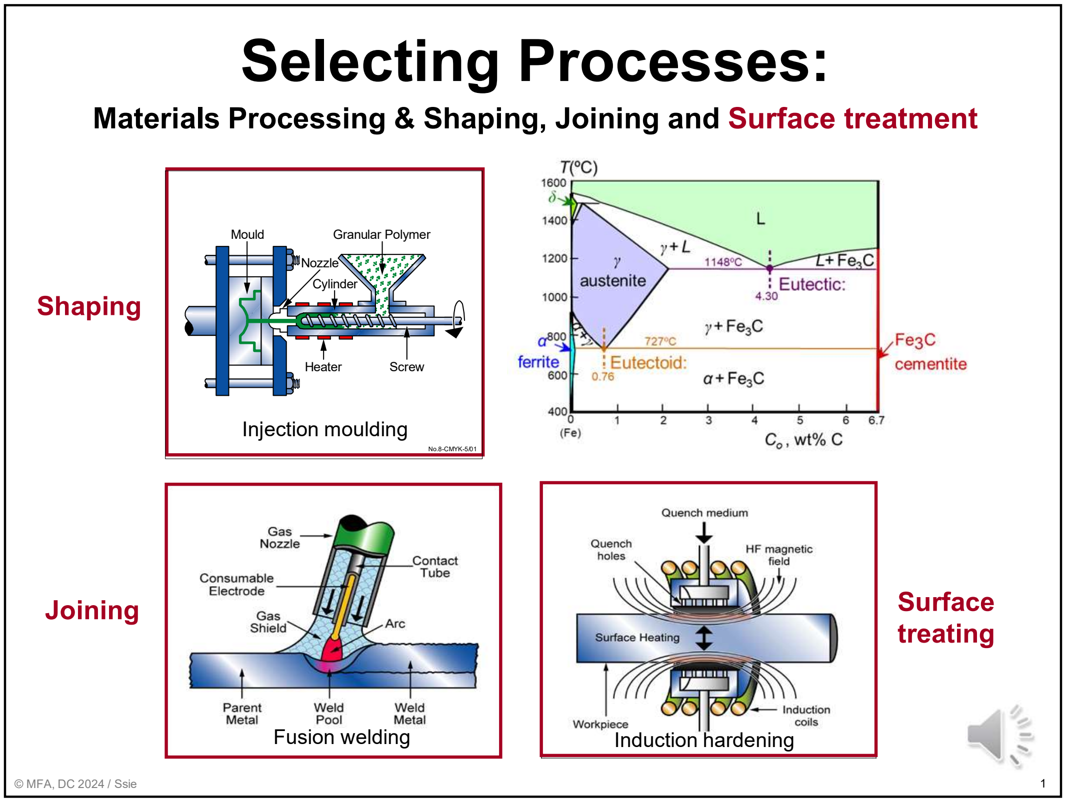

Selecting Processes:

Materials Processing & Shaping, Joining and Surface treatment

Shaping

Injection moulding

Joining

Fusion welding

Induction hardening

Surface treating

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The Units

Unit 1. The worlds of materials and processes: families, classes, members, attributes

Unit 2. Materials charts: mapping the world of materials

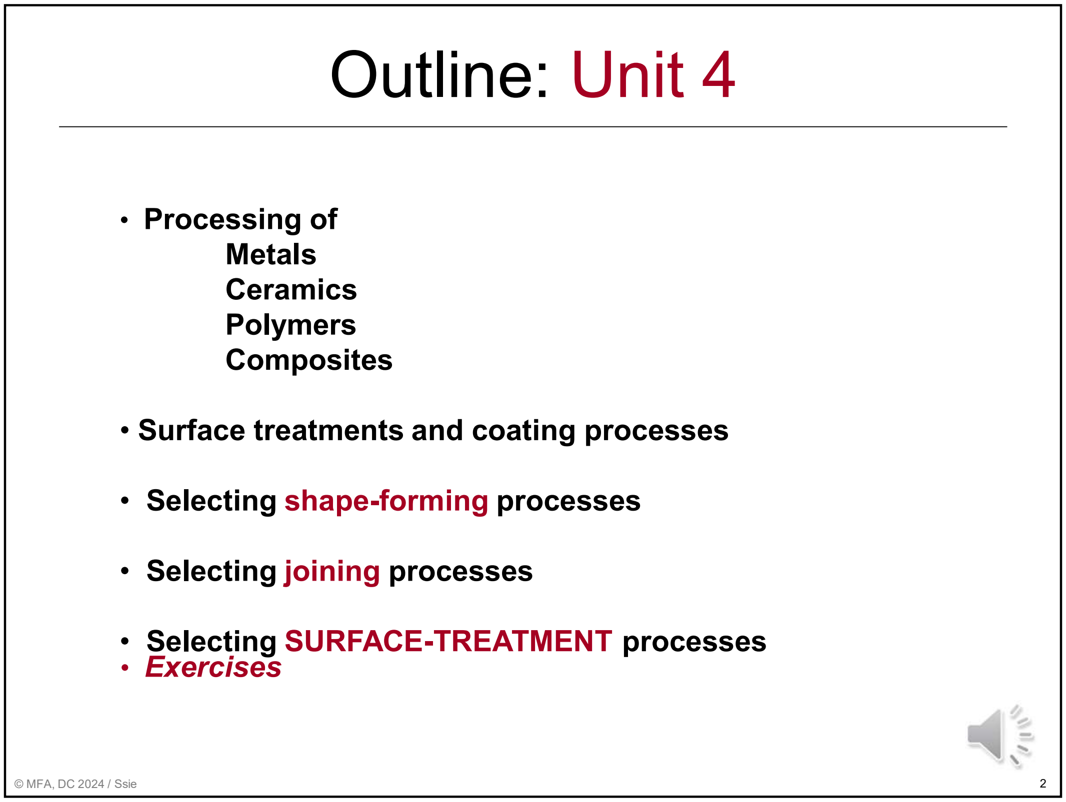
Unit 3. Translation and Screening: the first step in optimized selection

Unit 4. Selecting processes: shaping, joining and surface treatment

Unit 5. Ranking: refining the choice

Unit 6. Objectives in conflict: trade-off methods and penalty functions

Unit 7. Eco-selection: environmentally-informed material choice



Outline: Unit 4

- **Processing of**
  - **Metals**
  - **Ceramics**
  - **Polymers**
  - **Composites**
- **Surface treatments and coating processes**
- **Selecting shape-forming processes**
- **Selecting joining processes**
- **Selecting SURFACE-TREATMENT processes**
- ***Exercises***

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If materials are to be used, they must be **shaped**, **joined** and **finished**. The choice of material without is closely coupled to the way it will be processed. Here we examine the classification, characterization and selection of processes.

Applications and Processing of Metal Alloys

ISSUES TO ADDRESS...

- How are metal alloys classified and what are their common applications?
- What are some of the common fabrication techniques for metals?
- What heat treatment procedures are used to improve the mechanical properties of both ferrous and nonferrous alloys?

Classification of Metal Alloys

- Metal Alloys
  - Ferrous
    - Steels <1.4 wt% C
    - Cast Irons 3-4.5 wt% C
  - Nonferrous

Adapted from Fig. 11.1, *Callister & Rethwisch 10e*.

microstructure: ferrite, graphite/cementite

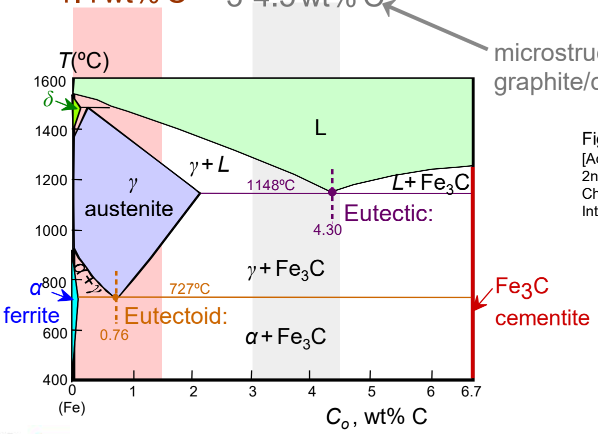

Fig. 9.24, *Callister & Rethwisch 10e*. [Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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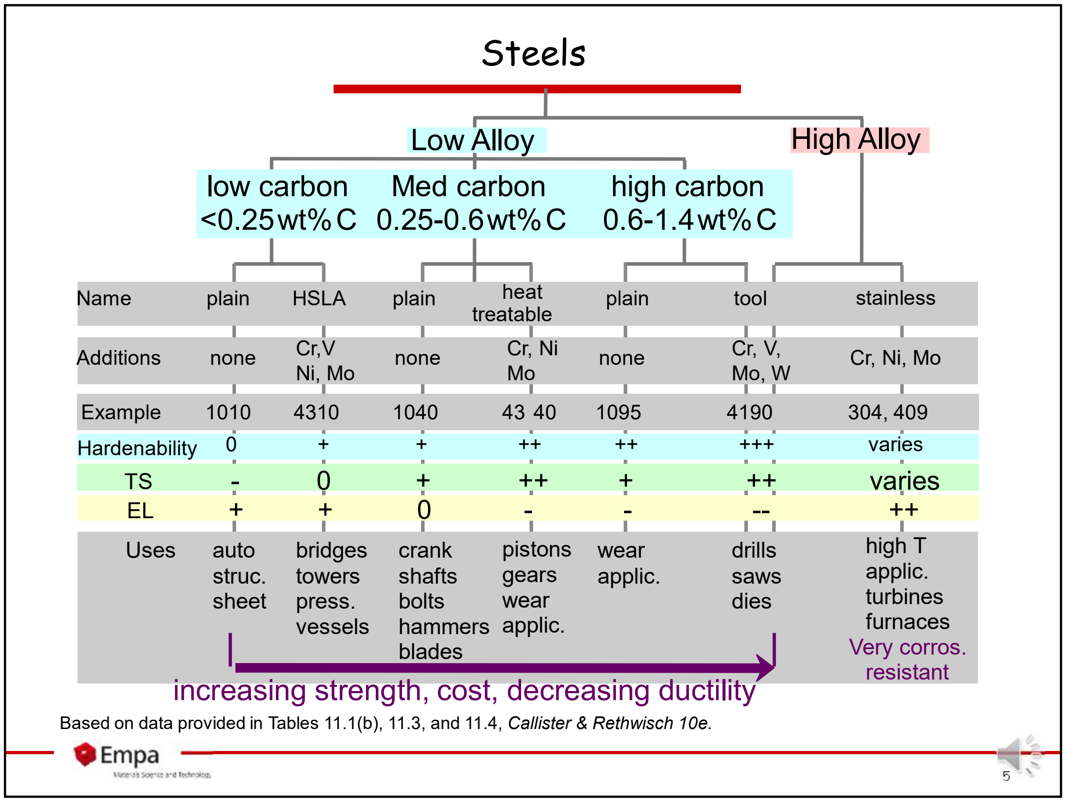


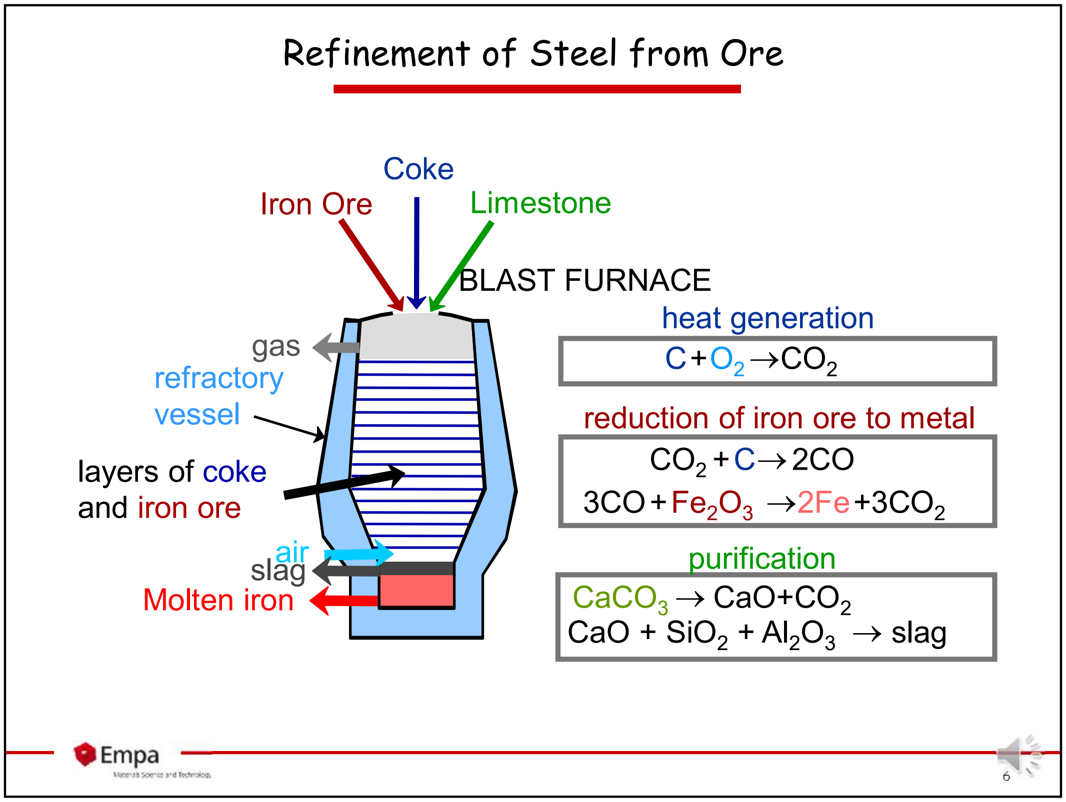
Steels

Low Alloy | High Alloy

	Low Alloy						High Alloy
	low carbon <0.25 wt% C		Med carbon 0.25-0.6 wt% C		high carbon 0.6-1.4 wt% C		
Name	plain	HSLA	plain	heat treatable	plain	tool	stainless
Additions	none	Cr,V Ni, Mo	none	Cr, Ni Mo	none	Cr, V, Mo, W	Cr, Ni, Mo
Example	1010	4310	1040	4340	1095	4190	304, 409
Hardenability	0	+	+	++	++	+++	varies
TS	-	0	+	++	+	++	varies
EL	+	+	0	-	-	--	++
Uses	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applic.	wear applic.	drills saws dies	high T applic. turbines furnaces Very corros. resistant

increasing strength, cost, decreasing ductility

Based on data provided in Tables 11.1(b), 11.3, and 11.4, *Callister & Rethwisch 10e.*



Refinement of Steel from Ore

heat generation

$C + O_2 \rightarrow CO_2$

reduction of iron ore to metal

$CO_2 + C \rightarrow 2CO$

$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$

purification

$CaCO_3 \rightarrow CaO + CO_2$

$CaO + SiO_2 + Al_2O_3 \rightarrow$ slag

Ferrous Alloys

Iron-based alloys

- Steels
- Cast Irons

Nomenclature for steels (AISI/SAE)
10xx Plain Carbon Steels
11xx Plain Carbon Steels (resulfurized for machinability)
15xx Mn (1.00 - 1.65%)
40xxMo (0.20 ~ 0.30%)
43xxNi (1.65 - 2.00%), Cr (0.40 - 0.90%), Mo (0.20 - 0.30%)
44xxMo (0.5%)

where xx is wt% C x 100
example: 1060 steel – plain carbon steel with 0.60 wt% C

Stainless Steel >11% Cr

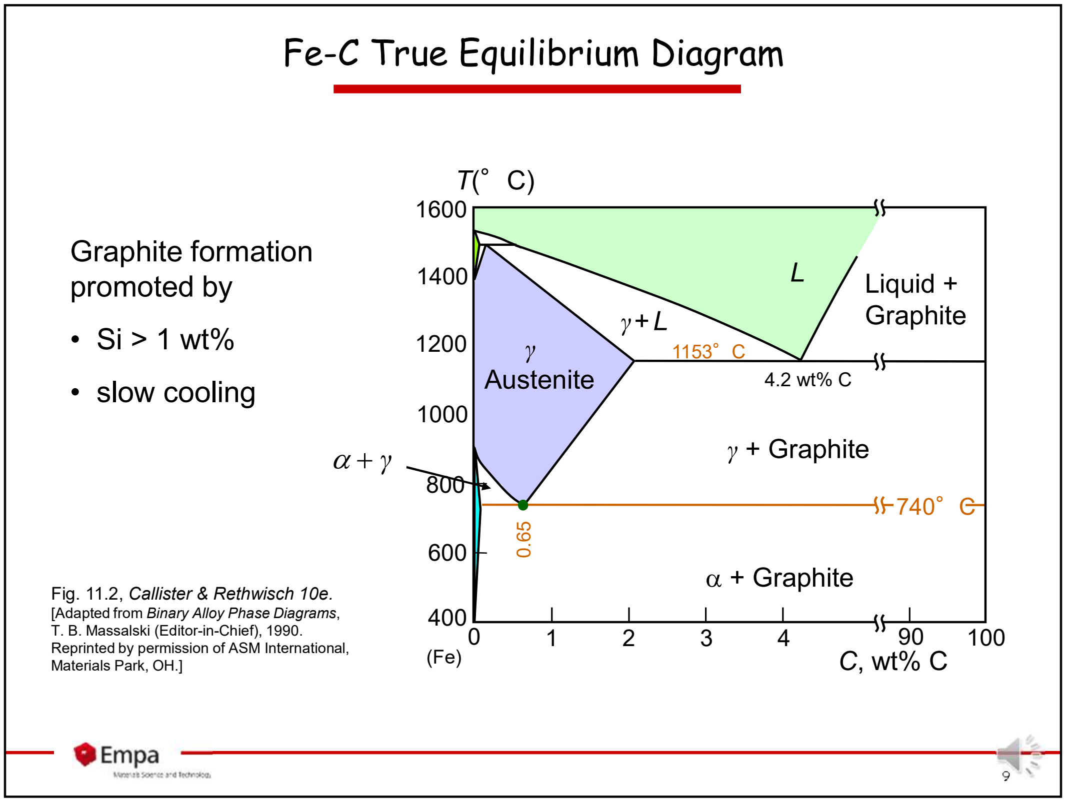
Cast Irons

- Ferrous alloys with > 2.1 wt% C
  - more commonly 3 - 4.5 wt% C
- Low melting – relatively easy to cast
- Generally brittle

- Cementite decomposes to ferrite + graphite

  $Fe_3C \rightarrow 3\ Fe\ (\alpha) + C\ (graphite)$

  - generally a slow process



Fe-C True Equilibrium Diagram

Graphite formation promoted by

- Si > 1 wt%
- slow cooling

Fig. 11.2, *Callister & Rethwisch 10e*.
[Adapted from *Binary Alloy Phase Diagrams*, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

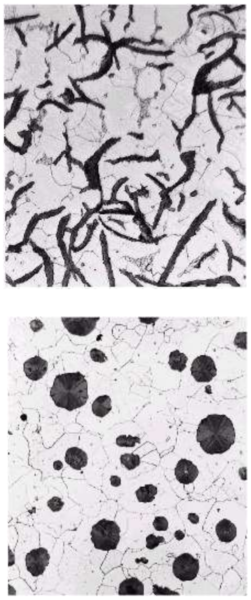
Types of Cast Iron

Gray iron

- graphite flakes
- weak & brittle in tension
- stronger in compression
- excellent vibrational dampening
- wear resistant

Ductile iron

- add Mg and/or Ce
- graphite as nodules not flakes
- matrix often pearlite – stronger but less ductile



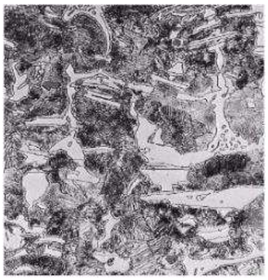
Figs. 11.3(a) & (b), *Callister & Rethwisch 10e.* [Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC (now the National Institute of Standards and Technology, Gaithersburg, MD]

Types of Cast Iron (cont.)

White iron

- < 1 wt% Si
- pearlite + cementite
- very hard and brittle

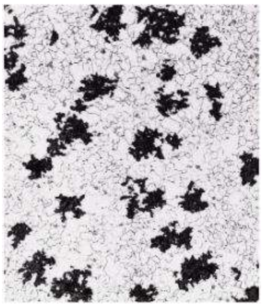
Figs. 11.3(c) & (d), *Callister & Rethwisch 10e.*



Courtesy of Amcast Industrial Corporation

Malleable iron

- heat treat white iron at 800-900° C
- graphite in rosettes
- reasonably strong and ductile

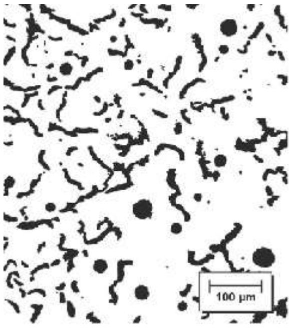


Reprinted with permission of the Iron Castings Society, Des Plaines, IL

Types of Cast Iron (cont.)

Compacted graphite iron

- relatively high thermal conductivity
- good resistance to thermal shock
- lower oxidation at elevated temperatures

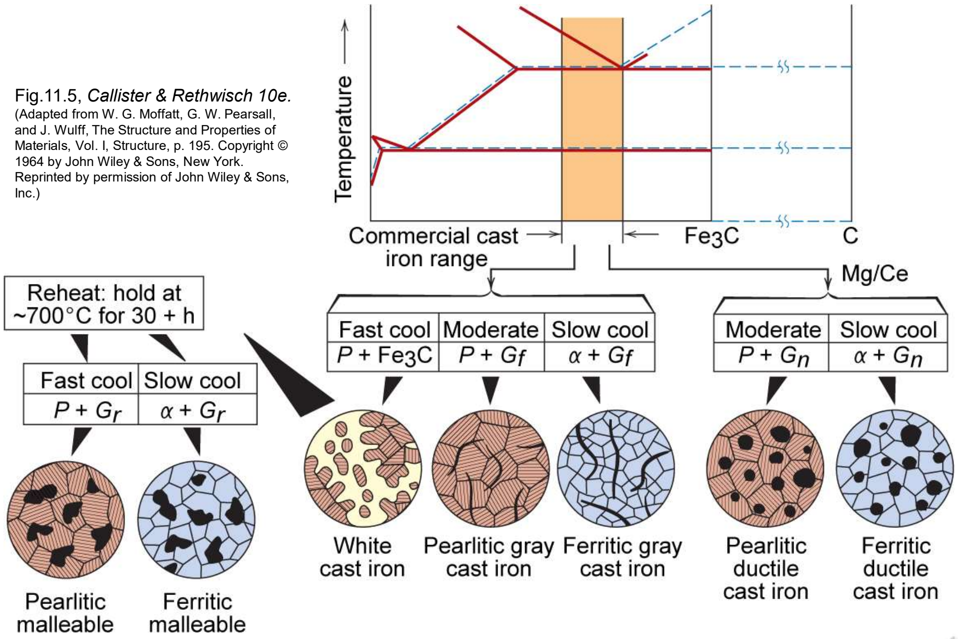


Courtesy of Sinter-Cast, Ltd.

Fig. 11.3(e), *Callister & Rethwisch 10e*.

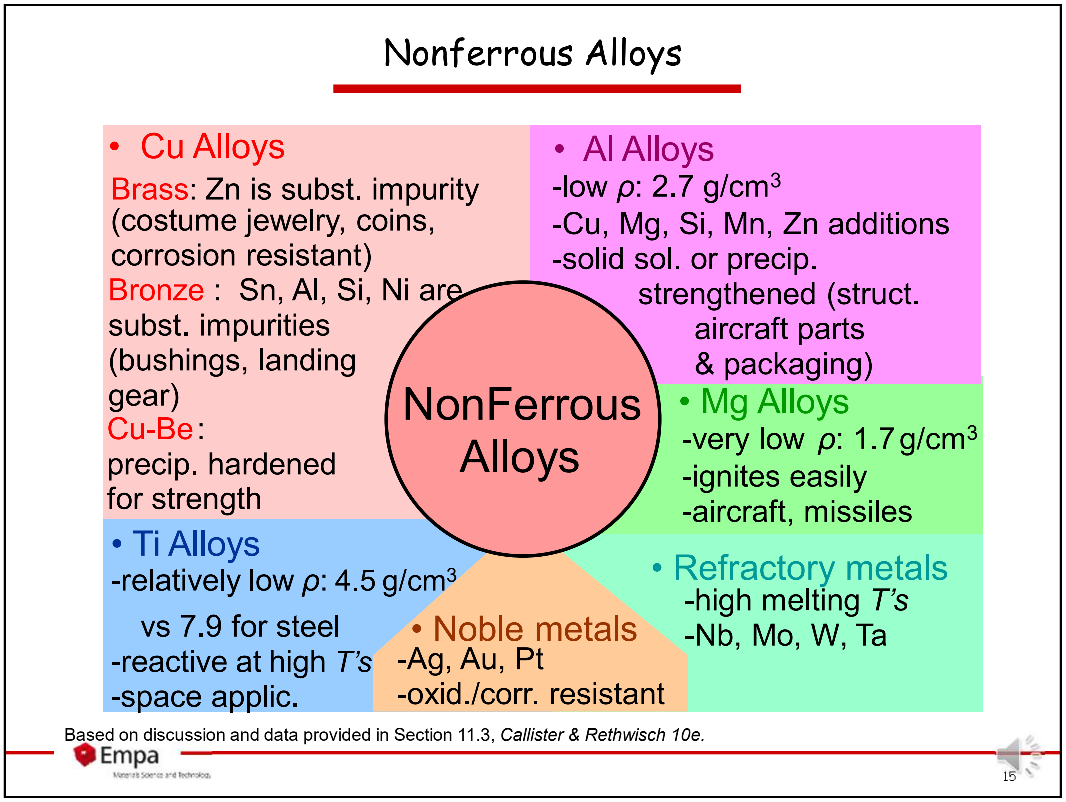
Production of Cast Irons

Fig.11.5, *Callister & Rethwisch 10e.* (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 195. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Limitations of Ferrous Alloys

1) Relatively high densities
2) Relatively low electrical conductivities
3) Generally poor corrosion resistance



Nonferrous Alloys

- Cu Alloys

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze : Sn, Al, Si, Ni are subst. impurities (bushings, landing gear)

Cu-Be: precip. hardened for strength

- Al Alloys

-low ρ: 2.7 g/cm^3
-Cu, Mg, Si, Mn, Zn additions
-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

NonFerrous Alloys

- Mg Alloys

-very low ρ: 1.7 g/cm^3
-ignites easily
-aircraft, missiles

- Ti Alloys

-relatively low ρ: 4.5 g/cm^3 vs 7.9 for steel
-reactive at high *T's*
-space applic.

- Noble metals

-Ag, Au, Pt
-oxid./corr. resistant

- Refractory metals

-high melting *T's*
-Nb, Mo, W, Ta

Based on discussion and data provided in Section 11.3, *Callister & Rethwisch 10e.*

Metal Fabrication

- How do we fabricate metals?
  - Blacksmith - hammer (forged)
  - Cast molten metal into mold

- Forming Operations
  - Rough stock formed to final shape

Hot working	vs.	Cold working
• Deformation temperature high enough for recrystallization		• Deformation below recrystallization temperature
• Large deformations		• Strain hardening occurs
		• Small deformations

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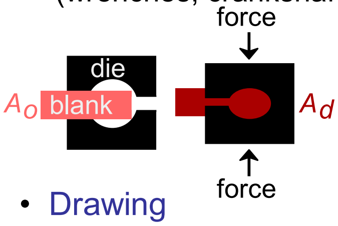
Metal Fabrication Methods (i)

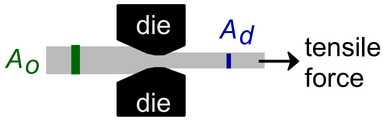
FORMING CASTING MISCELLANEOUS

- Forging (Hammering; Stamping)
  (wrenches, crankshafts)



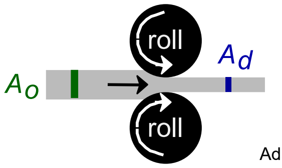
often at elev. *T*

- Drawing
  (rods, wire, tubing)



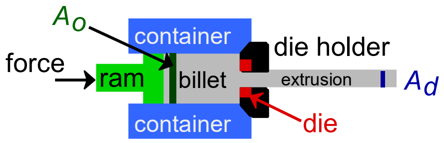
die must be well lubricated & clean

- Rolling (Hot or Cold Rolling)
  (I-beams, rails, sheet & plate)



Adapted from Fig. 11.9, *Callister & Rethwisch 10e.*

- Extrusion
  (rods, tubing)



ductile metals, e.g. Cu, Al (hot)

Metal Fabrication Methods (ii)

FORMING CASTING MISCELLANEOUS

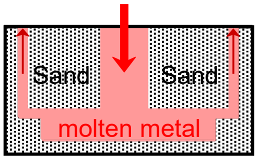
- Casting- mold is filled with molten metal
  - metal melted in furnace, perhaps alloying elements added, then cast in a mold
  - common and inexpensive
  - gives good production of shapes
  - weaker products, internal defects
  - good option for brittle materials

Metal Fabrication Methods (iii)

FORMING CASTING MISCELLANEOUS

- Sand Casting

  (large parts, e.g.,
  auto engine blocks)

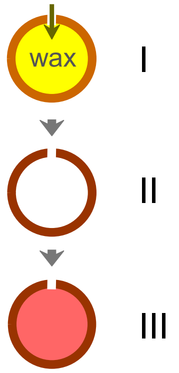


- What material will withstand $T > 1600^\circ$ C and is inexpensive and easy to mold?
- Answer: sand!!!
- To create mold, pack sand around form (pattern) of desired shape

Metal Fabrication Methods (iv)

FORMING CASTING MISCELLANEOUS

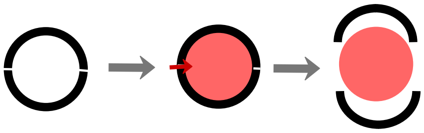
- Investment Casting
  (low volume, complex shapes
  e.g., jewelry, turbine blades)
  - Stage I — Mold formed by pouring plaster of paris around wax pattern. Plaster allowed to harden.
  - Stage II — Wax is melted and then poured from mold—hollow mold cavity remains.
  - Stage III — Molten metal is poured into mold and allowed to solidify.



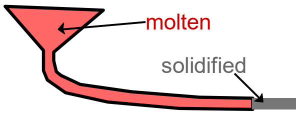
Metal Fabrication Methods (v)

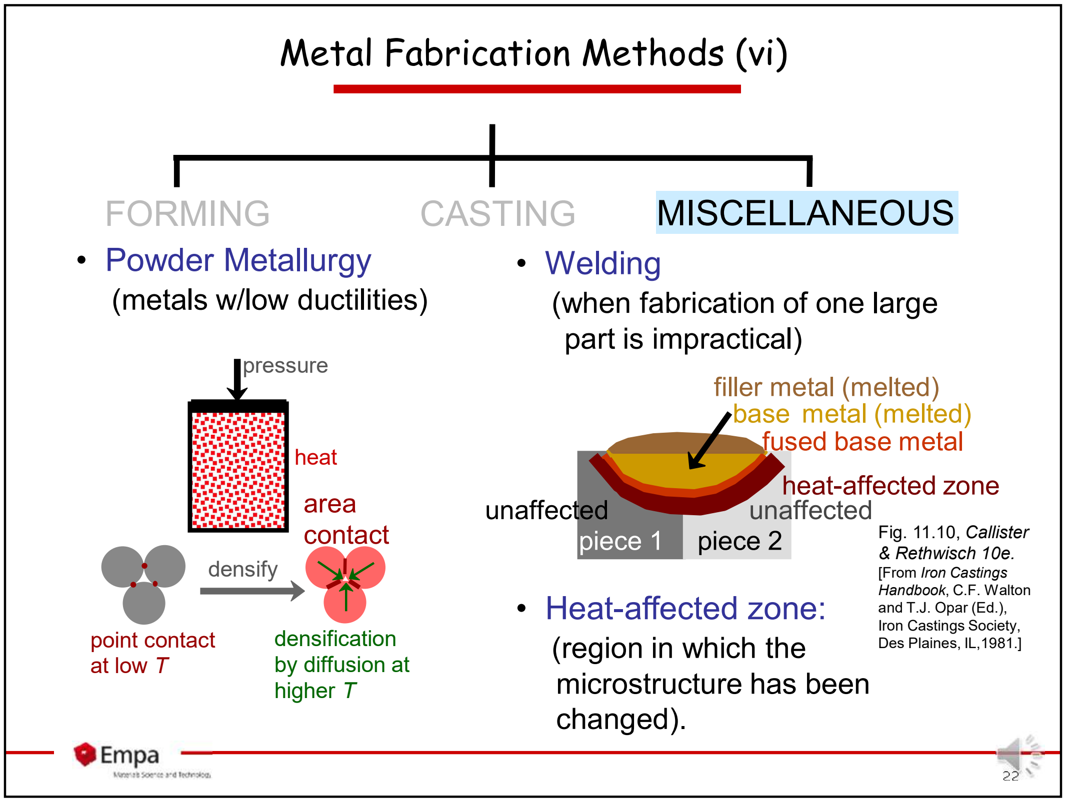
FORMING CASTING MISCELLANEOUS

- Die Casting
  - -- high volume
  - -- for alloys having low melting temperatures



- Continuous Casting
  - -- simple shapes (e.g., rectangular slabs, cylinders)





Metal Fabrication Methods (vi)

FORMING CASTING **MISCELLANEOUS**

- Powder Metallurgy
  (metals w/low ductilities)

- Welding
  (when fabrication of one large part is impractical)

Fig. 11.10, *Callister & Rethwisch 10e*. [From *Iron Castings Handbook*, C.F. Walton and T.J. Opar (Ed.), Iron Castings Society, Des Plaines, IL,1981.]

- Heat-affected zone:
  (region in which the microstructure has been changed).

Thermal Processing of Metals

Annealing: Heat to T_{anneal}, then cool slowly.

Types of Annealing

- **Stress Relief**: Reduce stresses resulting from:
  - plastic deformation
  - nonuniform cooling
  - phase transform.

- **Spheroidize** (steels): Make very soft steels for good machining. Heat just below $T_{\text{eutectoid}}$ & hold for 15-25 h.

- **Full Anneal** (steels): Make soft steels for good forming. Heat to get γ, then furnace-cool to obtain coarse pearlite.

- **Normalize** (steels): Deform steel with large grains. Then heat treat to allow recrystallization and formation of smaller grains.

- **Process Anneal**: Negate effects of cold working by (recovery/ recrystallization)

Based on discussion in Section 11.8, *Callister & Rethwisch 10e*.

Heat Treatment Temperature-Time Paths

a) Full Annealing

b) Quenching

c) Tempering (Tempered Martensite)

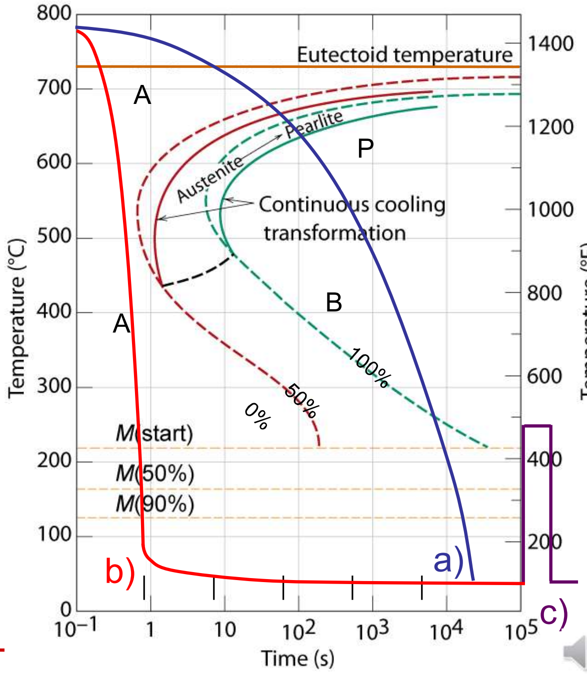


Fig. 10.25, *Callister & Rethwisch 10e*. [Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

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Hardenability -- Steels

- Hardenability – measure of the ability to form martensite
- Jominy end quench test used to measure hardenability.

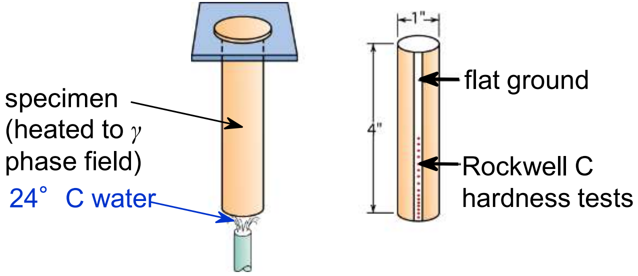


Fig. 11.15, *Callister & Rethwisch 10e*.
(Adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1978.)

- Plot hardness versus distance from the quenched end.

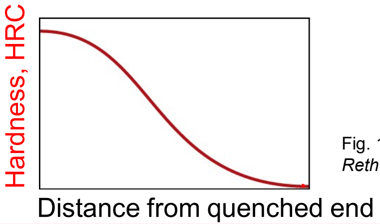


Fig. 11.16, *Callister & Rethwisch 10e*.

Reason Why Hardness Changes with Distance

- The cooling rate decreases with distance from quenched end.

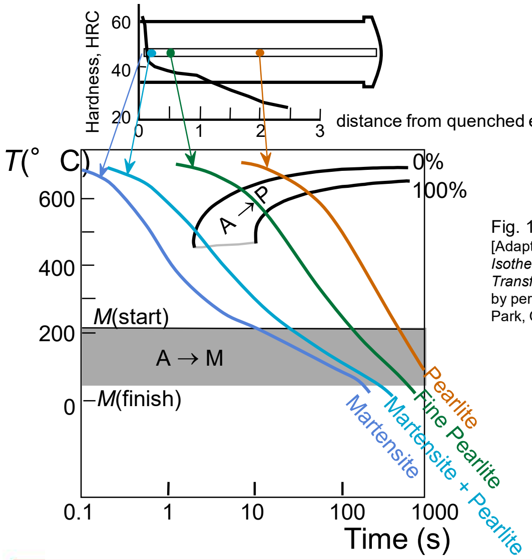
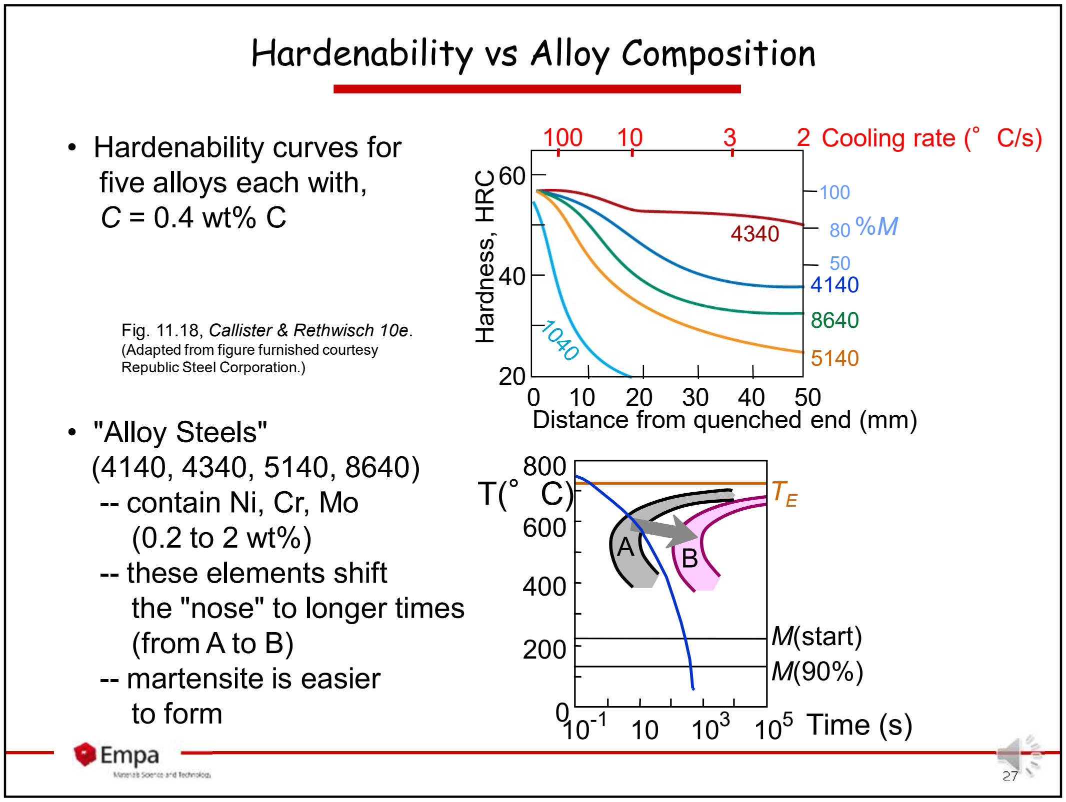


Fig. 11.17, *Callister & Rethwisch 10e*. [Adapted from H. Boyer (Ed.), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

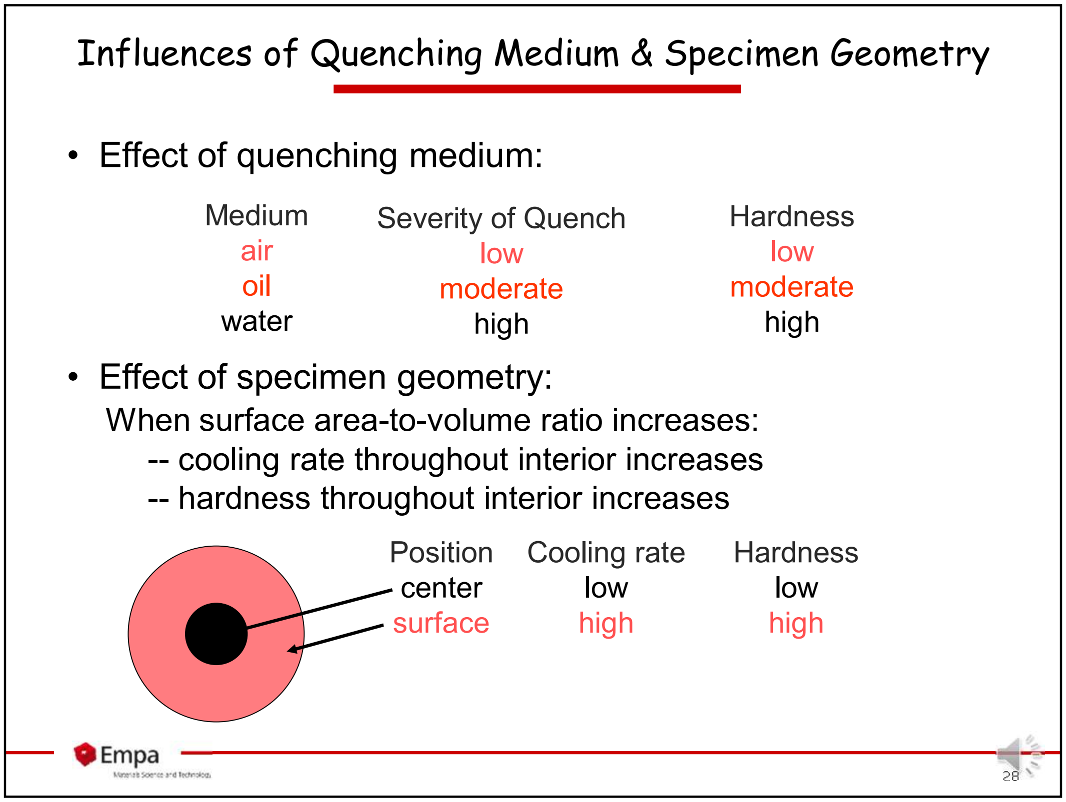


Hardenability vs Alloy Composition

- Hardenability curves for five alloys each with, C = 0.4 wt% C

Fig. 11.18, *Callister & Rethwisch 10e*. (Adapted from figure furnished courtesy Republic Steel Corporation.)

- "Alloy Steels" (4140, 4340, 5140, 8640)
  - -- contain Ni, Cr, Mo (0.2 to 2 wt%)
  - -- these elements shift the "nose" to longer times (from A to B)
  - -- martensite is easier to form



Influences of Quenching Medium & Specimen Geometry

- Effect of quenching medium:

Medium	Severity of Quench	Hardness
air	low	low
oil	moderate	moderate
water	high	high

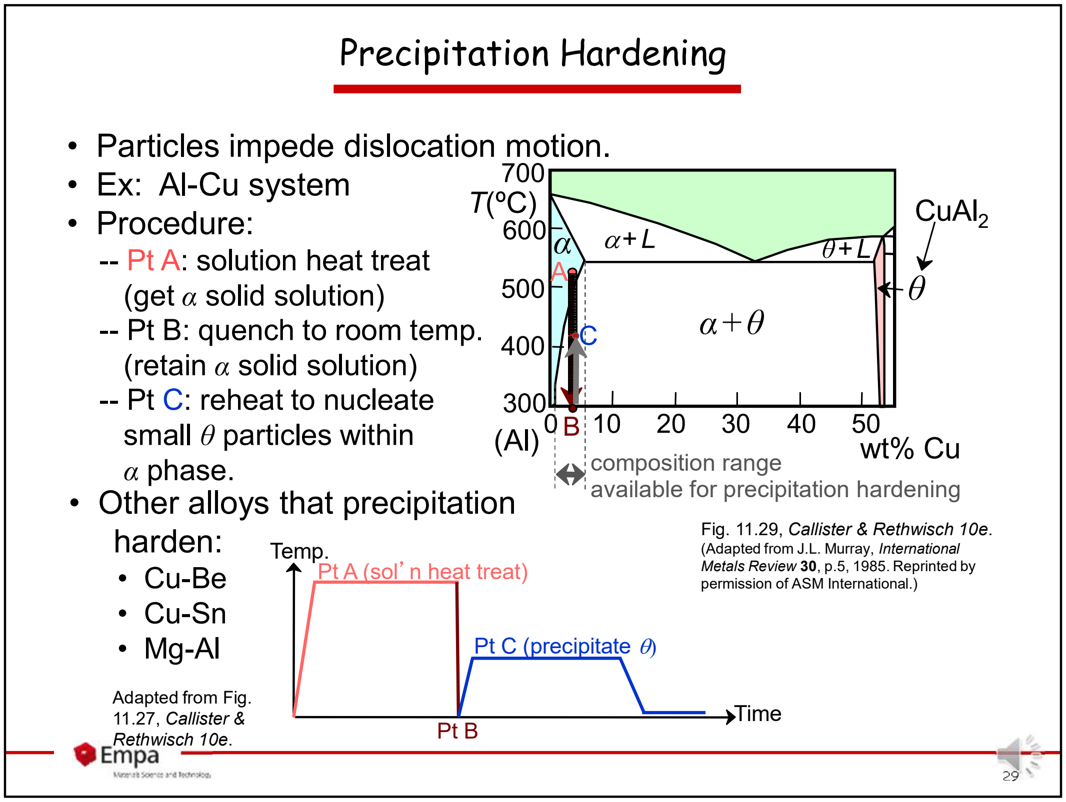
- Effect of specimen geometry:

When surface area-to-volume ratio increases:

-- cooling rate throughout interior increases

-- hardness throughout interior increases

Position	Cooling rate	Hardness
center	low	low
surface	high	high



Precipitation Hardening

- Particles impede dislocation motion.
- Ex: Al-Cu system
- Procedure:
  - -- Pt A: solution heat treat (get α solid solution)
  - -- Pt B: quench to room temp. (retain α solid solution)
  - -- Pt C: reheat to nucleate small θ particles within α phase.
- Other alloys that precipitation harden:
  - Cu-Be
  - Cu-Sn
  - Mg-Al

Fig. 11.29, *Callister & Rethwisch 10e*. (Adapted from J.L. Murray, *International Metals Review* **30**, p.5, 1985. Reprinted by permission of ASM International.)

Adapted from Fig. 11.27, *Callister & Rethwisch 10e*.

Influence of Precipitation Heat Treatment on *TS*, %*EL*

- 2014 Al Alloy:

- Maxima on *TS* curves.
- Increasing *T* accelerates process.

- Minima on %*EL* curves.

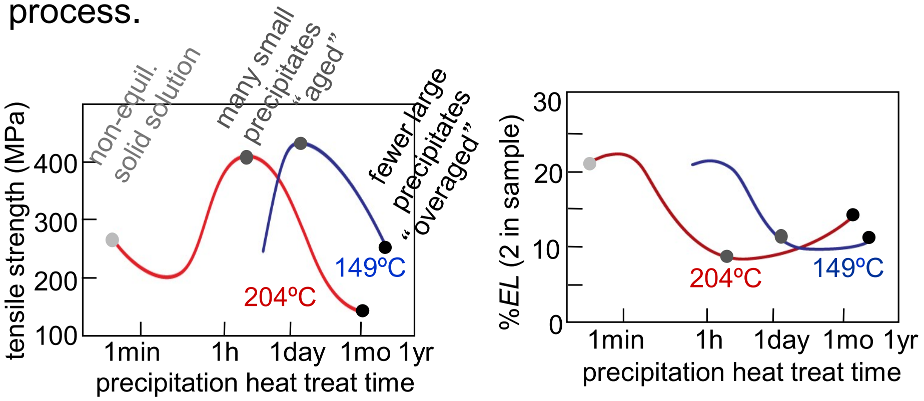


Fig. 11.32, *Callister & Rethwisch 10e.* [Adapted from *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

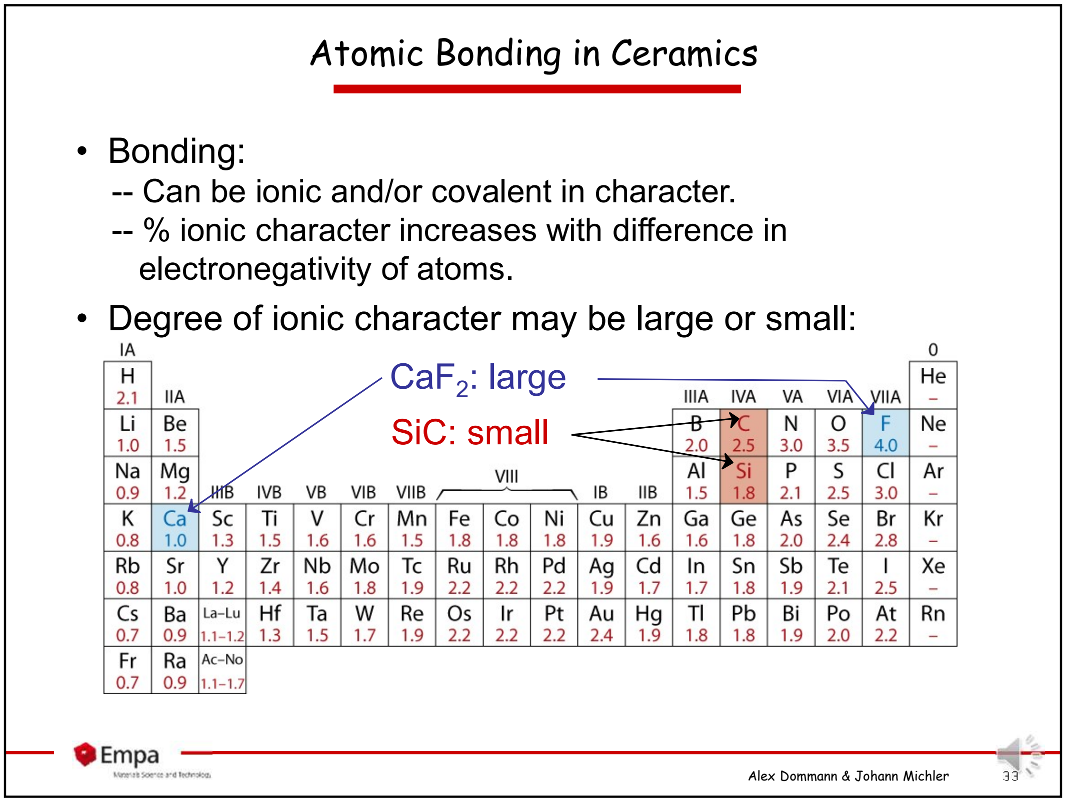
Summary

- Ferrous alloys: steels and cast irons
- Non-ferrous alloys:
  - -- Cu, Al, Ti, and Mg alloys; refractory alloys; and noble metals.
- Metal fabrication techniques:
  - -- forming, casting, miscellaneous.
- Hardenability of metals
  - -- measure of ability of a steel to be heat treated.
  - -- increases with alloy content.
- Precipitation hardening
  - --hardening, strengthening due to formation of precipitate particles.
  - --Al, Mg alloys precipitation hardenable.

Chapter 12: Structures & Properties of Ceramics

ISSUES TO ADDRESS...

- How do the crystal structures of ceramic materials differ from those for metals?
- How do point defects in ceramics differ from those defects found in metals?
- How are impurities accommodated in the ceramic lattice?
- In what ways are ceramic phase diagrams different from phase diagrams for metals?
- How are the mechanical properties of ceramics measured, and how do they differ from those for metals?



Atomic Bonding in Ceramics

- Bonding:
  - Can be ionic and/or covalent in character.
  - % ionic character increases with difference in electronegativity of atoms.
- Degree of ionic character may be large or small:

CaF$_2$: large

SiC: small

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
H 2.1																	He –
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne –
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar –
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr –
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 1.8	Tc 1.9	Ru 2.2	Rh 2.2	Pd 2.2	Ag 1.9	Cd 1.7	In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5	Xe –
Cs 0.7	Ba 0.9	La–Lu 1.1–1.2	Hf 1.3	Ta 1.5	W 1.7	Re 1.9	Os 2.2	Ir 2.2	Pt 2.2	Au 2.4	Hg 1.9	Tl 1.8	Pb 1.8	Bi 1.9	Po 2.0	At 2.2	Rn –
Fr 0.7	Ra 0.9	Ac–No 1.1–1.7															

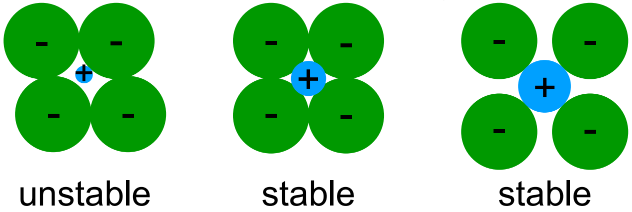
Ceramic Crystal Structures

Oxide structures

- oxygen anions larger than metal cations
- close packed oxygen in a lattice (usually FCC)
- cations fit into interstitial sites among oxygen ions

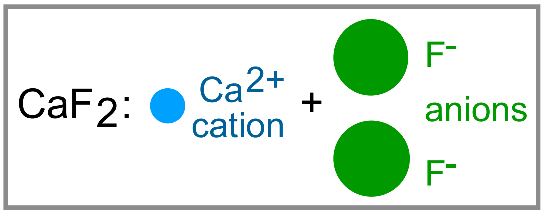
Factors that Determine Crystal Structure

1. Relative sizes of ions – Formation of stable structures:
   --maximize the # of oppositely charged ion neighbors.

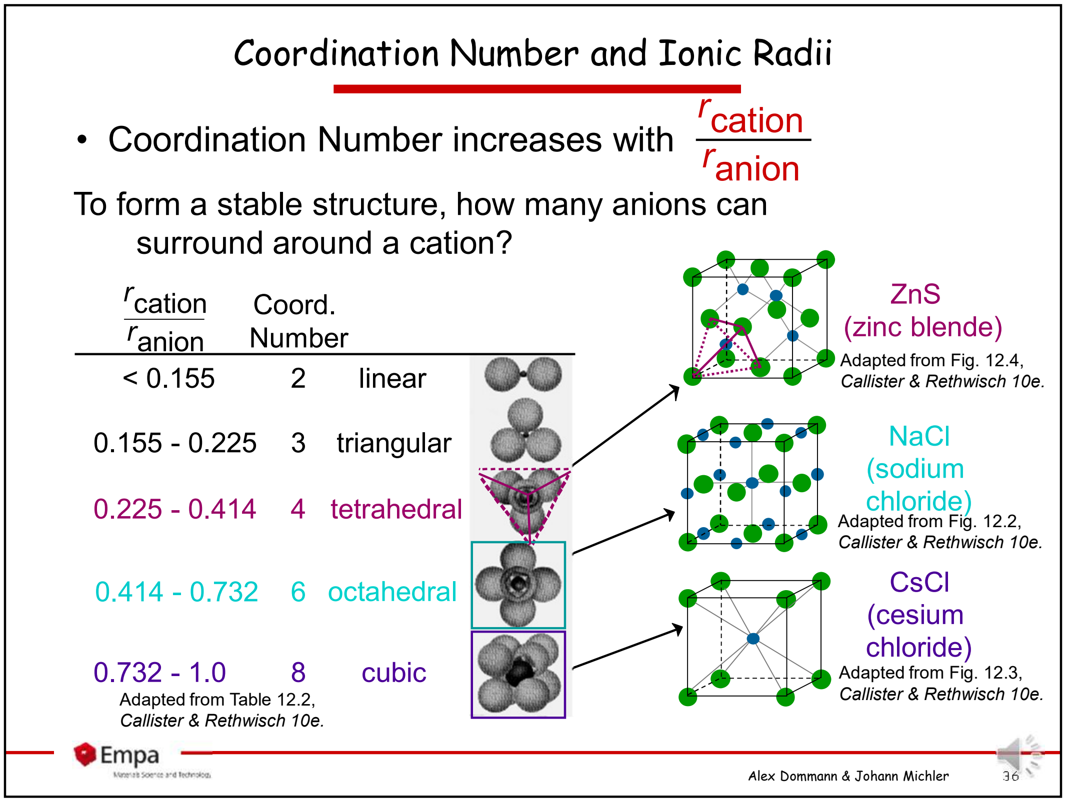


Adapted from Fig. 12.1, *Callister & Rethwisch 10e.*

2. Maintenance of Charge Neutrality :
   --Net charge in ceramic should be zero.
   --Reflected in chemical formula: $A_m X_p$



m, p values to achieve charge neutrality



Coordination Number and Ionic Radii

- Coordination Number increases with $\frac{r_{cation}}{r_{anion}}$

To form a stable structure, how many anions can surround around a cation?

$\frac{r_{cation}}{r_{anion}}$	Coord. Number	
< 0.155	2	linear
0.155 - 0.225	3	triangular
0.225 - 0.414	4	tetrahedral
0.414 - 0.732	6	octahedral
0.732 - 1.0	8	cubic

Adapted from Table 12.2, *Callister & Rethwisch 10e.*

ZnS (zinc blende)

Adapted from Fig. 12.4, *Callister & Rethwisch 10e.*

NaCl (sodium chloride)

Adapted from Fig. 12.2, *Callister & Rethwisch 10e.*

CsCl (cesium chloride)

Adapted from Fig. 12.3, *Callister & Rethwisch 10e.*

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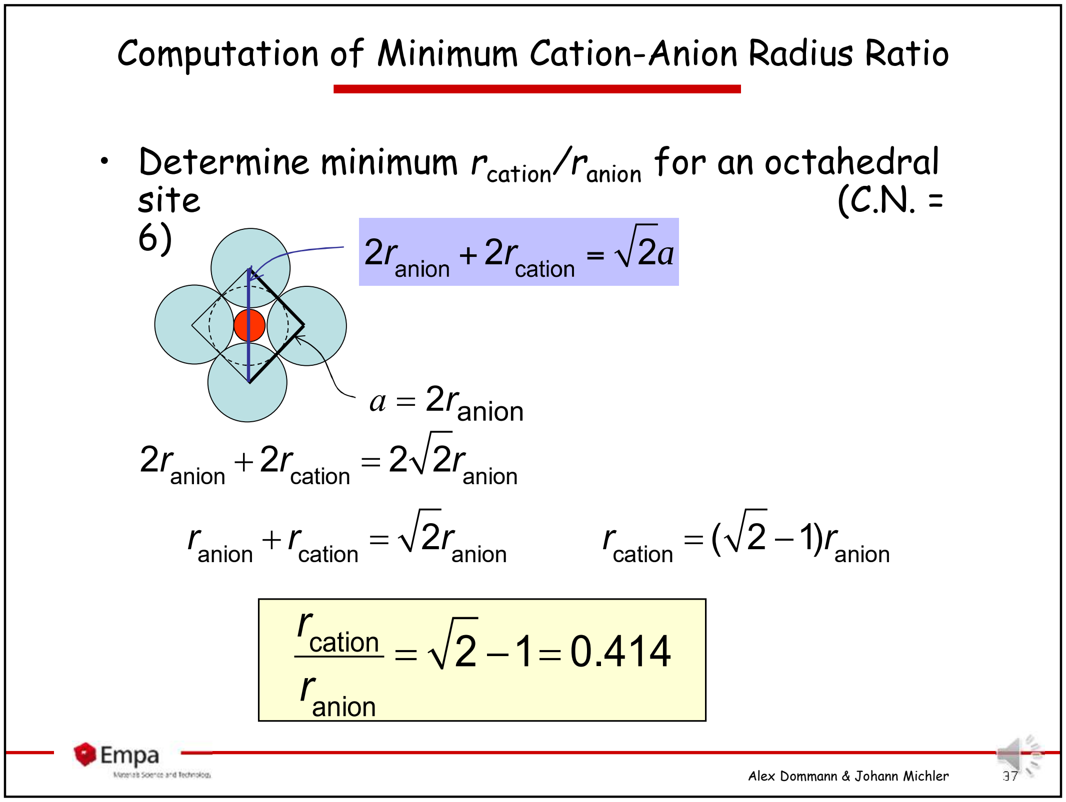

Computation of Minimum Cation-Anion Radius Ratio

- Determine minimum $r_{\text{cation}}/r_{\text{anion}}$ for an octahedral site (C.N. = 6)

$$2r_{\text{anion}} + 2r_{\text{cation}} = \sqrt{2}a$$

$$a = 2r_{\text{anion}}$$

$$2r_{\text{anion}} + 2r_{\text{cation}} = 2\sqrt{2}r_{\text{anion}}$$

$$r_{\text{anion}} + r_{\text{cation}} = \sqrt{2}r_{\text{anion}} \qquad r_{\text{cation}} = (\sqrt{2}-1)r_{\text{anion}}$$

$$\boxed{\frac{r_{\text{cation}}}{r_{\text{anion}}} = \sqrt{2}-1 = 0.414}$$

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Bond Hybridization

Bond Hybridization is possible when there is significant covalent bonding

- hybrid electron orbitals form
- For example for SiC
    - $X_{Si} = 1.8$ and $X_C = 2.5$

$$\%\ \text{ionic character} = 100\ \{1\text{-}\exp[-0.25(X_{\text{Si}} - X_{\text{C}})^2]\} = 11.5\%$$

- ~ 89% covalent bonding
- Both Si and C prefer sp^3 hybridization
- Therefore, for SiC, Si atoms occupy tetrahedral sites

Example Problem: Predicting the Crystal Structure of FeO

- On the basis of ionic radii, what crystal structure would you predict for FeO?

Cation	Ionic radius (nm)
Al^{3+}	0.053
Fe^{2+}	0.077
Fe^{3+}	0.069
Ca^{2+}	0.100
Anion	
O^{2-}	0.140
Cl^{-}	0.181
F^{-}	0.133

Data from Table 12.3, *Callister & Rethwisch 10e.*

- Answer:

$$\frac{r_{\text{cation}}}{r_{\text{anion}}} = \frac{0.077}{0.140}$$

$$= 0.550$$

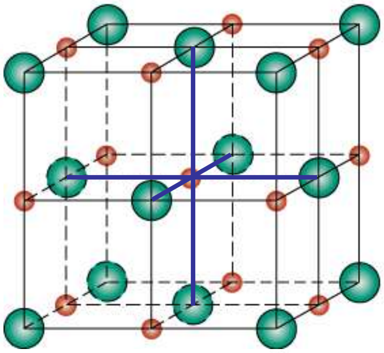
based on this ratio,
-- coord # = 6 because

$0.414 < 0.550 < 0.732$

-- crystal structure is NaCl

Rock Salt Structure

Same concepts can be applied to ionic solids in general.
Example: NaCl (rock salt) structure



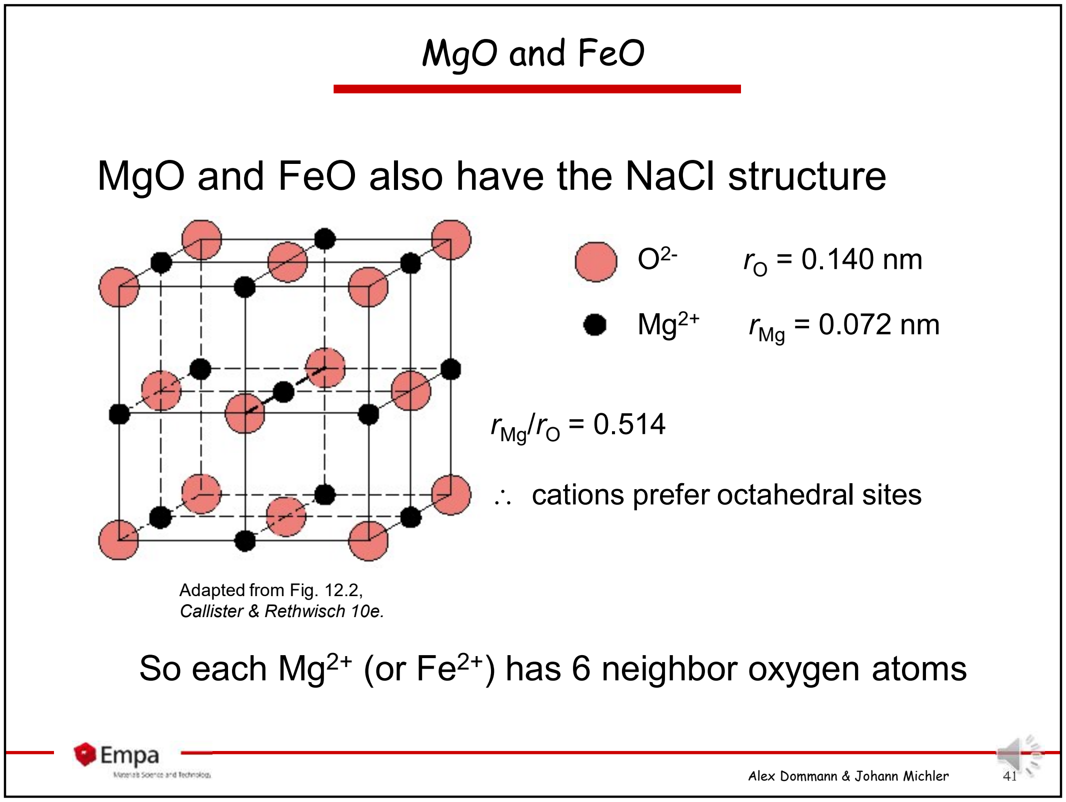
Adapted from Fig. 12.2,
Callister & Rethwisch 10e.

● Na^+ r_{Na} = 0.102 nm

● Cl^- r_{Cl} = 0.181 nm

r_{Na}/r_{Cl} = 0.564

∴ cations (Na^+) prefer octahedral sites



MgO and FeO

MgO and FeO also have the NaCl structure

● O^{2-} $r_O = 0.140$ nm

● Mg^{2+} $r_{Mg} = 0.072$ nm

$r_{Mg}/r_O = 0.514$

∴ cations prefer octahedral sites

Adapted from Fig. 12.2,
Callister & Rethwisch 10e.

So each Mg^{2+} (or Fe^{2+}) has 6 neighbor oxygen atoms

AX Crystal Structures

AX–Type Crystal Structures include NaCl, CsCl, and zinc blende

Cesium Chloride structure:

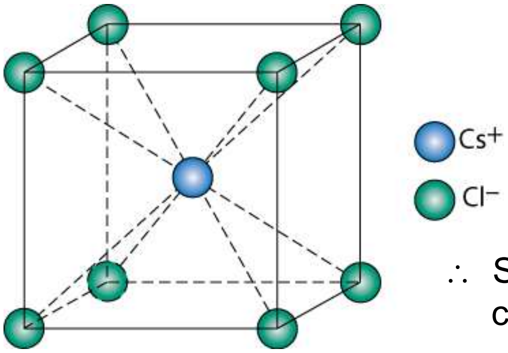


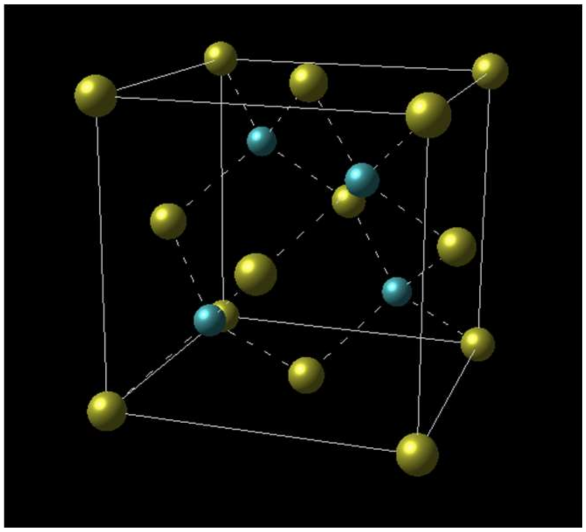
Fig. 12.3, *Callister & Rethwisch 10e.*

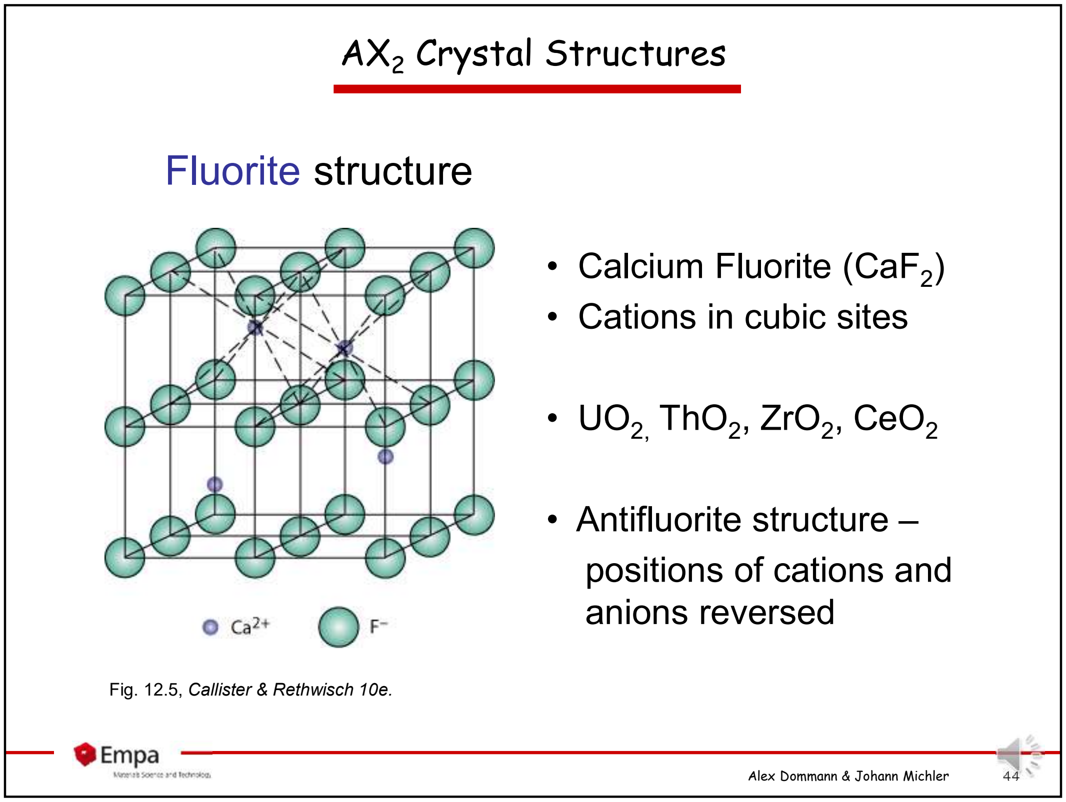
$$\frac{r_{Cs^+}}{r_{Cl^-}} = \frac{0.170}{0.181} = 0.939$$

$\therefore$ Since $0.732 < 0.939 < 1.0$, cubic sites preferred

So each Cs^+ has 8 neighbor Cl^-

VMSE Screenshot – Zinc Blende Unit Cell





AX_2 Crystal Structures

Fluorite structure

- Calcium Fluorite (CaF_2)
- Cations in cubic sites
- UO_2, ThO_2, ZrO_2, CeO_2
- Antifluorite structure – positions of cations and anions reversed

Fig. 12.5, *Callister & Rethwisch 10e.*

ABX_3 Crystal Structures

- Perovskite structure

Ex: complex oxide
$BaTiO_3$

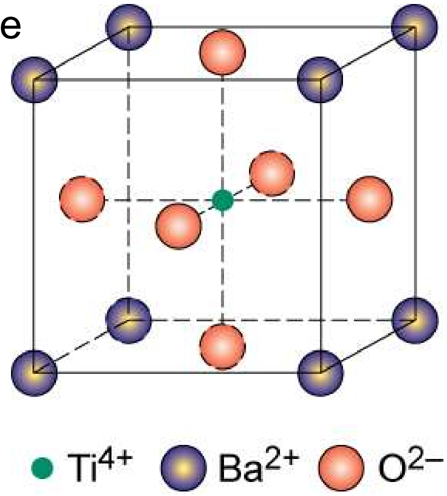


Fig. 12.6, *Callister & Rethwisch 10e.*

Density Computations for Ceramics

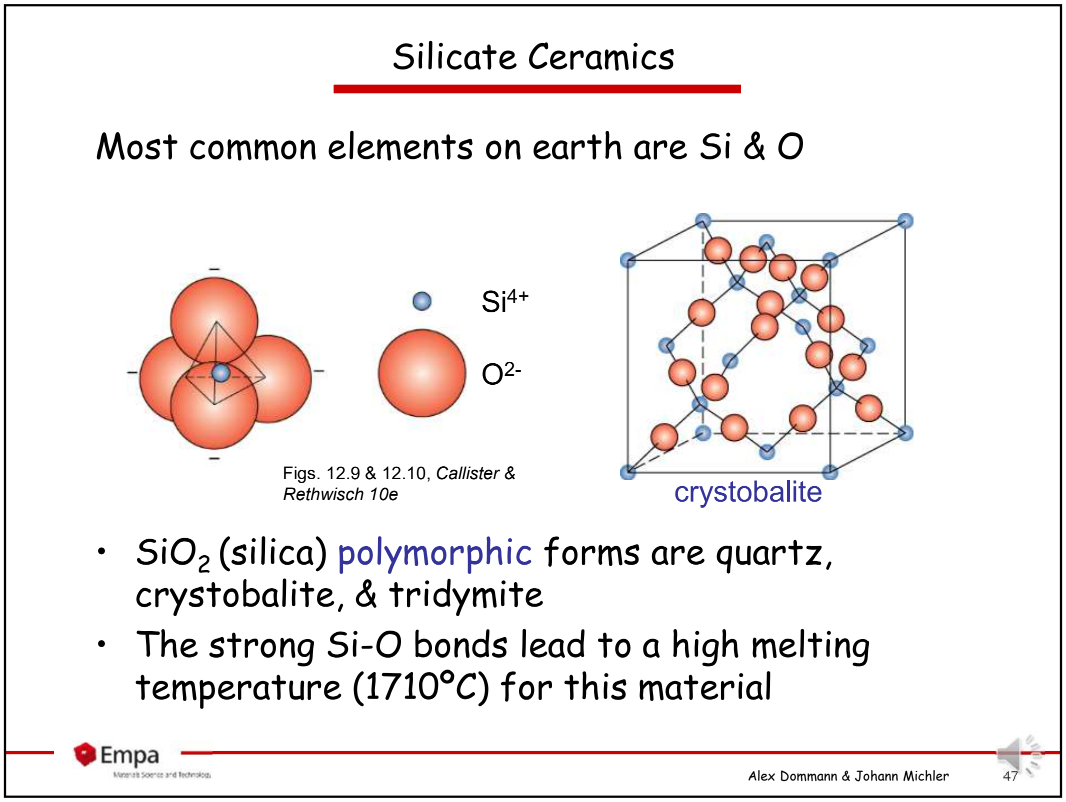
Number of formula units/unit cell

$$\rho = \frac{n'(\Sigma A_C + \Sigma A_A)}{V_C N_A}$$

Avogadro's number

Volume of unit cell

ΣA_C = sum of atomic weights of all cations in formula unit
ΣA_A = sum of atomic weights of all anions in formula unit



Silicate Ceramics

Most common elements on earth are Si & O

Figs. 12.9 & 12.10, *Callister & Rethwisch 10e*

crystobalite

- SiO_2 (silica) polymorphic forms are quartz, crystobalite, & tridymite
- The strong Si-O bonds lead to a high melting temperature (1710°C) for this material

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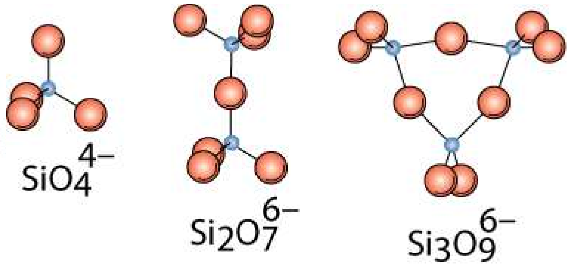
Silicates

Bonding of adjacent SiO_4^{4-} accomplished by the sharing of common corners, edges, or faces

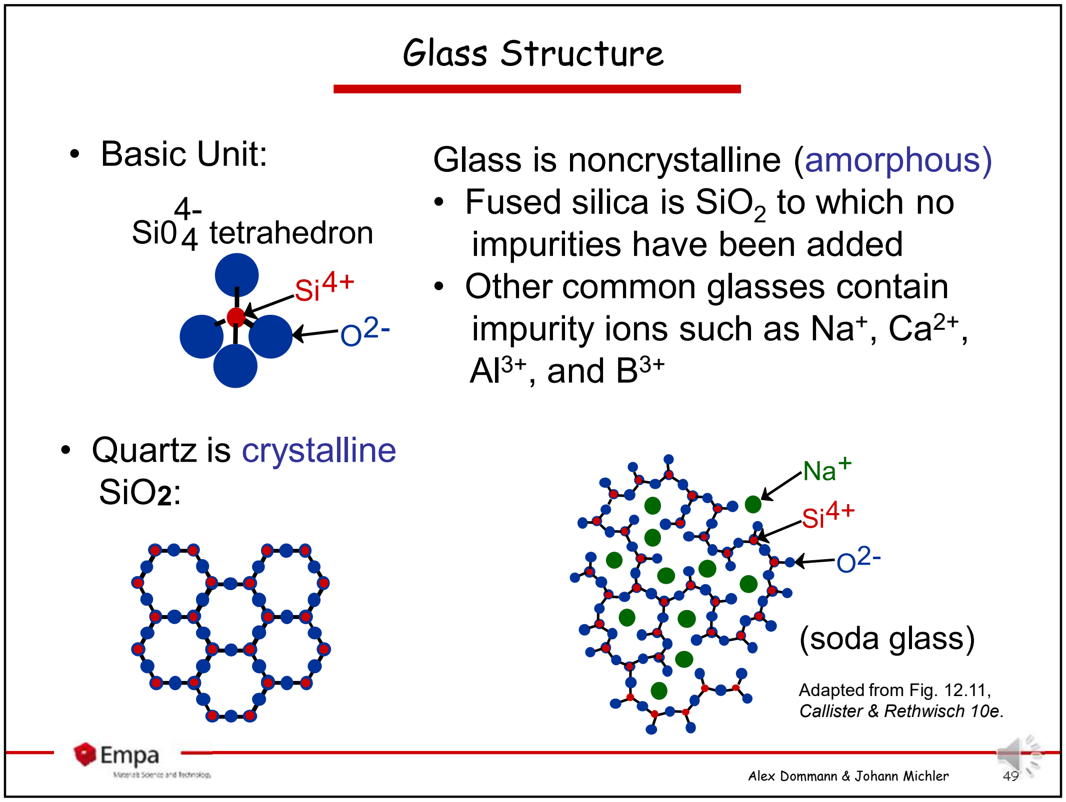


Adapted from Fig. 12.12, *Callister & Rethwisch 10e.*

Mg_2SiO_4 $Ca_2MgSi_2O_7$

Presence of cations such as Ca^{2+}, Mg^{2+}, & Al^{3+}

1. maintain charge neutrality, and
2. ionically bond SiO_4^{4-} to one another



Glass Structure

- Basic Unit:

SiO_4^{4-} tetrahedron

Glass is noncrystalline (amorphous)

- Fused silica is SiO_2 to which no impurities have been added
- Other common glasses contain impurity ions such as Na^+, Ca^{2+}, Al^{3+}, and B^{3+}

- Quartz is crystalline SiO_2:

(soda glass)

Adapted from Fig. 12.11, *Callister & Rethwisch 10e.*

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Layered Silicates

- Layered silicates (e.g., clays, mica, talc)
  - SiO_4 tetrahedra connected together to form 2-D plane
- A net negative charge is associated with each $(Si_2O_5)^{2-}$ unit
- Negative charge balanced by adjacent plane rich in positively charged cations

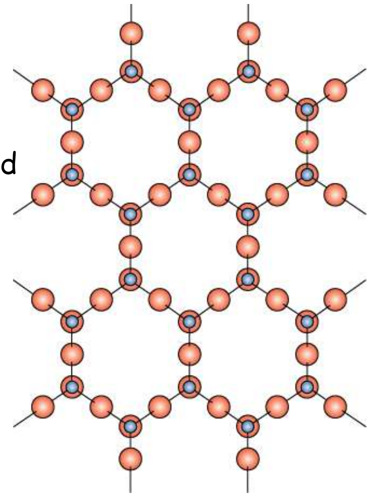
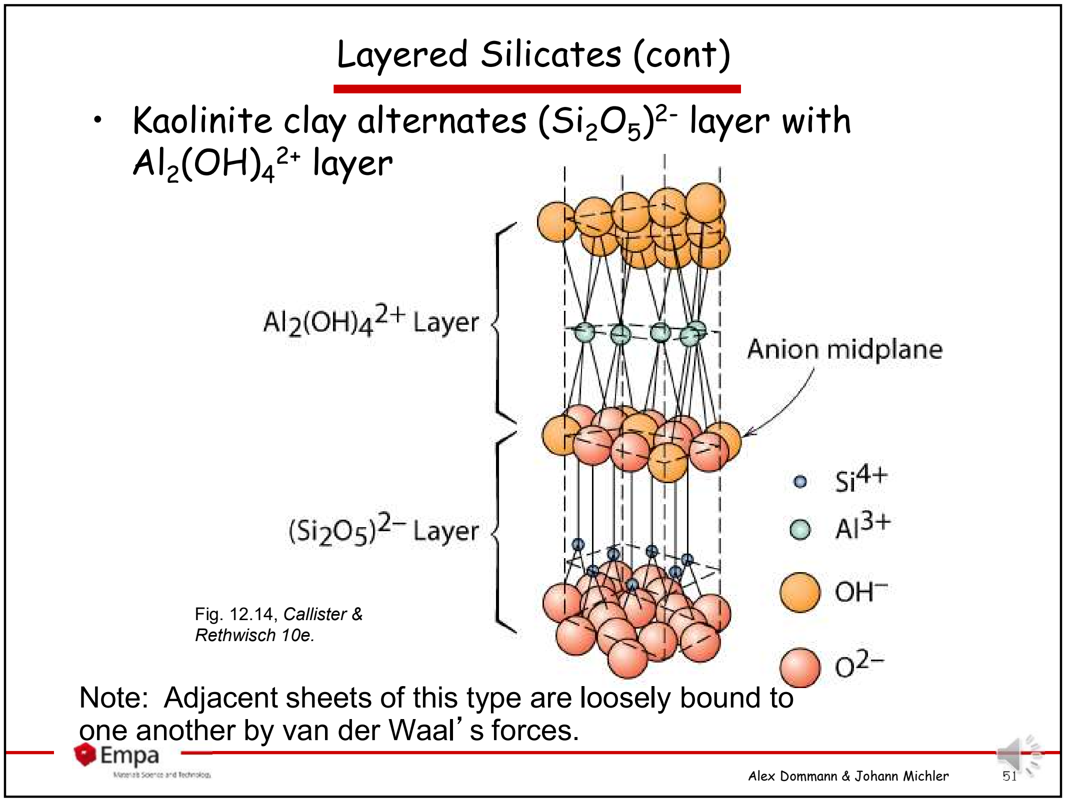


Fig. 12.13, *Callister & Rethwisch 10e.*



Layered Silicates (cont)

- Kaolinite clay alternates $(Si_2O_5)^{2-}$ layer with $Al_2(OH)_4^{2+}$ layer

Fig. 12.14, *Callister & Rethwisch 10e.*

Note: Adjacent sheets of this type are loosely bound to one another by van der Waal's forces.

Polymorphic Forms of Carbon

Diamond

- tetrahedral bonding of carbon
  - hardest material known
  - very high thermal conductivity
- large single crystals – gem stones
- small crystals – used to grind/cut other materials
- diamond thin films
  - hard surface coatings – used for cutting tools, medical devices, etc.

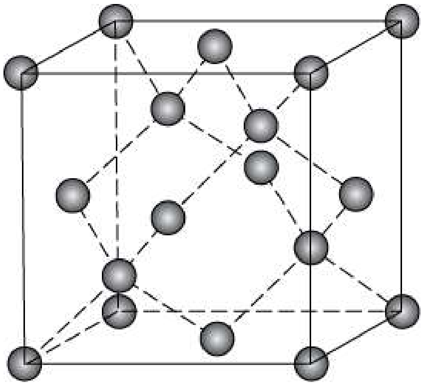


Fig. 12.16, *Callister & Rethwisch 10e.*

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Polymorphic Forms of Carbon (cont)

Graphite

- layered structure – parallel hexagonal arrays of carbon atoms

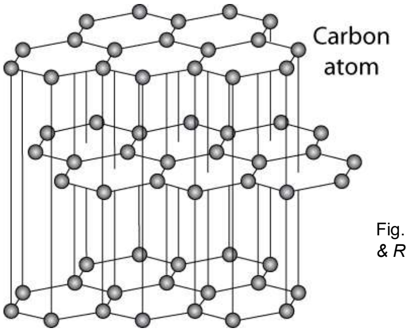


Fig. 12.17, *Callister & Rethwisch 10e.*

- weak van der Waal's forces between layers
- planes slide easily over one another -- good lubricant

Point Defects in Ceramics (i)

- Vacancies
  - -- vacancies exist in ceramics for both cations and anions
- Interstitials
  - -- interstitials exist for cations
  - -- interstitials are not normally observed for anions because anions are large relative to the interstitial sites

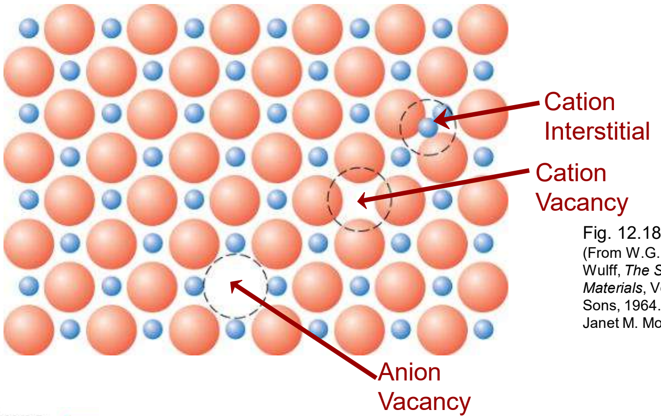


Fig. 12.18, *Callister & Rethwisch 10e.* (From W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. 1, *Structure*, John Wiley & Sons, 1964. Reproduced with permission of Janet M. Moffatt.)

Point Defects in Ceramics (ii)

- **Frenkel Defect**
  -- a cation vacancy-cation interstitial pair.
- **Shottky Defect**
  -- a paired set of cation and anion vacancies.

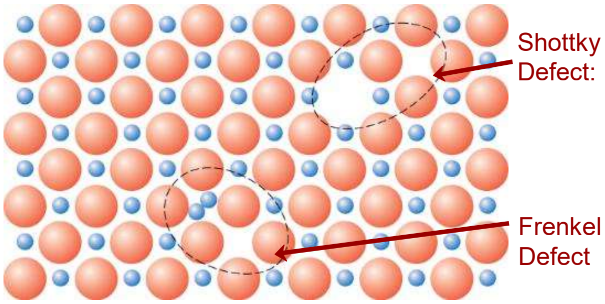
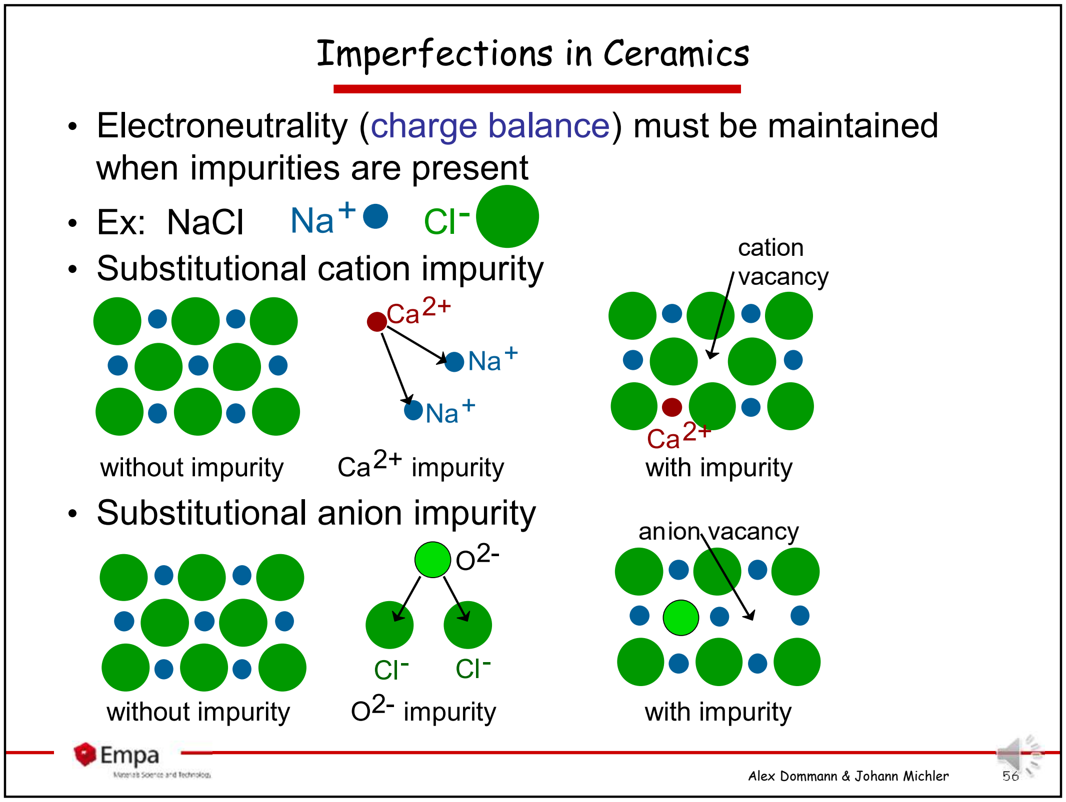


Fig. 12.19, *Callister & Rethwisch 10e.* (From W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. 1, *Structure*, John Wiley & Sons, 1964. Reproduced with permission of Janet M. Moffatt.)

- Equilibrium concentration of defects $\propto e^{-Q_D/kT}$



Imperfections in Ceramics

- Electroneutrality (charge balance) must be maintained when impurities are present
- Ex: NaCl Na^+ ● Cl^- ●
- Substitutional cation impurity

- Substitutional anion impurity

Ceramic Phase Diagrams

MgO-Al_2O_3 diagram:

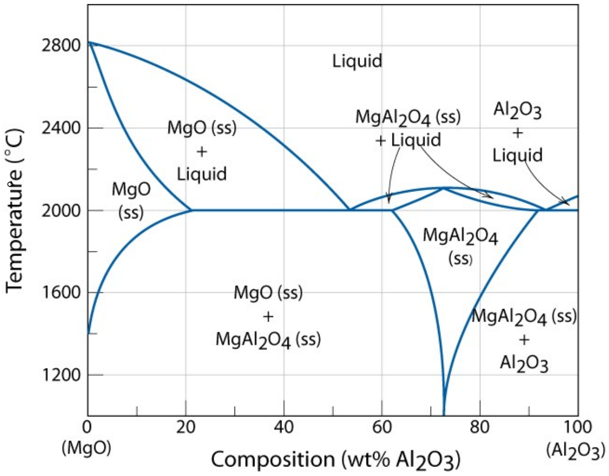


Fig. 12.23, Callister & Rethwisch 10e.
[Adapted from B. Hallstedt, "Thermodynamic Assessment of the System MgO–Al_2O_3," *J. Am. Ceram. Soc.*, 75[6], 1992, p.1502. Reprinted by permission of the American Ceramic Society.]

Applications and Processing of Ceramics

ISSUES TO ADDRESS...

- How do we classify ceramics?
- What are some applications of ceramics?
- How is processing of ceramics different than for metals?

Classification of Ceramics

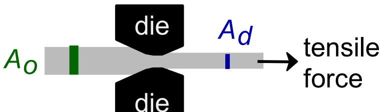
Ceramic Materials

- Glasses
  - -optical
  - -composite reinforce
  - -containers/ household
- Clay products
  - -whiteware
  - -structural
- Refractories
  - -bricks for high *T* (furnaces)
- Abrasives
  - -sandpaper
  - -cutting
  - -polishing
- Cements
  - -composites
  - -structural
- Ceramic biomaterials
  - -implants
- Carbon
  - -composites
  - -abrasives
- Advanced ceramics
  - -engine
    - rotors
    - valves
    - bearings
  - -sensors

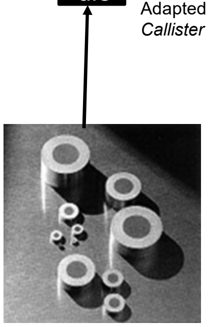
Adapted from Fig. 13.1 and discussion in
Sections 13.2-10, *Callister & Rethwisch 10e.*

Ceramics Application: Die Blanks

- Die blanks:
  -- Need wear resistant properties!
- Die surface:
  -- 4 µm polycrystalline diamond particles that are sintered onto a cemented tungsten carbide substrate.
  -- polycrystalline diamond gives uniform hardness in all directions to reduce wear.



Adapted from Fig. 11.9(d), *Callister & Rethwisch 10e.*

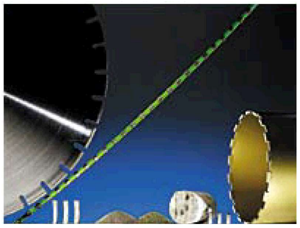


Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.

Ceramics Application: Cutting Tools

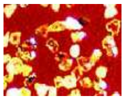
- Tools:
  - -- for grinding glass, tungsten, carbide, ceramics
  - -- for cutting Si wafers
  - -- for oil drilling
- Materials:
  - -- manufactured single crystal or polycrystalline diamonds in a metal or resin matrix.
  - -- polycrystalline diamonds resharpen by microfracturing along cleavage planes.

oil drill bits



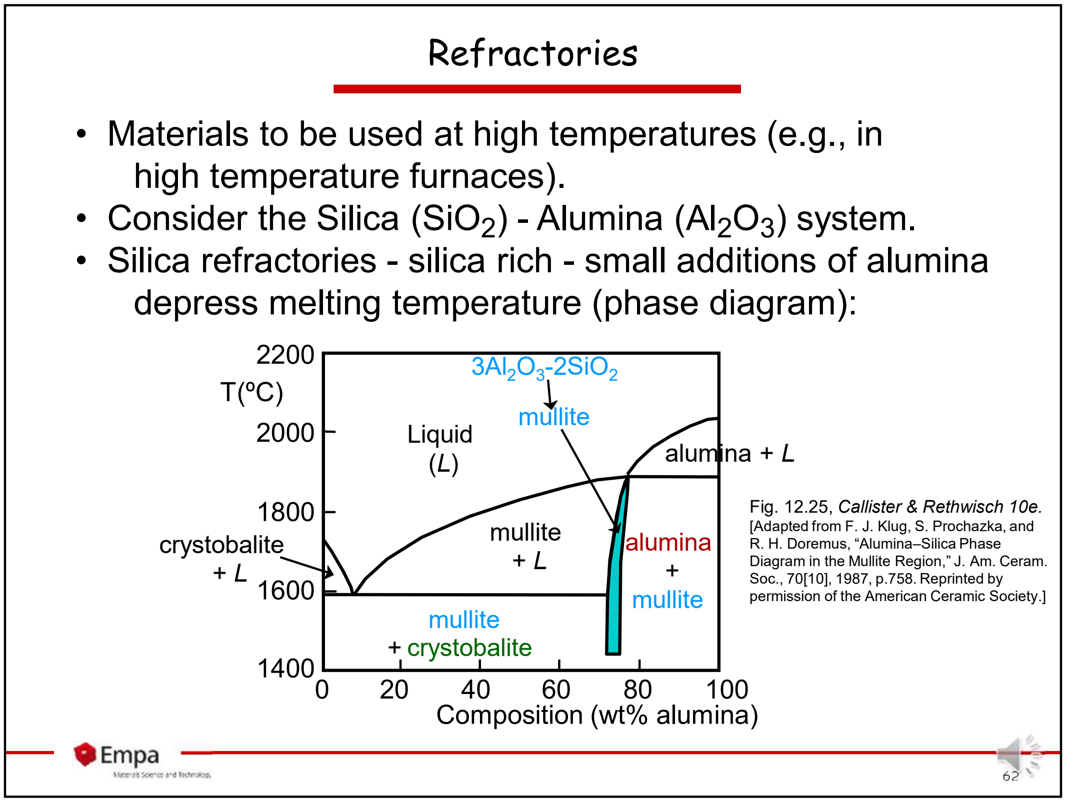
blades

Single crystal diamonds



polycrystalline diamonds in a resin matrix.

Photos courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.



Refractories

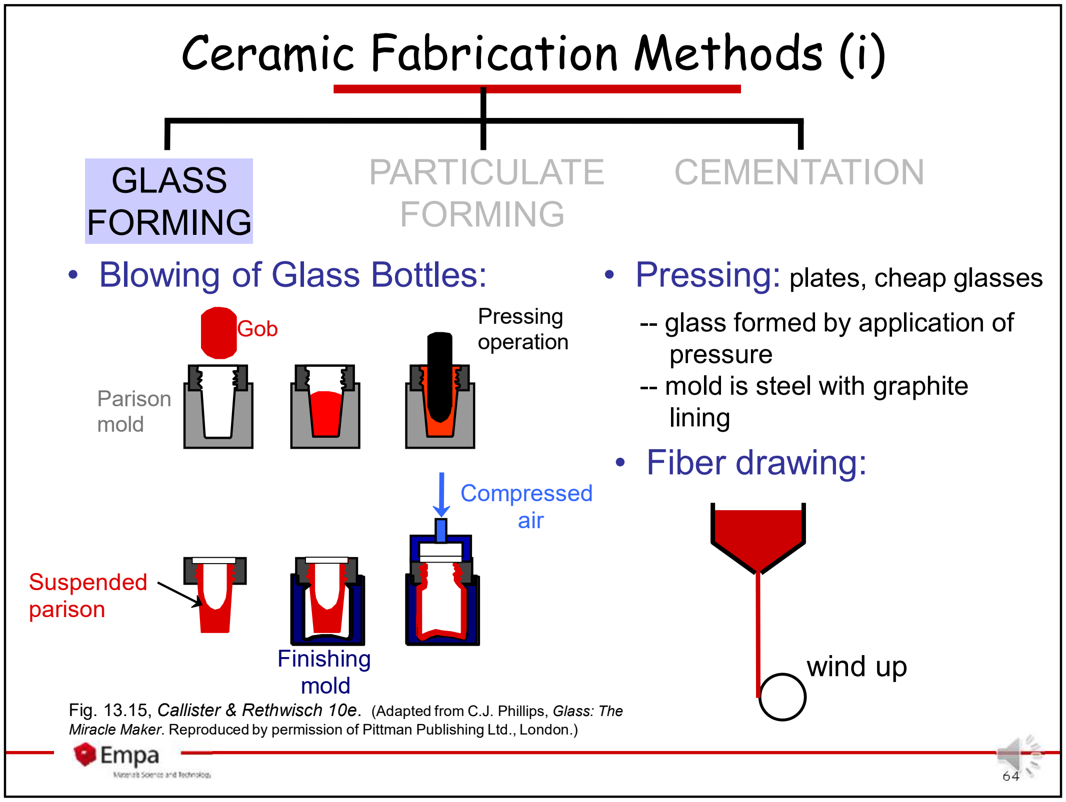
- Materials to be used at high temperatures (e.g., in high temperature furnaces).
- Consider the Silica (SiO_2) - Alumina (Al_2O_3) system.
- Silica refractories - silica rich - small additions of alumina depress melting temperature (phase diagram):

Fig. 12.25, *Callister & Rethwisch 10e.* [Adapted from F. J. Klug, S. Prochazka, and R. H. Doremus, "Alumina–Silica Phase Diagram in the Mullite Region," J. Am. Ceram. Soc., 70[10], 1987, p.758. Reprinted by permission of the American Ceramic Society.]

Advanced Ceramics: Materials for Automobile Engines

- Advantages:
  - Operate at high temperatures – high efficiencies
  - Low frictional losses
  - Operate without a cooling system
  - Lower weights than current engines
- Disadvantages:
  - Ceramic materials are brittle
  - Difficult to remove internal voids (that weaken structures)
  - Ceramic parts are difficult to form and machine

- Potential candidate materials: Si_3N_4, SiC, & ZrO_2
- Possible engine parts: engine block & piston coatings



Ceramic Fabrication Methods (i)

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

- Blowing of Glass Bottles:

- Pressing: plates, cheap glasses
  -- glass formed by application of pressure
  -- mold is steel with graphite lining
- Fiber drawing:

Fig. 13.15, *Callister & Rethwisch 10e*. (Adapted from C.J. Phillips, *Glass: The Miracle Maker*. Reproduced by permission of Pittman Publishing Ltd., London.)

Sheet Glass Forming

- Sheet forming – continuous casting
  - sheets are formed by floating the molten glass on a pool of molten tin

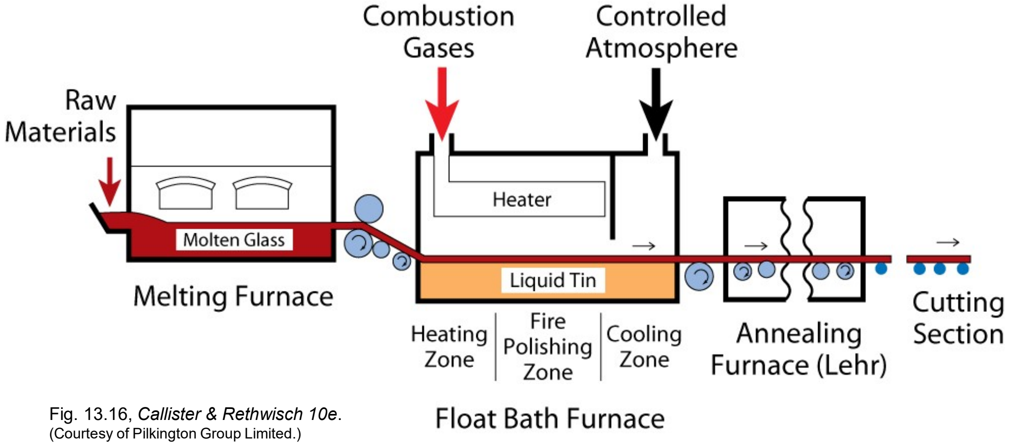
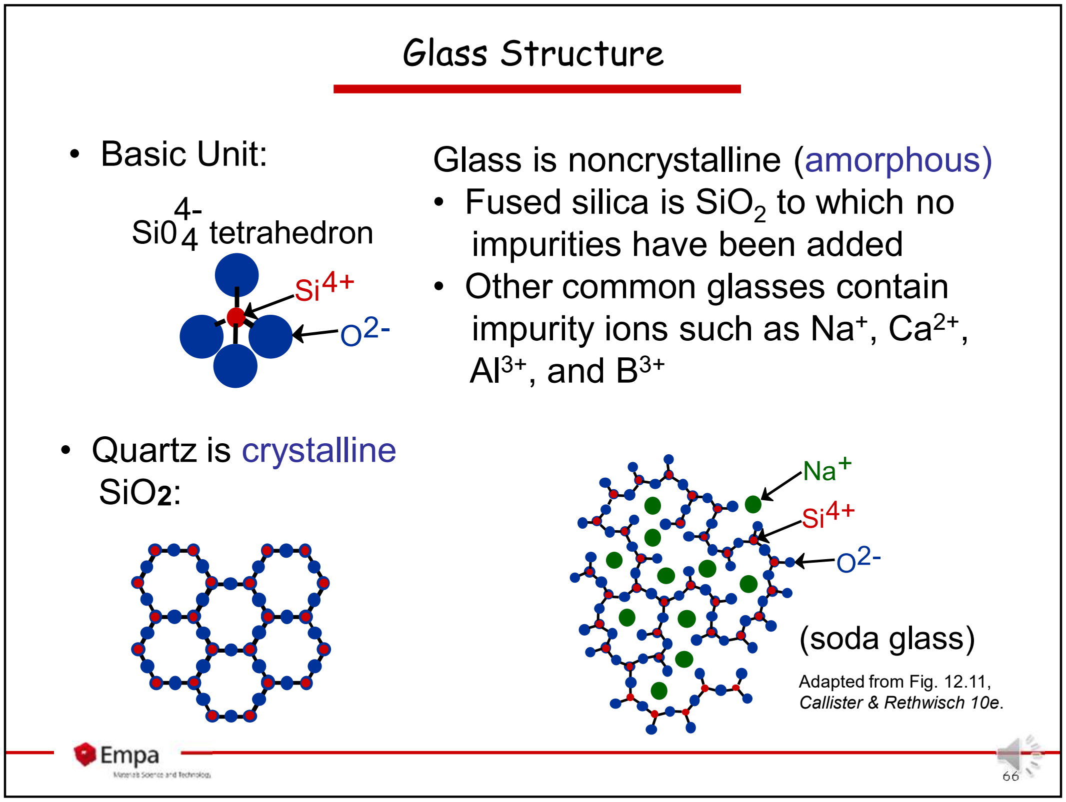


Fig. 13.16, *Callister & Rethwisch 10e*.
(Courtesy of Pilkington Group Limited.)



Glass Structure

- Basic Unit:

SiO_4^{4-} tetrahedron

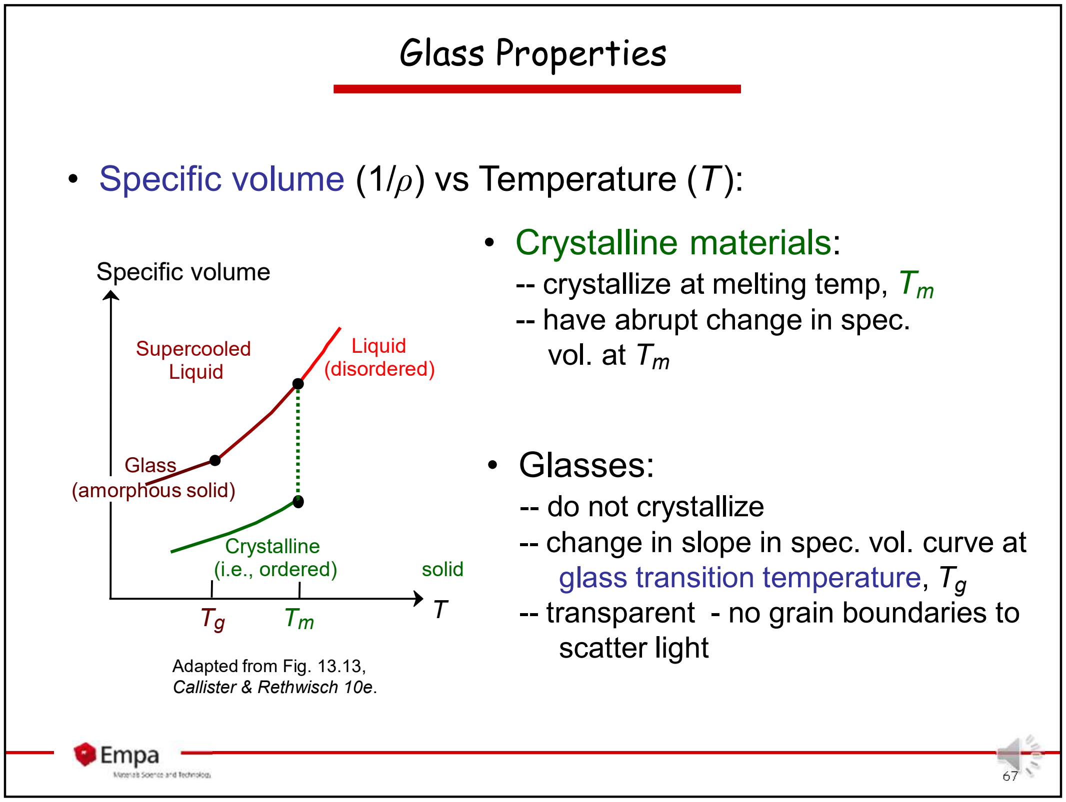
- Quartz is crystalline SiO_2:

Glass is noncrystalline (amorphous)

- Fused silica is SiO_2 to which no impurities have been added
- Other common glasses contain impurity ions such as Na^+, Ca^{2+}, Al^{3+}, and B^{3+}

(soda glass)

Adapted from Fig. 12.11, *Callister & Rethwisch 10e.*



Glass Properties

- Specific volume ($1/\rho$) vs Temperature (T):

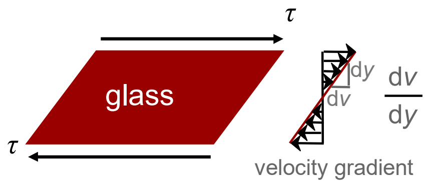
Adapted from Fig. 13.13, *Callister & Rethwisch 10e*.

- Crystalline materials:
  - -- crystallize at melting temp, T_m
  - -- have abrupt change in spec. vol. at T_m

- Glasses:
  - -- do not crystallize
  - -- change in slope in spec. vol. curve at glass transition temperature, T_g
  - -- transparent - no grain boundaries to scatter light

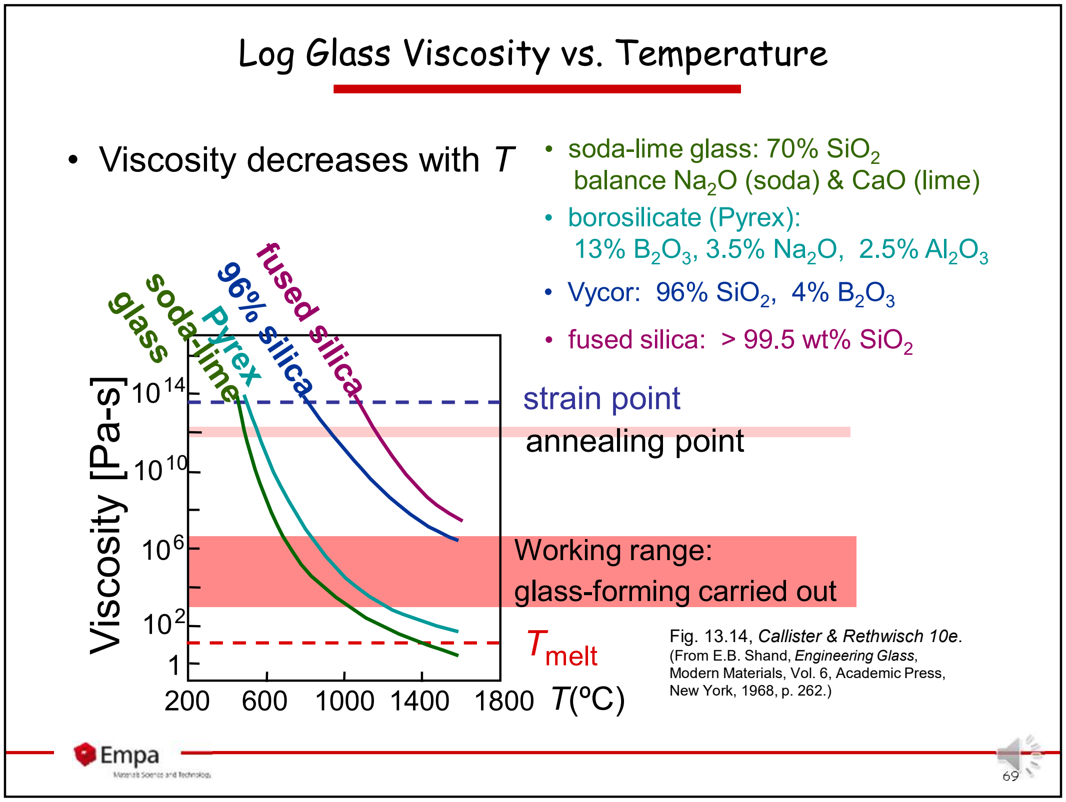
Glass Properties: Viscosity

- Viscosity, η:
  -- relates shear stress (τ) and velocity gradient *(dv/dy):*



$$\eta = \frac{\tau}{dv\,/\,dy}$$

η has units of (Pa-s)



Log Glass Viscosity vs. Temperature

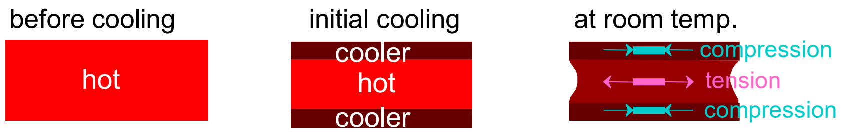
- Viscosity decreases with *T*

- soda-lime glass: 70% SiO_2 balance Na_2O (soda) & CaO (lime)
- borosilicate (Pyrex): 13% B_2O_3, 3.5% Na_2O, 2.5% Al_2O_3
- Vycor: 96% SiO_2, 4% B_2O_3
- fused silica: > 99.5 wt% SiO_2

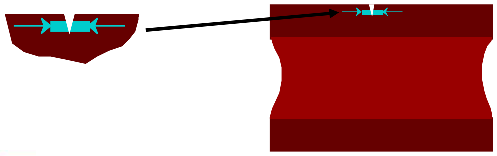
Fig. 13.14, *Callister & Rethwisch 10e*.
(From E.B. Shand, *Engineering Glass*, Modern Materials, Vol. 6, Academic Press, New York, 1968, p. 262.)

Heat Treating Glass

- Annealing:
  -- removes internal stresses caused by uneven cooling.
- Tempering:
  -- puts surface of glass part into compression
  -- suppresses growth of cracks from surface scratches.
  -- sequence:



-- Result: surface crack growth is suppressed.



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Ceramic Fabrication Methods (iia)

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

Hydroplastic forming:

- Mill (grind) and screen constituents: desired particle size
- Extrude this mass (e.g., into a brick)

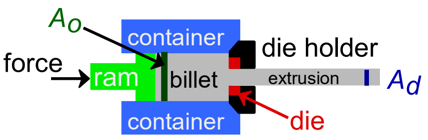
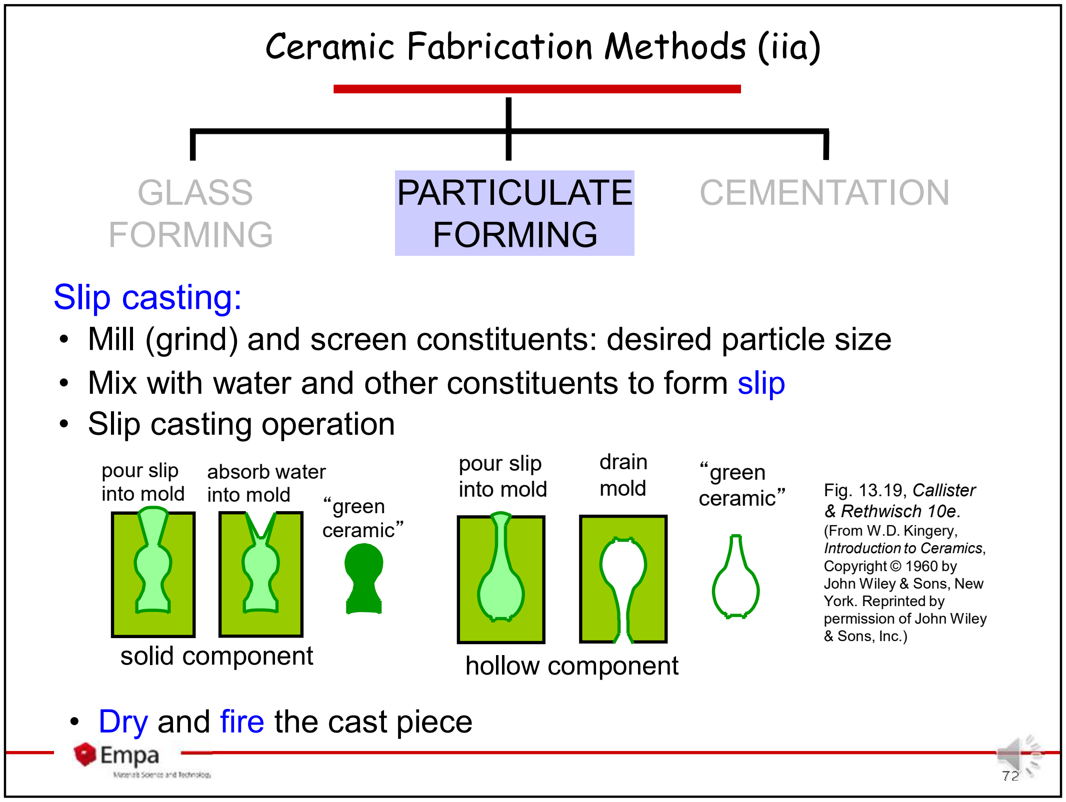


Fig. 11.9 (c), *Callister & Rethwisch 10e*.

- Dry and fire the formed piece



Ceramic Fabrication Methods (iia)

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

Slip casting:

- Mill (grind) and screen constituents: desired particle size
- Mix with water and other constituents to form slip
- Slip casting operation

Fig. 13.19, *Callister & Rethwisch 10e*. (From W.D. Kingery, *Introduction to Ceramics*, Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

- Dry and fire the cast piece

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Typical Porcelain Composition

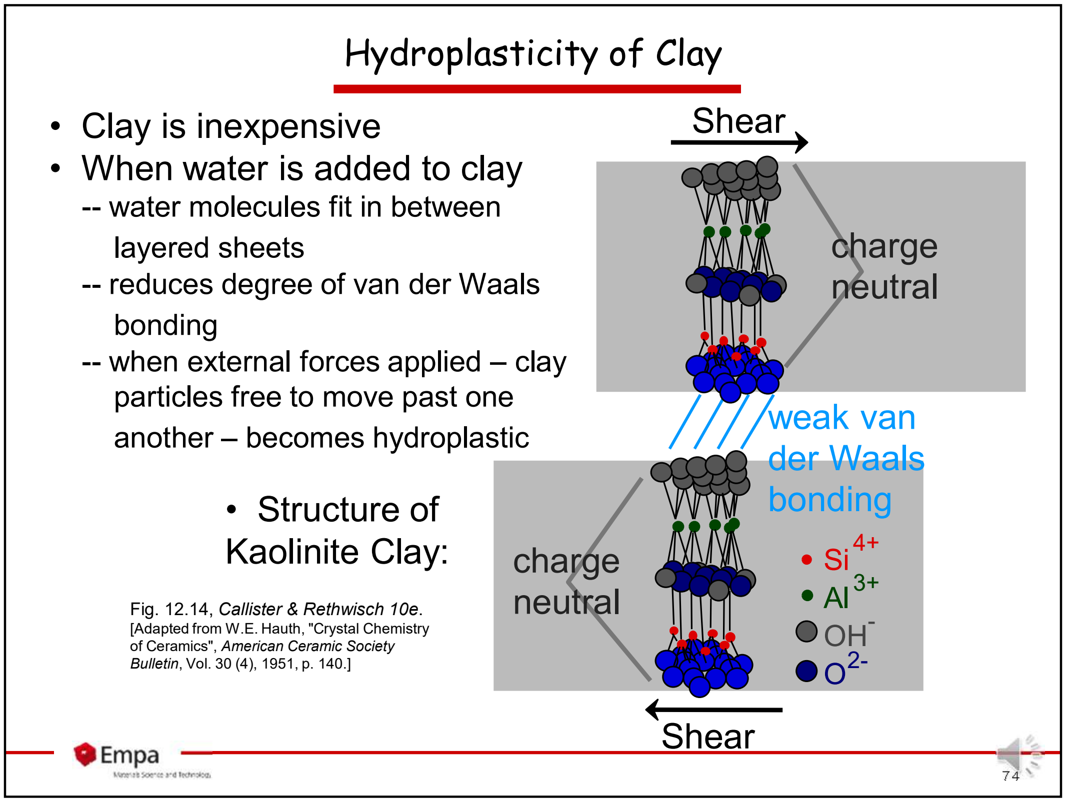
(50%) 1. Clay

(25%) 2. Filler – e.g. quartz (finely ground)

(25%) 3. Fluxing agent (Feldspar)

-- aluminosilicates plus K^+, Na^+, Ca^+

-- upon firing - forms low-melting-temp. glass



Hydroplasticity of Clay

- Clay is inexpensive
- When water is added to clay
  -- water molecules fit in between layered sheets
  -- reduces degree of van der Waals bonding
  -- when external forces applied – clay particles free to move past one another – becomes hydroplastic

- Structure of Kaolinite Clay:

Fig. 12.14, *Callister & Rethwisch 10e*. [Adapted from W.E. Hauth, "Crystal Chemistry of Ceramics", *American Ceramic Society Bulletin*, Vol. 30 (4), 1951, p. 140.]

Drying and Firing

- Drying: as water is removed - interparticle spacings decrease – shrinkage .

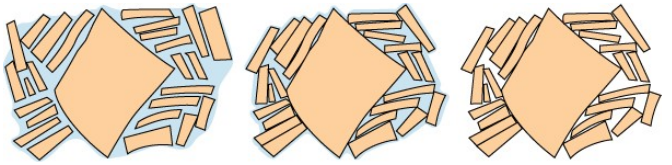


Fig. 13.20, *Callister & Rethwisch 10e*. (From W.D. Kingery, *Introduction to Ceramics*, Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Drying too fast causes sample to warp or crack due to non-uniform shrinkage

- Firing:
  - -- heat treatment between 900-1400° C
  - -- vitrification: liquid glass forms from clay and flux – flows between SiO_2 particles. (Flux lowers melting temperature).

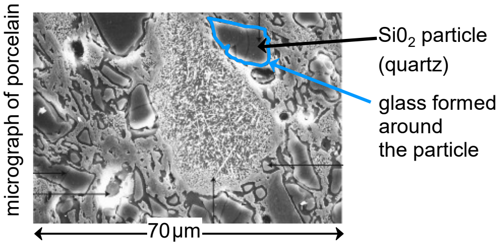


Fig. 13.21, *Callister & Rethwisch 10e*. (Courtesy H.G. Brinkies, Swinburne University of Technology, Hawthorn Campus, Hawthorn, Victoria, Australia.)

Ceramic Fabrication Methods (iib)

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

Powder Pressing: used for both clay and non-clay compositions.

- Powder (plus binder) compacted by pressure in a mold
  - -- Uniaxial compression - compacted in single direction
  - -- Isostatic (hydrostatic) compression - pressure applied by fluid - powder in rubber envelope
  - -- Hot pressing - pressure + heat

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Sintering

Sintering occurs during firing of a piece that has been powder pressed

-- powder particles coalesce and reduction of pore size

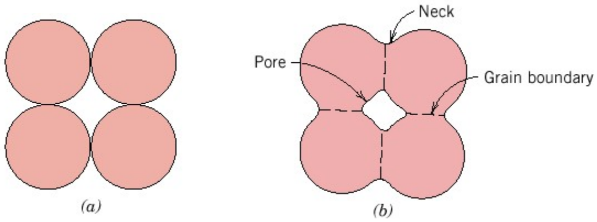


Fig. 13.23, *Callister & Rethwisch 10e*.

Aluminum oxide powder:

-- sintered at 1700° C
for 6 minutes.

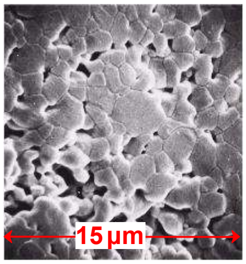
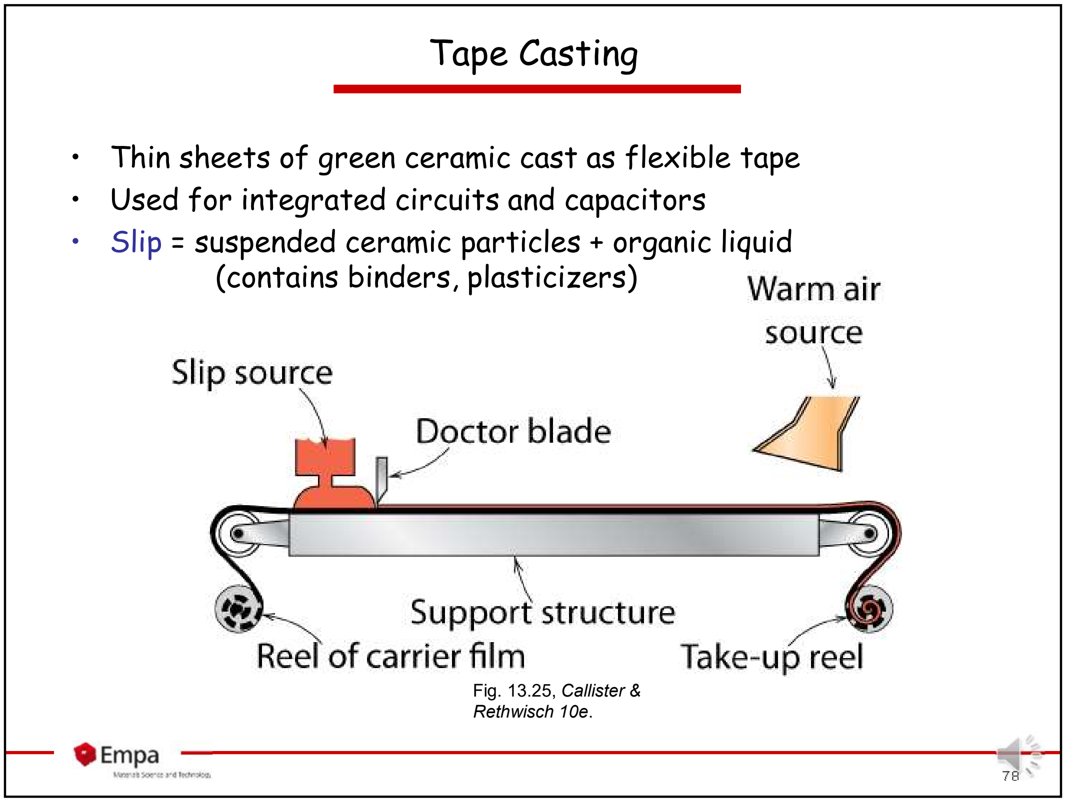


Fig. 13.24, *Callister & Rethwisch 10e*. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, Introduction to Ceramics, 2nd edition, p. 483. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Tape Casting

- Thin sheets of green ceramic cast as flexible tape
- Used for integrated circuits and capacitors
- Slip = suspended ceramic particles + organic liquid (contains binders, plasticizers)

Fig. 13.25, *Callister & Rethwisch 10e*.

Ceramic Fabrication Methods (iii)

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

- Hardening of a paste – paste formed by mixing cement material with water
- Formation of rigid structures having varied and complex shapes
- Hardening process – hydration (complex chemical reactions involving water and cement particles)
- Portland cement – production of:
  - -- mix clay and lime-bearing minerals
  - -- calcine (heat to 1400° C)
  - -- grind into fine powder

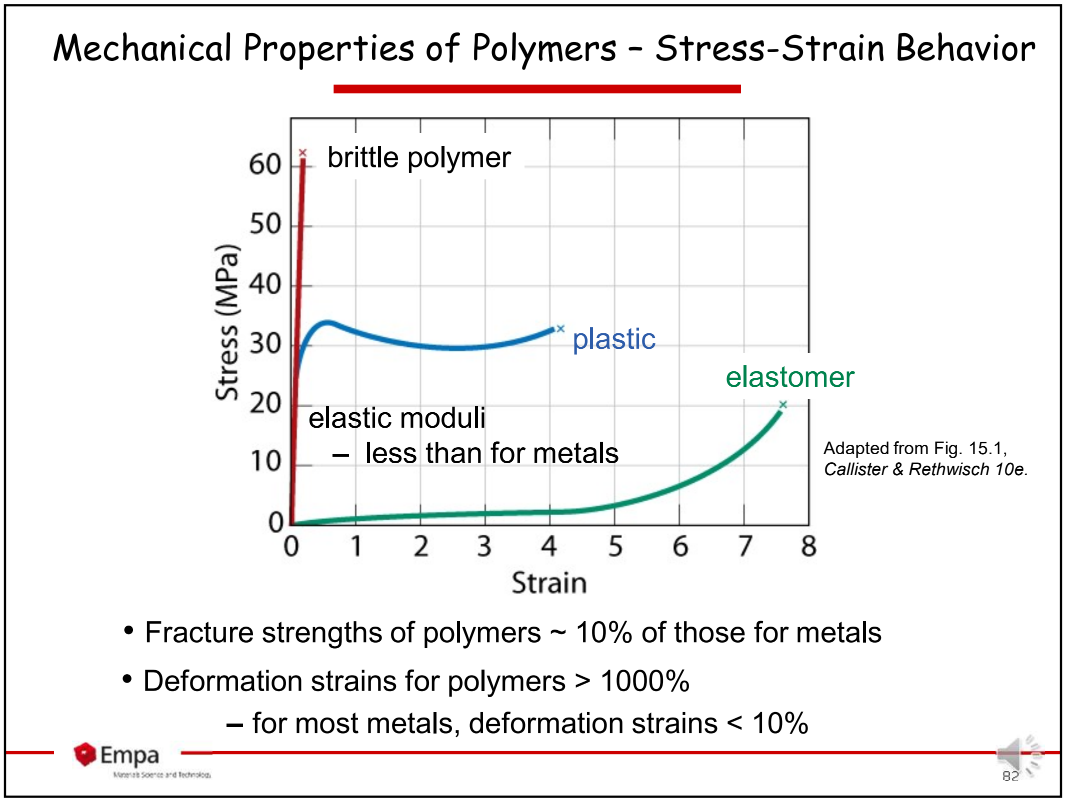
Summary

- Categories of ceramics:
  - -- glasses
  - -- refractories
  - -- advanced ceramics
  - -- clay products
  - -- cements
- Ceramic Fabrication techniques:
  - -- glass forming (pressing, blowing, fiber drawing).
  - -- particulate forming (hydroplastic forming, slip casting, powder pressing, tape casting)
  - -- cementation
- Heat treating procedures
  - -- glasses—annealing, tempering
  - -- particulate formed pieces—drying, firing (sintering)

Characteristics, Applications & Processing of Polymers

ISSUES TO ADDRESS...

- What are the tensile properties of polymers and how are they affected by basic microstructural features?
- Hardening, anisotropy, and annealing in polymers.
- How does the elevated temperature mechanical response of polymers compare to ceramics and metals?
- What are the primary polymer processing methods?

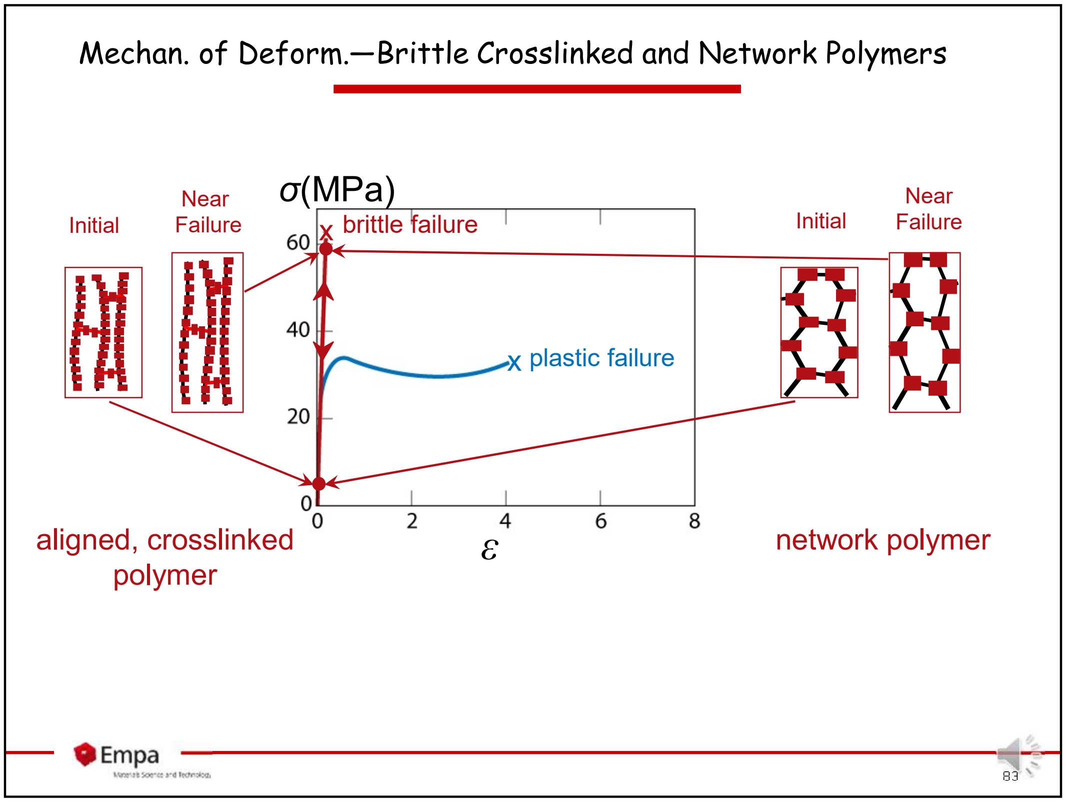


Mechanical Properties of Polymers – Stress-Strain Behavior

elastic moduli
– less than for metals

Adapted from Fig. 15.1, *Callister & Rethwisch 10e.*

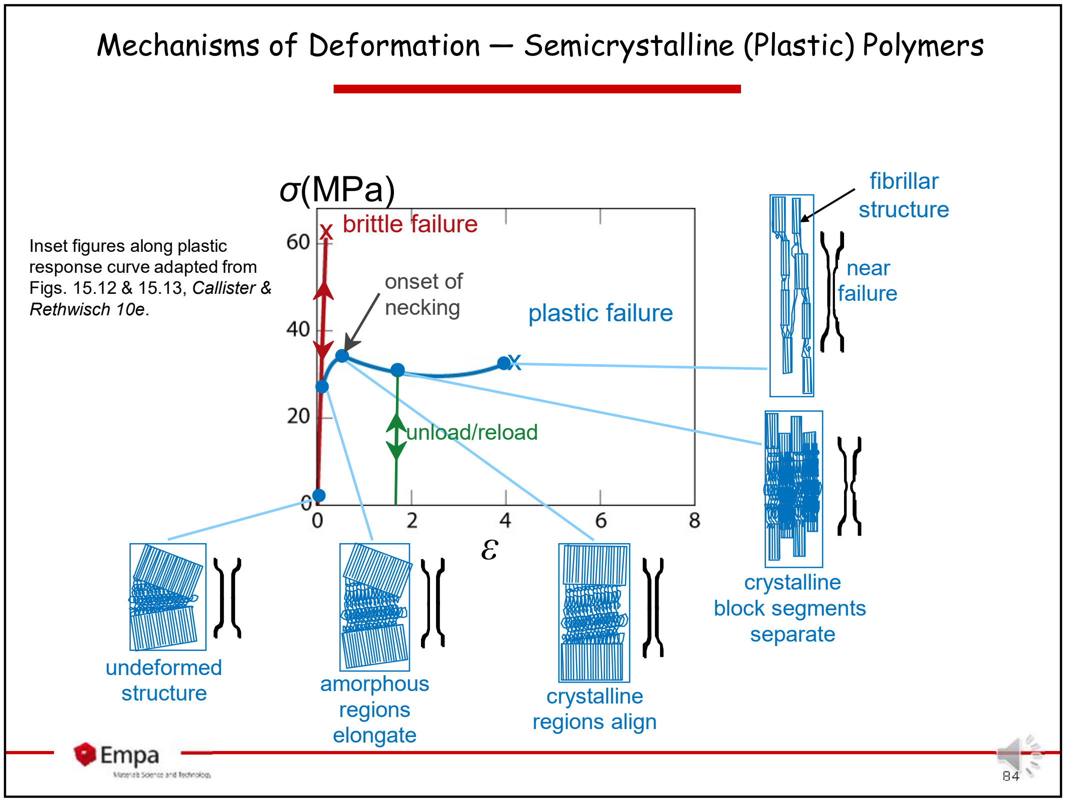
- Fracture strengths of polymers ~ 10% of those for metals
- Deformation strains for polymers > 1000%
  - for most metals, deformation strains < 10%



Mechan. of Deform.—Brittle Crosslinked and Network Polymers

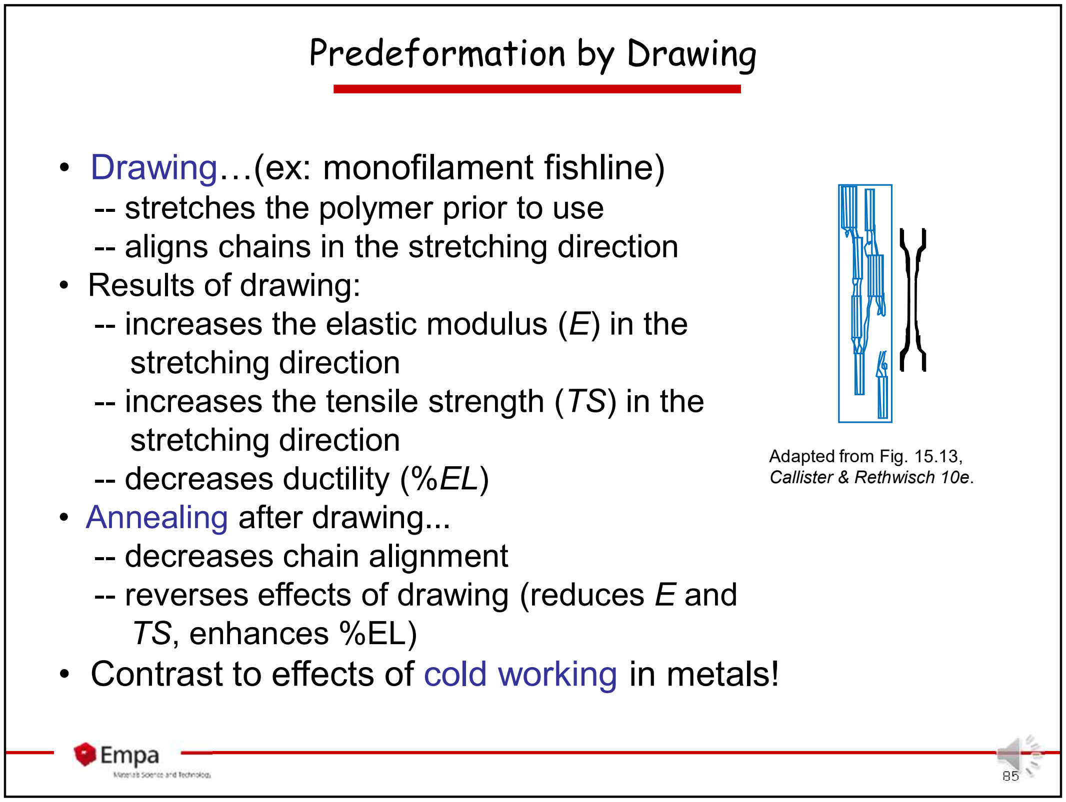
aligned, crosslinked polymer

network polymer



Mechanisms of Deformation — Semicrystalline (Plastic) Polymers

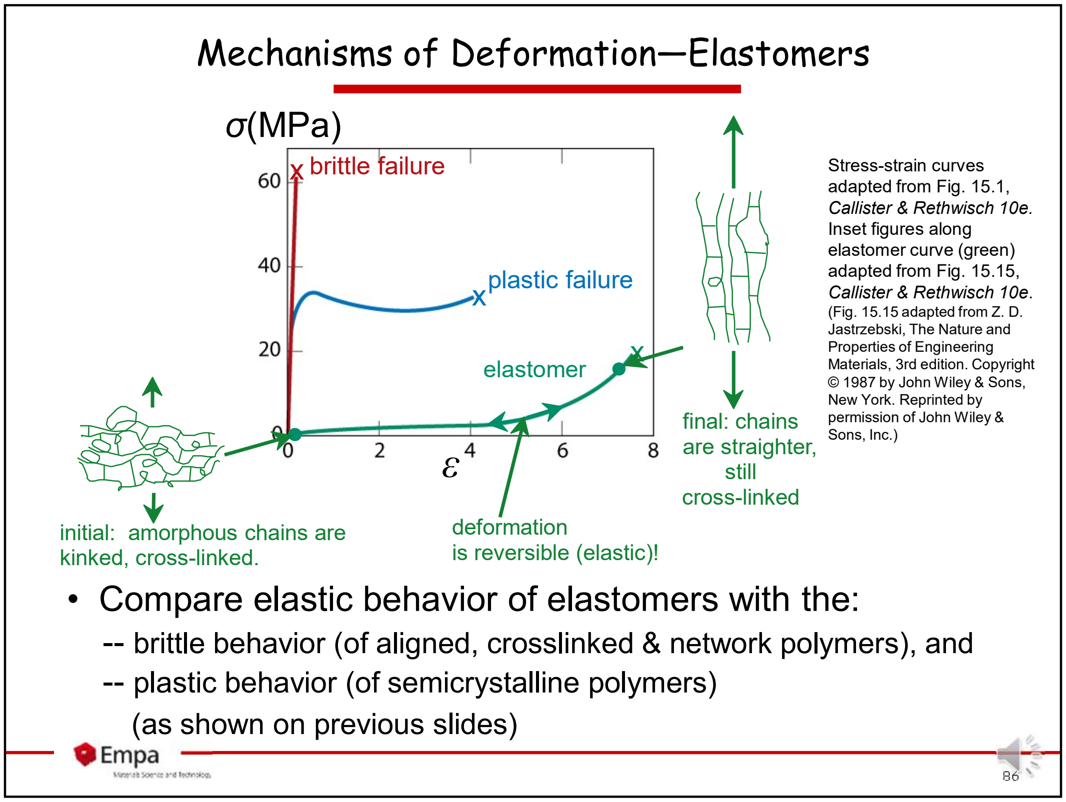
Inset figures along plastic response curve adapted from Figs. 15.12 & 15.13, *Callister & Rethwisch 10e*.



Predeformation by Drawing

- Drawing…(ex: monofilament fishline)
  -- stretches the polymer prior to use
  -- aligns chains in the stretching direction
- Results of drawing:
  -- increases the elastic modulus (*E*) in the stretching direction
  -- increases the tensile strength (*TS*) in the stretching direction
  -- decreases ductility (%*EL*)
- Annealing after drawing...
  -- decreases chain alignment
  -- reverses effects of drawing (reduces *E* and *TS*, enhances %EL)
- Contrast to effects of cold working in metals!

Adapted from Fig. 15.13, *Callister & Rethwisch 10e*.



Mechanisms of Deformation—Elastomers

Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 10e.* Inset figures along elastomer curve (green) adapted from Fig. 15.15, *Callister & Rethwisch 10e.* (Fig. 15.15 adapted from Z. D. Jastrzebski, The Nature and Properties of Engineering Materials, 3rd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

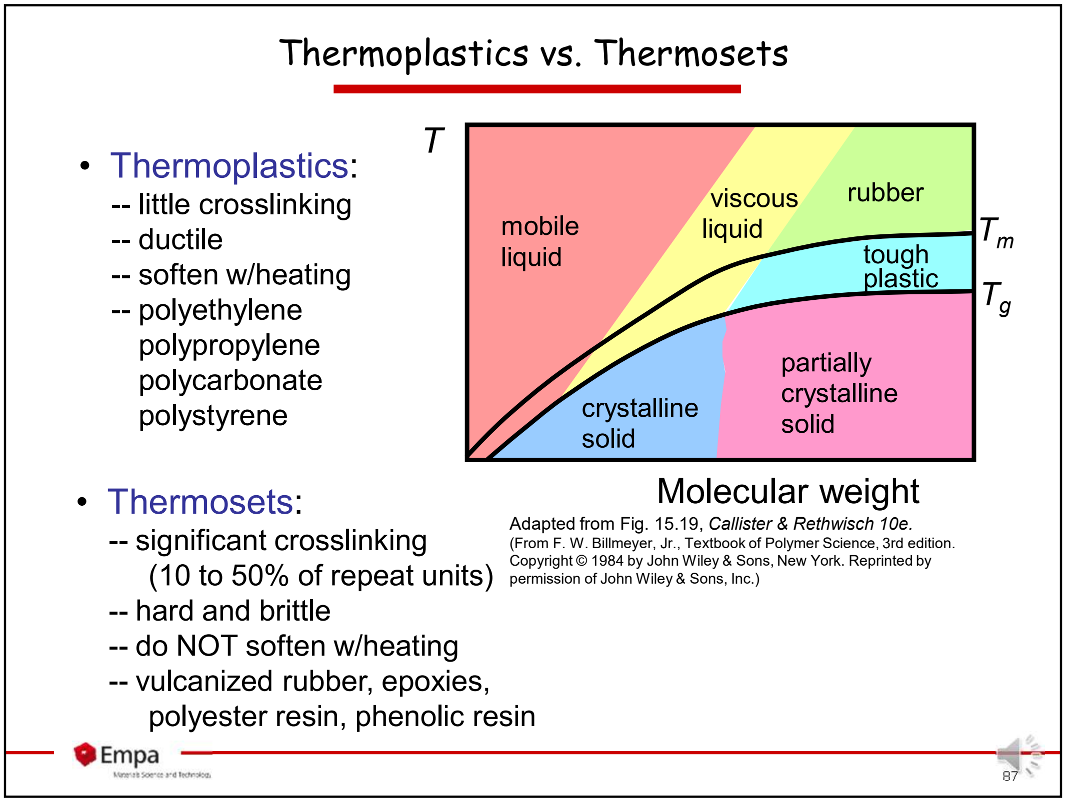
initial: amorphous chains are kinked, cross-linked.

deformation is reversible (elastic)!

final: chains are straighter, still cross-linked

- Compare elastic behavior of elastomers with the:
  - -- brittle behavior (of aligned, crosslinked & network polymers), and
  - -- plastic behavior (of semicrystalline polymers)

    (as shown on previous slides)



Thermoplastics vs. Thermosets

- Thermoplastics:
  - -- little crosslinking
  - -- ductile
  - -- soften w/heating
  - -- polyethylene
    polypropylene
    polycarbonate
    polystyrene

Adapted from Fig. 15.19, *Callister & Rethwisch 10e*.
(From F. W. Billmeyer, Jr., Textbook of Polymer Science, 3rd edition. Copyright © 1984 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

- Thermosets:
  - -- significant crosslinking
    (10 to 50% of repeat units)
  - -- hard and brittle
  - -- do NOT soften w/heating
  - -- vulcanized rubber, epoxies,
    polyester resin, phenolic resin

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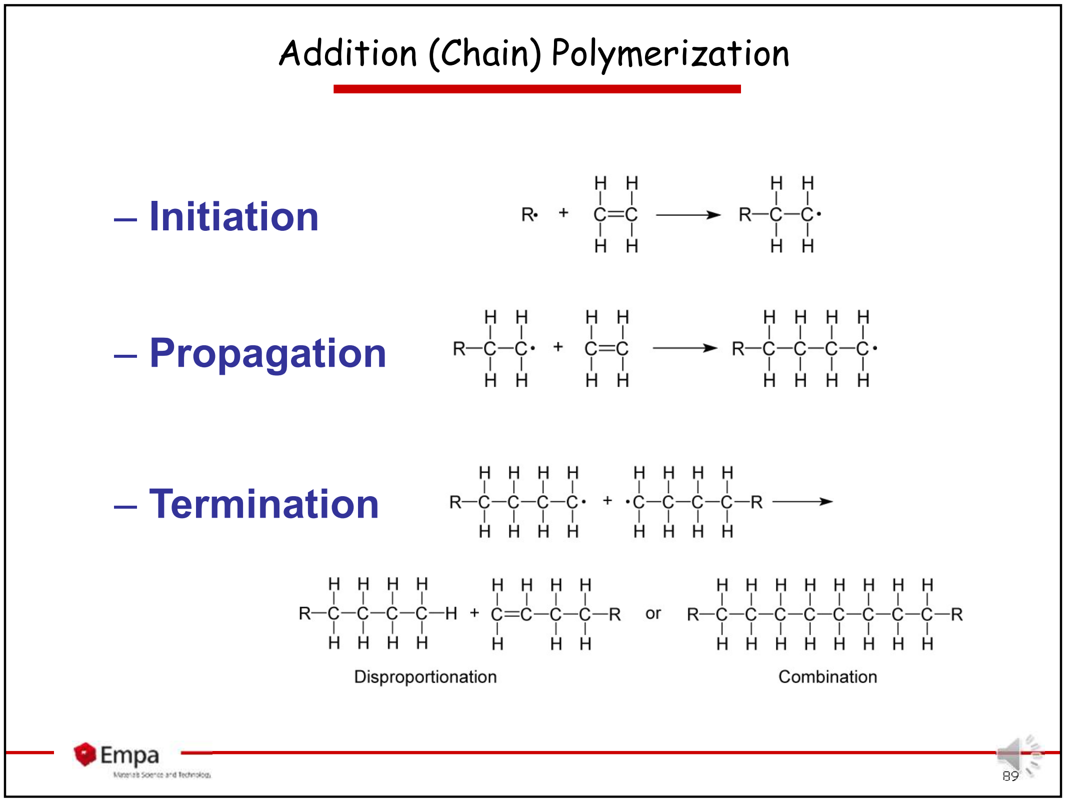
Polymer Formation

- There are two types of polymerization
  - Addition (or chain) polymerization
  - Condensation (step) polymerization



Addition (Chain) Polymerization

- **Initiation**

$$R\cdot + CH_2{=}CH_2 \longrightarrow R{-}CH_2{-}CH_2\cdot$$

- **Propagation**

$$R{-}CH_2{-}CH_2\cdot + CH_2{=}CH_2 \longrightarrow R{-}CH_2{-}CH_2{-}CH_2{-}CH_2\cdot$$

- **Termination**

$$R{-}CH_2{-}CH_2{-}CH_2{-}CH_2\cdot + \cdot CH_2{-}CH_2{-}CH_2{-}CH_2{-}R \longrightarrow$$

$$R{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}H + CH_2{=}CH{-}CH_2{-}CH_2{-}R \quad \text{or} \quad R{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}R$$

Disproportionation

Combination

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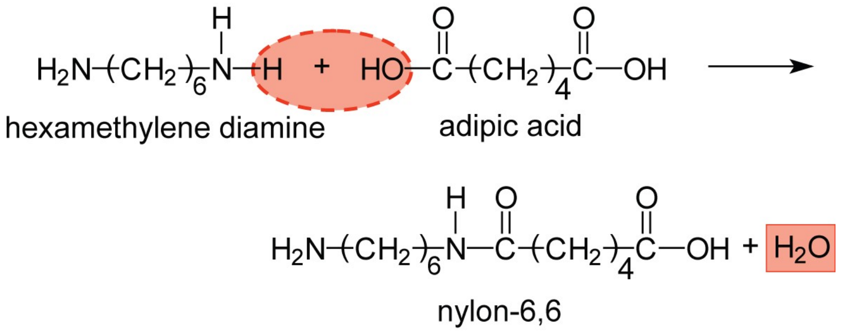
Condensation (Step) Polymerization



$$H_2N-(CH_2)_6-\overset{H}{\overset{|}{N}}-H + HO-\overset{O}{\overset{\|}{C}}-(CH_2)_4-\overset{O}{\overset{\|}{C}}-OH \longrightarrow H_2N-(CH_2)_6-\overset{H}{\overset{|}{N}}-\overset{O}{\overset{\|}{C}}-(CH_2)_4-\overset{O}{\overset{\|}{C}}-OH + \boxed{H_2O}$$

Polymer Additives

Improve mechanical properties, processability, durability, etc.

- Fillers
  - Added to improve tensile strength & abrasion resistance, toughness & decrease cost
  - ex: carbon black, silica gel, wood flour, glass, limestone, talc, etc.
- Plasticizers
  - Added to reduce the glass transition temperature T_g below room temperature
  - Presence of plasticizer transforms brittle polymer to a ductile one
  - Commonly added to PVC - otherwise it is brittle

Polymer Additives (cont.)

- Stabilizers
  - Antioxidants
  - UV protectants
- Lubricants
  - Added to allow easier processing
  - polymer “slides” through dies easier
  - ex: sodium stearate
- Colorants
  - Dyes and pigments
- Flame Retardants
  - Substances containing chlorine, fluorine, and boron

Processing of Plastics

- Thermoplastic
  - can be reversibly cooled & reheated, i.e. recycled
  - heat until soft, shape as desired, then cool
  - ex: polyethylene, polypropylene, polystyrene.
- Thermoset
  - when heated forms a molecular network (chemical reaction)
  - degrades (doesn't melt) when heated
  - a prepolymer molded into desired shape, then chemical reaction occurs
  - ex: urethane, epoxy

Processing Plastics – Compression Molding

Thermoplastics and thermosets

- polymer and additives placed in mold cavity
- mold heated and pressure applied
- fluid polymer assumes shape of mold

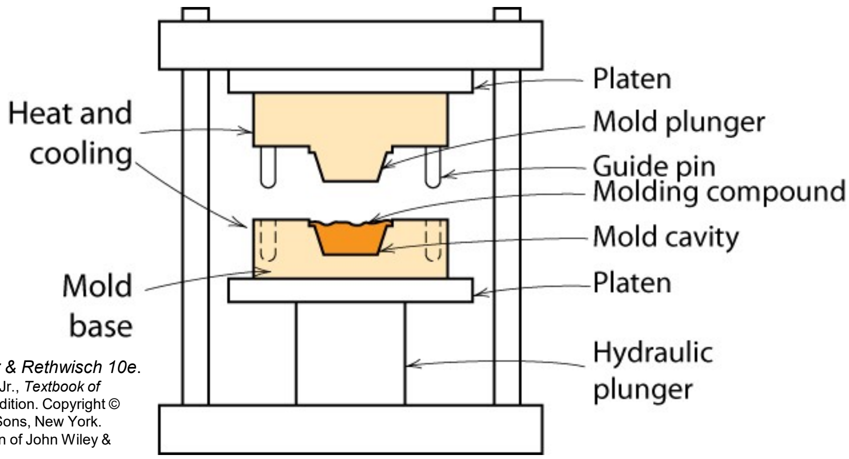
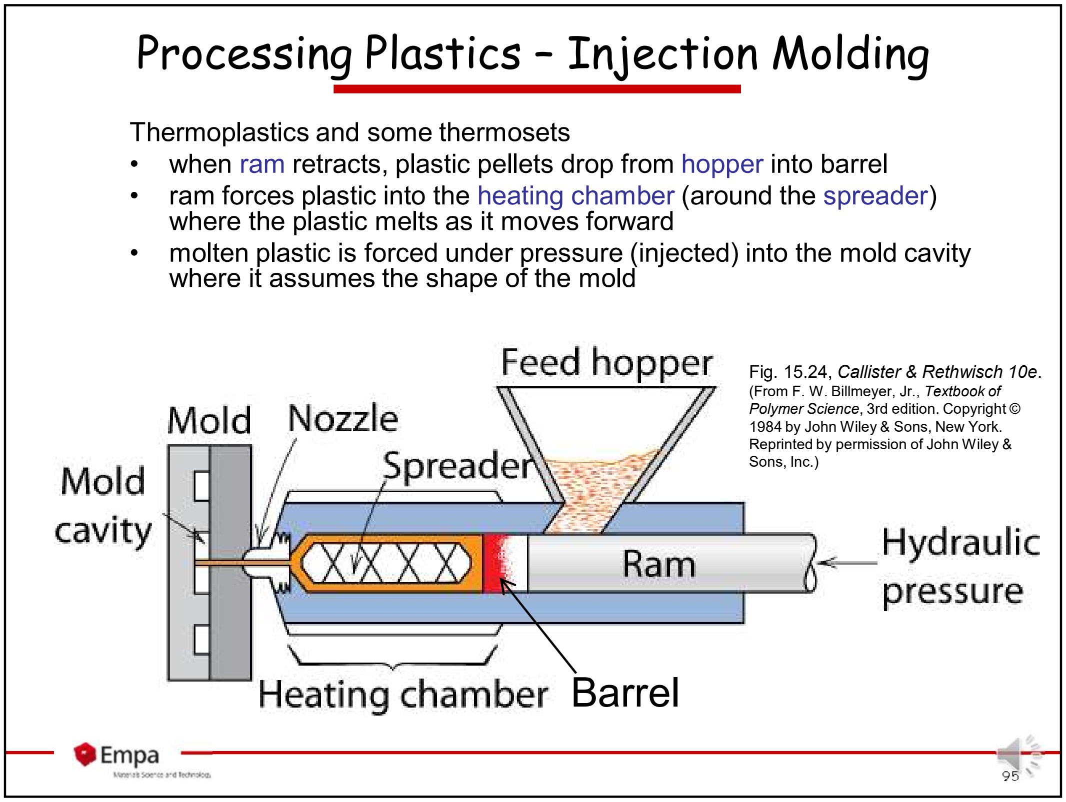


Fig. 15.23, *Callister & Rethwisch 10e*. (From F. W. Billmeyer, Jr., *Textbook of Polymer Science*, 3rd edition. Copyright © 1984 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

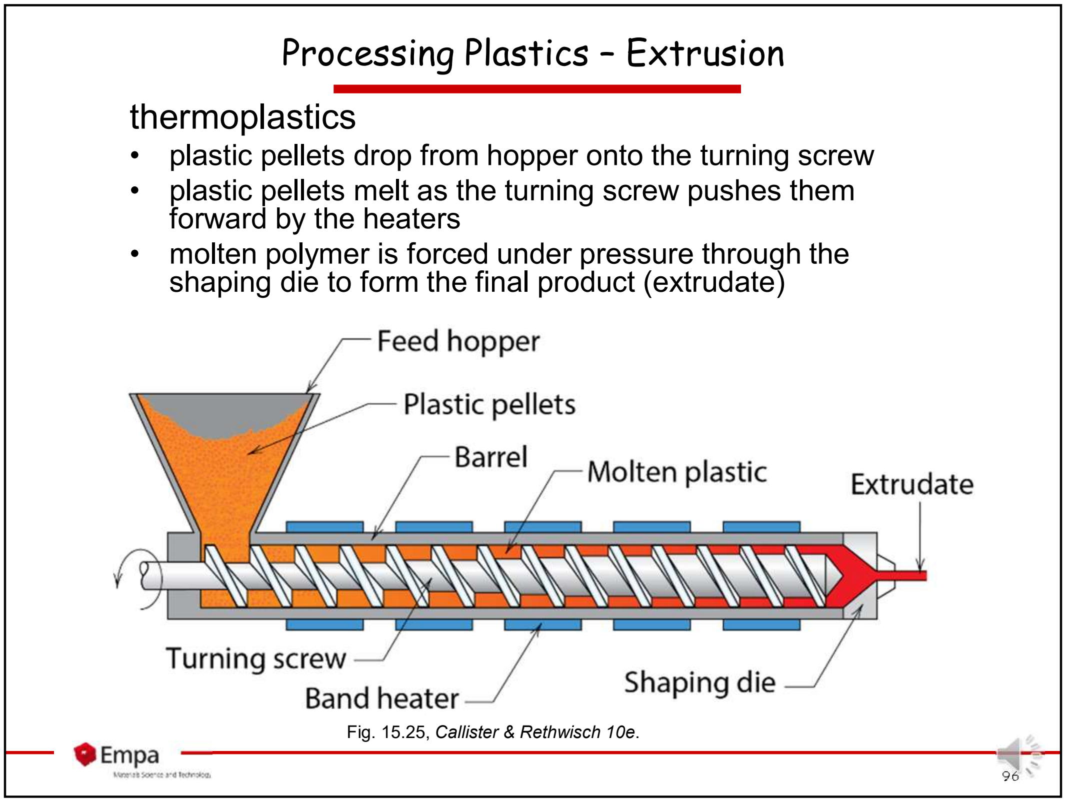


Processing Plastics – Injection Molding

Thermoplastics and some thermosets

- when ram retracts, plastic pellets drop from hopper into barrel
- ram forces plastic into the heating chamber (around the spreader) where the plastic melts as it moves forward
- molten plastic is forced under pressure (injected) into the mold cavity where it assumes the shape of the mold

Fig. 15.24, *Callister & Rethwisch 10e*. (From F. W. Billmeyer, Jr., *Textbook of Polymer Science*, 3rd edition. Copyright © 1984 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Processing Plastics – Extrusion

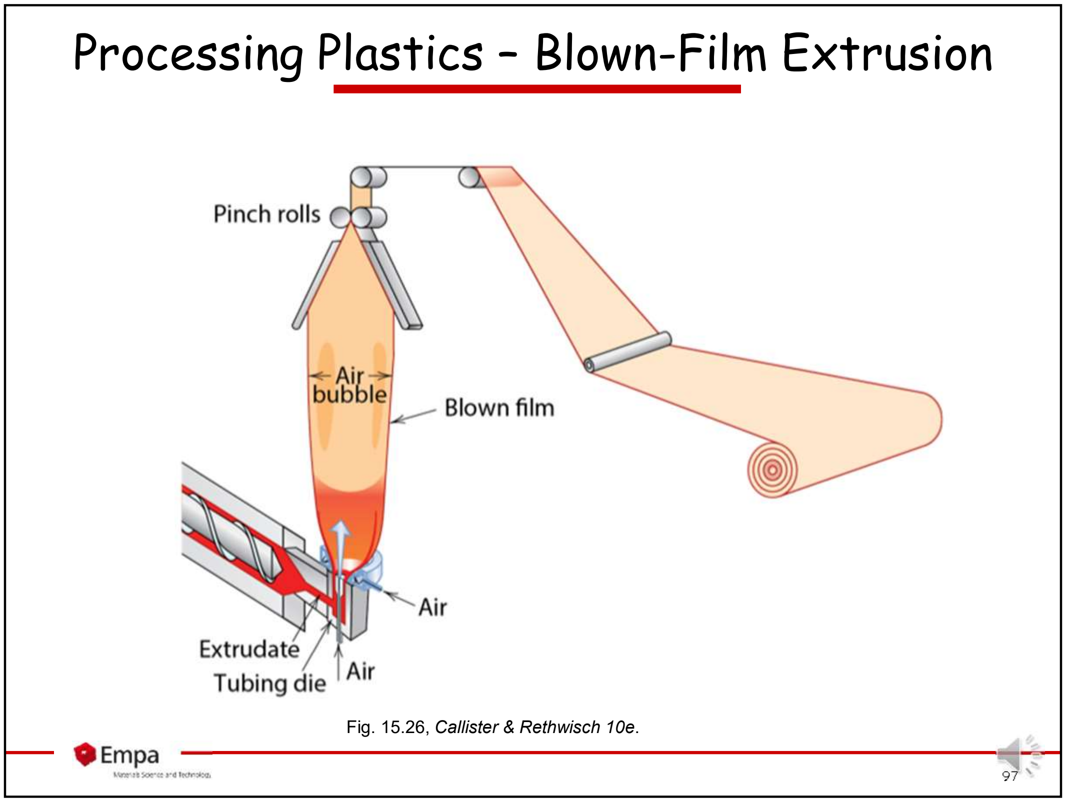
thermoplastics

- plastic pellets drop from hopper onto the turning screw
- plastic pellets melt as the turning screw pushes them forward by the heaters
- molten polymer is forced under pressure through the shaping die to form the final product (extrudate)

Fig. 15.25, *Callister & Rethwisch 10e*.

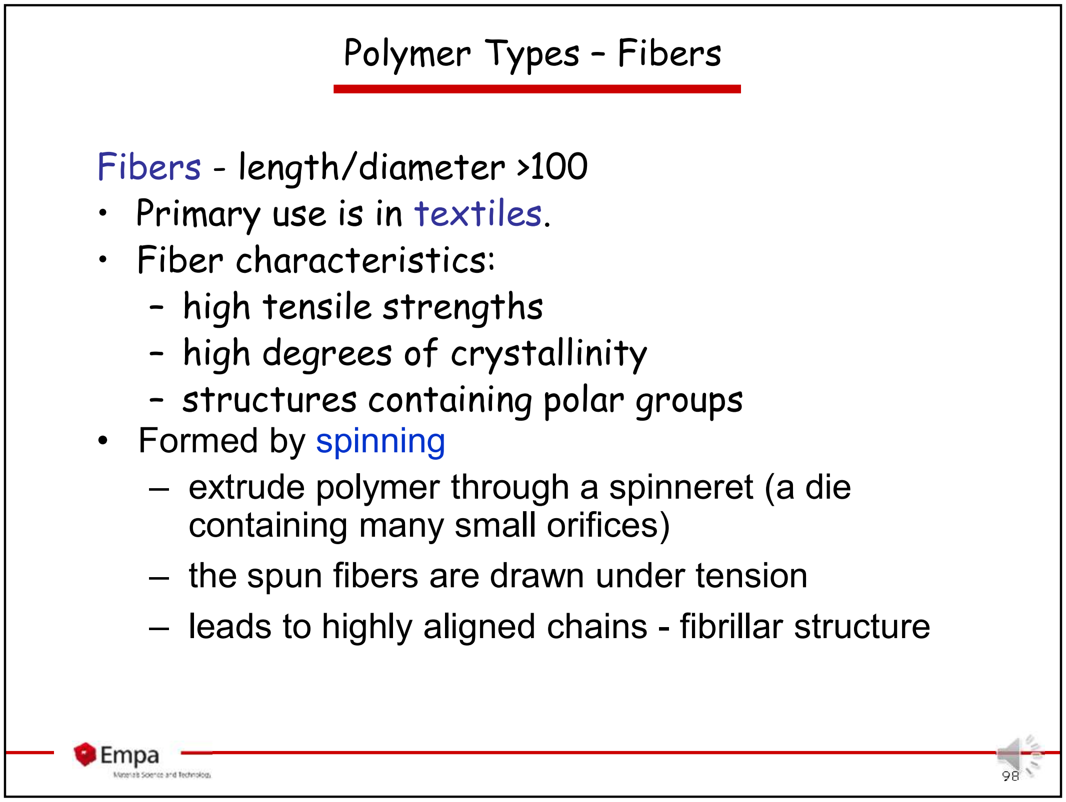
An extruder is a device that used a large screw to melt a polymer, compress it, & force it into a mold

Extremely commonly used



Processing Plastics – Blown-Film Extrusion

Fig. 15.26, *Callister & Rethwisch 10e*.



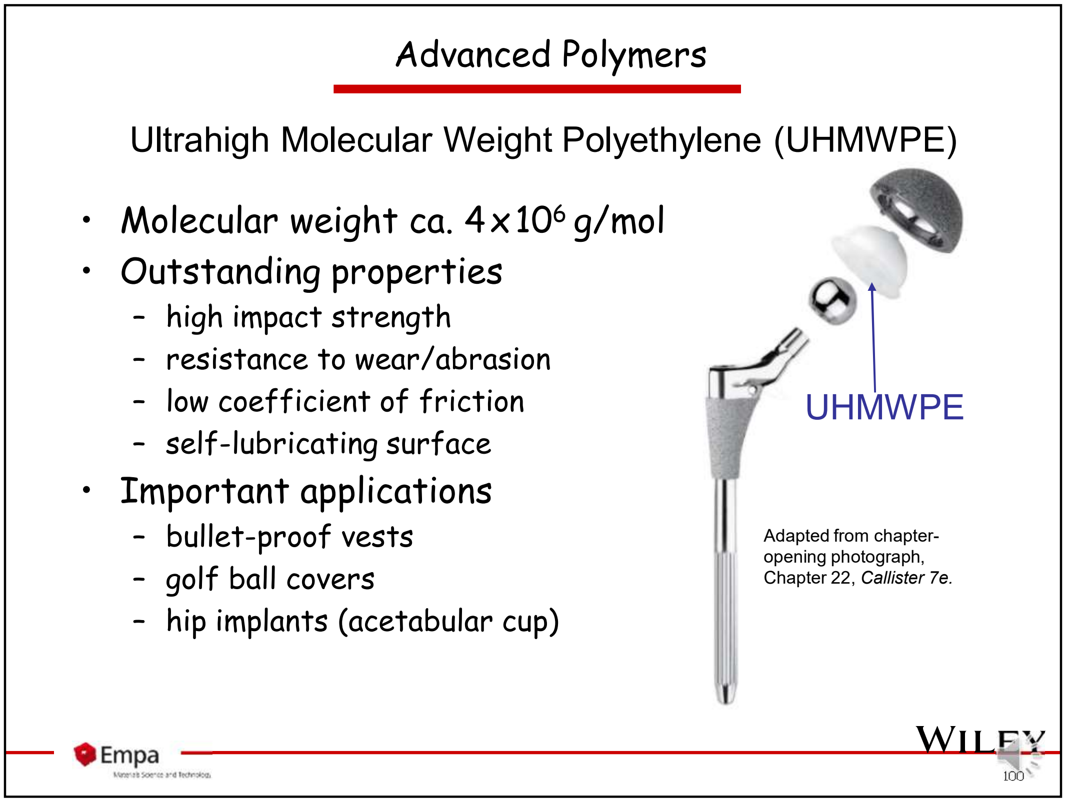
Polymer Types – Fibers

Fibers - length/diameter >100

- Primary use is in textiles.
- Fiber characteristics:
  - high tensile strengths
  - high degrees of crystallinity
  - structures containing polar groups
- Formed by spinning
  - extrude polymer through a spinneret (a die containing many small orifices)
  - the spun fibers are drawn under tension
  - leads to highly aligned chains - fibrillar structure

Polymer Types – Miscellaneous

- Coatings – thin polymer films applied to surfaces – i.e., paints, varnishes
  - protects from corrosion/degradation
  - decorative – improves appearance
  - can provide electrical insulation
- Adhesives – bonds two solid materials (adherands)
  - bonding types:
    1. Secondary – van der Waals forces
    2. Mechanical – penetration into pores/crevices
- Films – produced by blown film extrusion
- Foams – gas bubbles incorporated into plastic



Advanced Polymers

Ultrahigh Molecular Weight Polyethylene (UHMWPE)

- Molecular weight ca. 4×10^6 g/mol
- Outstanding properties
  - high impact strength
  - resistance to wear/abrasion
  - low coefficient of friction
  - self-lubricating surface
- Important applications
  - bullet-proof vests
  - golf ball covers
  - hip implants (acetabular cup)

Adapted from chapter-opening photograph, Chapter 22, *Callister 7e.*

Summary

- Limitations of polymers:
  - -- E, σ_y, K_c, $T_{\text{application}}$ are generally small.
  - -- Deformation is often time and temperature dependent.
- Thermoplastics (PE, PS, PP, PC):
  - -- Smaller E, σ_y, $T_{\text{application}}$
  - -- Larger K_c
  - -- Easier to form and recycle
- Elastomers (rubber):
  - -- Large reversible strains!
- Thermosets (epoxies, polyesters):
  - -- Larger E, σ_y, $T_{\text{application}}$
  - -- Smaller K_c

Summary

- Polymer Processing
  - compression and injection molding, extrusion, blown film extrusion
- Polymer melting and glass transition temperatures
- Polymer applications
  - elastomers
  - coatings
  - films
  - fibers
  - adhesives
  - foams
  - advanced polymeric materials

Chapter 16: Composites

ISSUES TO ADDRESS...

- What are the classes and types of composites?
- What are the advantages of using composite materials?
- How do we predict the stiffness and strength of the various types of composites?

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Composite

- Combination of two or more individual materials
- Design goal: obtain a more desirable combination of properties (principle of combined action)
    - e.g., low density and high strength

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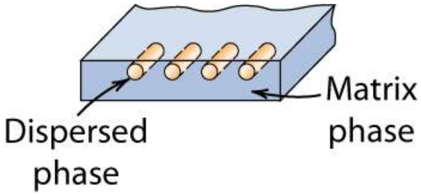
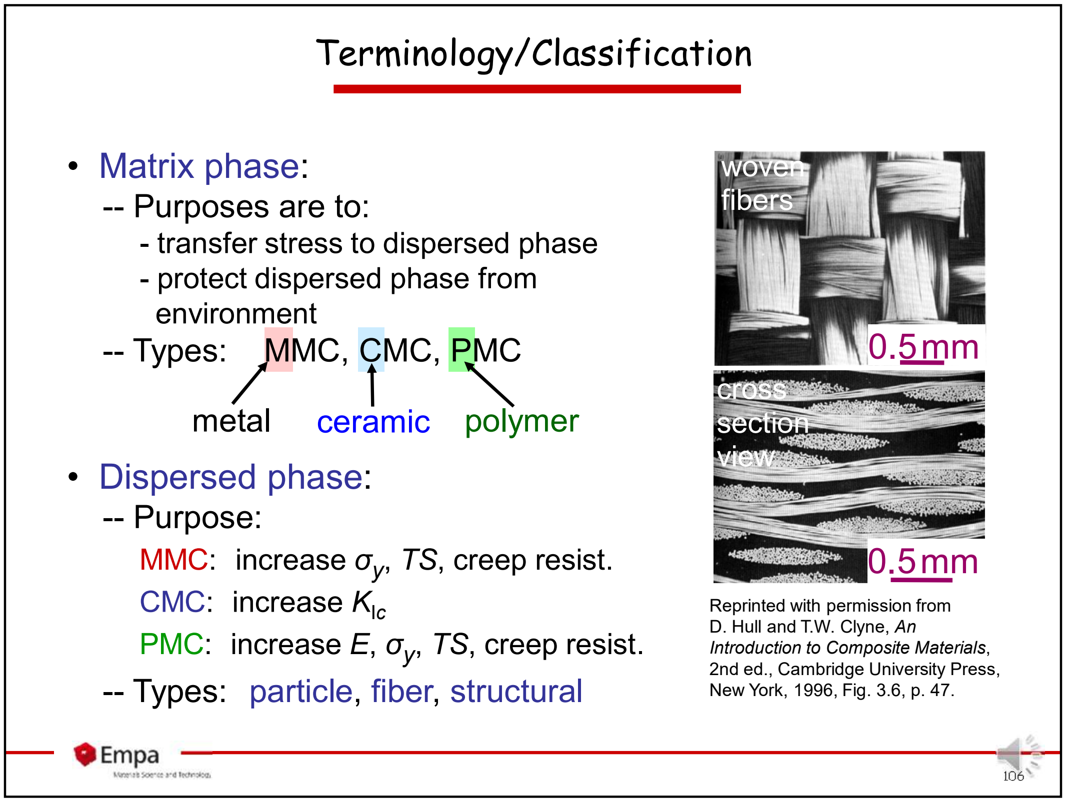
Terminology/Classification

- Composite:
  -- Multiphase material that is artificially made.
- Phase types:
  -- Matrix - is continuous
  -- Dispersed - is discontinuous and surrounded by matrix



Adapted from Fig. 16.1(a), *Callister & Rethwisch 10e*.



Terminology/Classification

- Matrix phase:
  - -- Purposes are to:
    - - transfer stress to dispersed phase
    - - protect dispersed phase from environment
  - -- Types: MMC, CMC, PMC

metal ceramic polymer

- Dispersed phase:
  - -- Purpose:
    - MMC: increase σ_y, TS, creep resist.
    - CMC: increase K_{Ic}
    - PMC: increase E, σ_y, TS, creep resist.
  - -- Types: particle, fiber, structural

Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.

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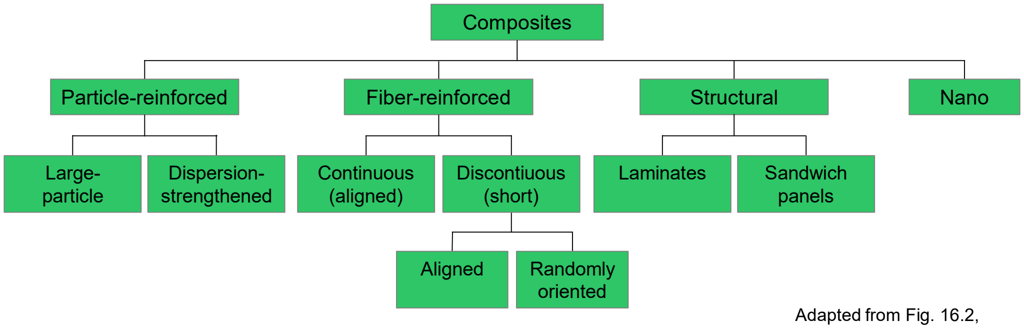
Classification of Composites


Composites

Particle-reinforced

Fiber-reinforced

Structural

Nano

Large-particle

Dispersion-strengthened

Continuous (aligned)

Discontiuous (short)

Laminates

Sandwich panels

Aligned

Randomly oriented

Adapted from Fig. 16.2, *Callister & Rethwisch 10e*.

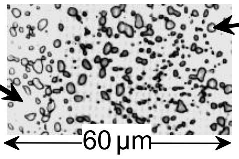
Classification: Particle-Reinforced (i)

Particle-reinforced Fiber-reinforced Structural

- Examples:

- Spheroidite steel

matrix: ferrite (α) (ductile)

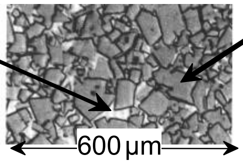


particles: cementite (Fe_3C) (brittle)

Fig. 10.19, *Callister & Rethwisch 10e*. (Copyright 1971 by United States Steel Corporation.)

- WC/Co cemented carbide

matrix: cobalt (ductile, tough)

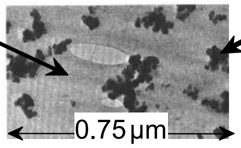


particles: WC (brittle, hard)

Fig. 16.4, *Callister & Rethwisch 10e*. (Courtesy of Carboloy Systems Department, General Electric Company.)

- Automobile tire rubber

matrix: rubber (compliant)



particles: carbon black (stiff)

Fig. 16.5, *Callister & Rethwisch 10e*. (Courtesy of Goodyear Tire and Rubber Company.)

Classification: Particle-Reinforced (ii)

Particle-reinforced Fiber-reinforced Structural

Concrete – gravel + sand + cement + water

- Why sand *and* gravel? Sand fills voids between gravel particles

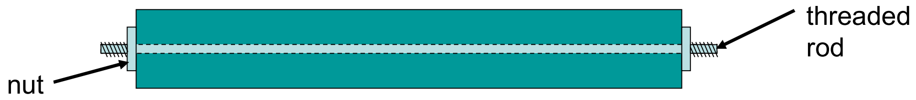
Reinforced concrete – Reinforce with steel rebar or remesh

- increases strength - even if cement matrix is cracked

Prestressed concrete

- Rebar/remesh placed under tension during setting of concrete
- Release of tension after setting places concrete in a state of compression
- To fracture concrete, applied tensile stress must exceed this compressive stress

Posttensioning – tighten nuts to place concrete under compression



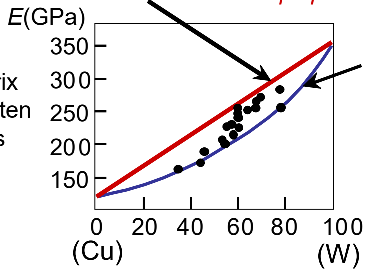
Classification: Particle-Reinforced (iii)

Particle-reinforced   Fiber-reinforced   Structural

- Elastic modulus, E_c, of composites:
  - -- two “rule of mixture” extremes:

upper limit: $E_c = V_m E_m + V_p E_p$

Data:
Cu matrix
w/tungsten
particles



lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Fig. 16.3, *Callister & Rethwisch 10e*.
(Reprinted with permission from R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM International, 100 Barr Harbor Drive, West Conschohocken, PA 19428.)

- Application to other properties:
  - -- Electrical conductivity, σ_e: Replace E’s in equations with σ_e’s.
  - -- Thermal conductivity, k: Replace E’s in equations with k’s.

Classification: Fiber-Reinforced (i)

Particle-reinforced | **Fiber-reinforced** | Structural

- Fibers very strong in tension
  - – Provide significant strength improvement to the composite
  - – Ex: fiber-glass - continuous glass filaments in a polymer matrix
    - Glass fibers
      - – strength and stiffness
    - Polymer matrix
      - – holds fibers in place
      - – protects fiber surfaces
      - – transfers load to fibers

Classification: Fiber-Reinforced (ii)

Particle-reinforced **Fiber-reinforced** Structural

- Fiber Types
  - Whiskers - thin single crystals - large length to diameter ratios
    - graphite, silicon nitride, silicon carbide
    - high crystal perfection – extremely strong, strongest known
    - very expensive and difficult to disperse
  - Fibers
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: alumina, aramid, E-glass, boron, UHMWPE
  - Wires
    - metals – steel, molybdenum, tungsten

Fiber Alignment

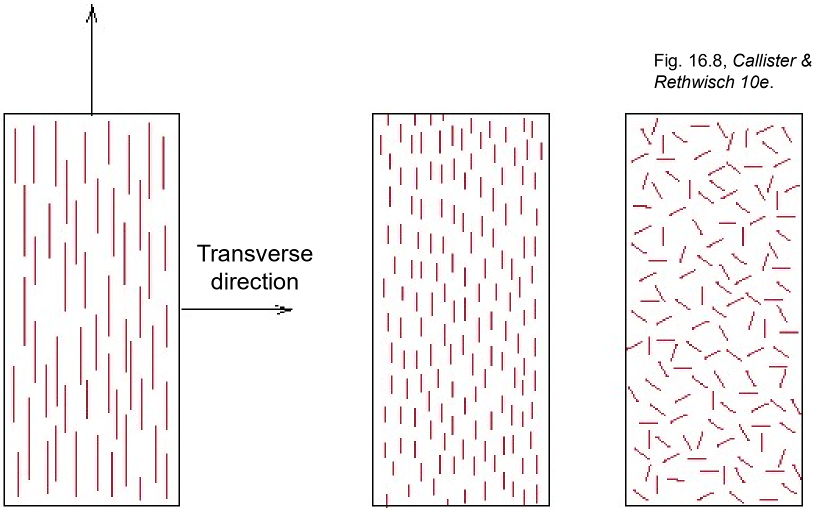


Fig. 16.8, *Callister & Rethwisch 10e*.

aligned
continuous

aligned random
discontinuous

WILEY

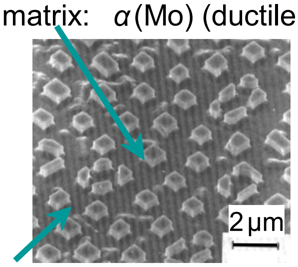
Classification: Fiber-Reinforced (iii)

Particle-reinforced | **Fiber-reinforced** | Structural

- Aligned Continuous fibers
- Examples:

-- Metal: γ'(Ni_3Al)-α(Mo) by eutectic solidification.

matrix: α(Mo) (ductile)

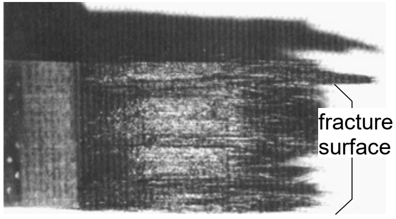


fibers: γ' (Ni_3Al) (brittle)

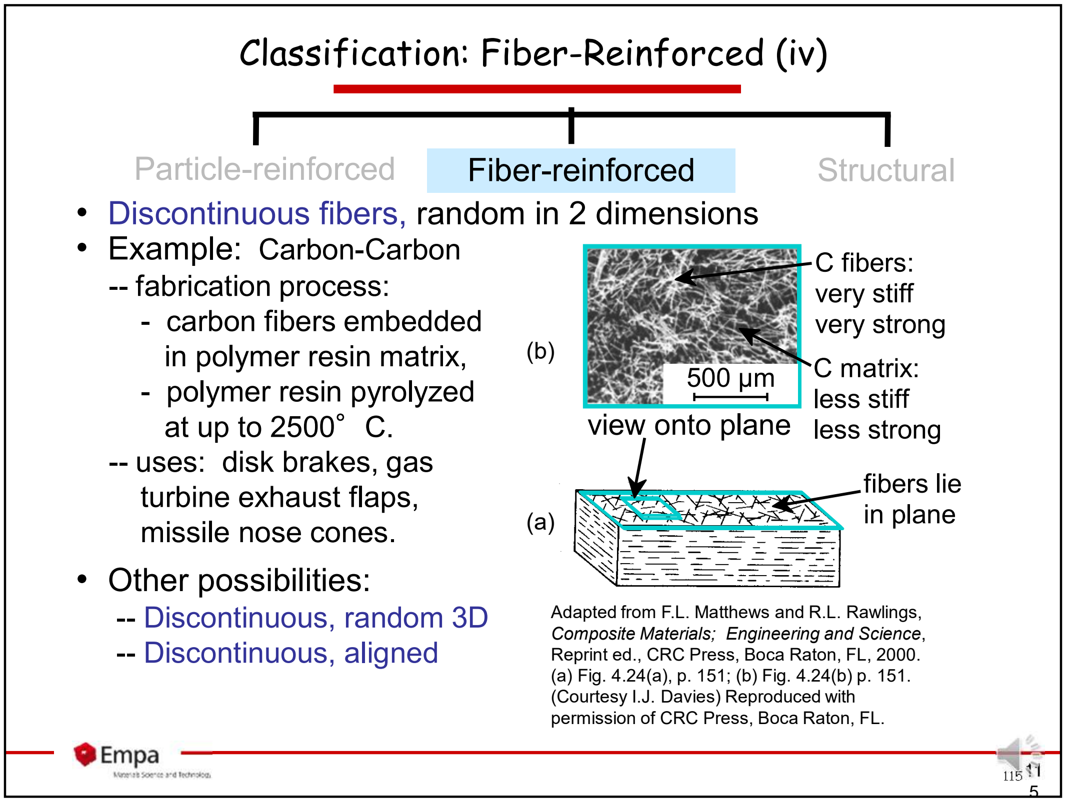
From W. Funk and E. Blank, "Creep deformation of Ni_3Al-Mo in-situ composites", *Metall. Trans. A* Vol. 19(4), pp. 987-998, 1988. Used with permission.

-- Ceramic: Glass w/SiC fibers formed by glass slurry

E_{glass} = 76 GPa; E_{SiC} = 400 GPa.



From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. Used with permission of CRC Press, Boca Raton, FL.

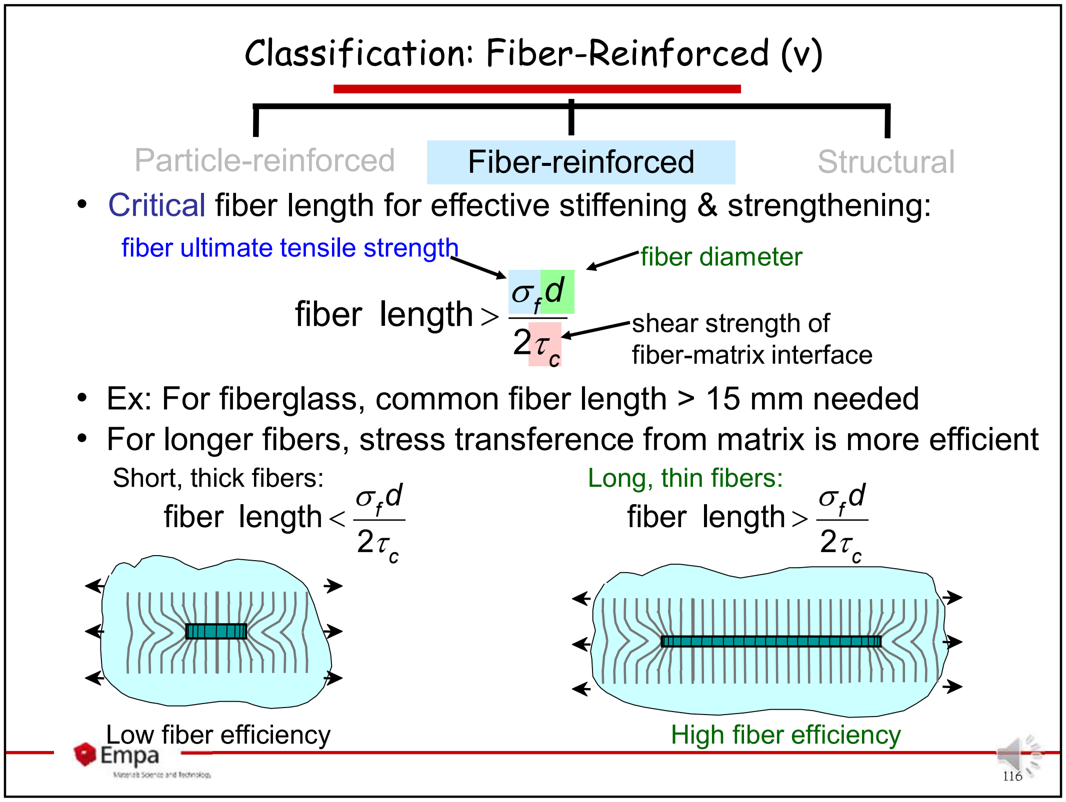


Classification: Fiber-Reinforced (iv)

Particle-reinforced | **Fiber-reinforced** | Structural

- Discontinuous fibers, random in 2 dimensions
- Example: Carbon-Carbon
  - -- fabrication process:
    - - carbon fibers embedded in polymer resin matrix,
    - - polymer resin pyrolyzed at up to 2500° C.
  - -- uses: disk brakes, gas turbine exhaust flaps, missile nose cones.
- Other possibilities:
  - -- Discontinuous, random 3D
  - -- Discontinuous, aligned

Adapted from F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151. (Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.



Classification: Fiber-Reinforced (v)

Particle-reinforced | **Fiber-reinforced** | Structural

- Critical fiber length for effective stiffening & strengthening:

fiber ultimate tensile strength

fiber diameter

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

shear strength of fiber-matrix interface

- Ex: For fiberglass, common fiber length > 15 mm needed
- For longer fibers, stress transference from matrix is more efficient

Short, thick fibers:

$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$

Long, thin fibers:

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

Low fiber efficiency

High fiber efficiency

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Composite Stiffness: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite modulus of elasticity for continuous fibers

- Longitudinal deformation

$\sigma_c = \sigma_m V_m + \sigma_f V_f$ and $\varepsilon_c = \varepsilon_m = \varepsilon_f$

volume fraction

isostrain

$$\therefore \quad \boxed{E_{cl} = E_m V_m + E_f V_f}$$

E_{cl} = longitudinal modulus

c = composite
f = fiber
m = matrix

Composite Stiffness: Transverse Loading

- In transverse loading the fibers carry less of the load

$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$ and $\sigma_c = \sigma_m = \sigma_f = \sigma$

isostress

$$\boxed{\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}}$$

E_{ct} = transverse modulus

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

c = composite
f = fiber
m = matrix

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Composite Stiffness

Particle-reinforced | **Fiber-reinforced** | Structural

- Estimate of E_{cd} for discontinuous fibers:

  -- valid when fiber length < $15\dfrac{\sigma_f d}{\tau_c}$

  -- Elastic modulus in fiber direction:

$$E_{cd} = E_m V_m + \overset{\uparrow}{K} E_f V_f$$

efficiency factor:

-- aligned: $K = 1$ (aligned parallel)
-- aligned: $K = 0$ (aligned perpendicular)
-- random 2D: $K = 3/8$ (2D isotropy)
-- random 3D: $K = 1/5$ (3D isotropy)

Table 16.3, *Callister & Rethwisch 10e*. (Source is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

Composite Strength

Particle-reinforced | **Fiber-reinforced** | Structural

- Estimate of σ^*_{cd} for discontinuous fibers:

1. When $l > l_c$

$$\sigma^*_{cd'} = \sigma^*_f V_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m (1 - V_f)$$

2. When $l < l_c$

$$\sigma^*_{cd'} = \frac{l\,\tau_c}{d} V_f + \sigma'_m (1 - V_f)$$

Composite Production Methods (i)

Pultrusion

- Continuous fibers pulled through resin tank to impregnate fibers with thermosetting resin
- Impregnated fibers pass through steel die that preforms to the desired shape
- Preformed stock passes through a curing die that is
  - precision machined to impart final shape
  - heated to initiate curing of the resin matrix

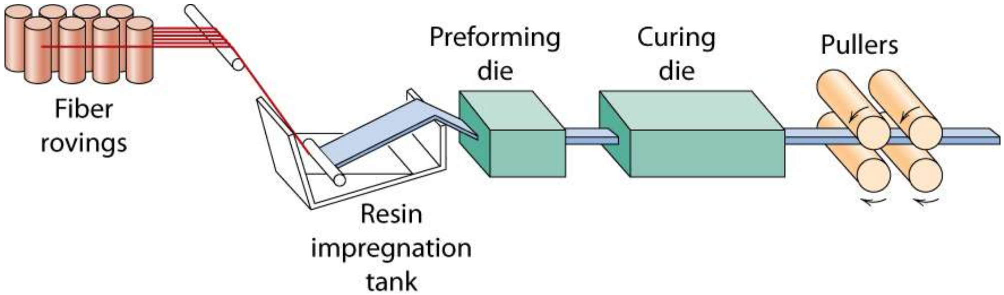


Fig. 16.13, *Callister & Rethwisch 10e*.

Composite Production Methods (ii)

- Filament Winding
  - Continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape
  - Fibers are fed through a resin bath to impregnate with thermosetting resin
  - Impregnated fibers are continuously wound (typically automatically) onto a mandrel
  - After appropriate number of layers added, curing is carried out either in an oven or at room temperature
  - The mandrel is removed to give the final product

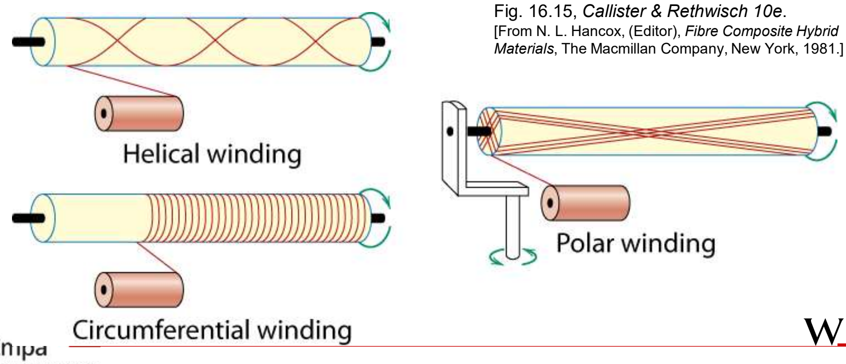
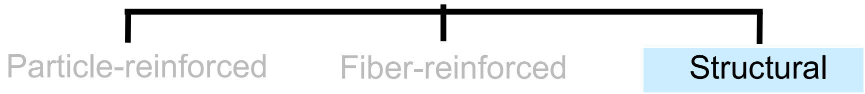


Fig. 16.15, *Callister & Rethwisch 10e*.
[From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]

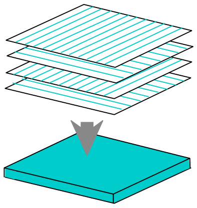
Classification: Structural



Particle-reinforced Fiber-reinforced **Structural**

- Laminates -

  -- stacked and bonded fiber-reinforced sheets
    - stacking sequence: e.g., 0º/90º
    - benefit: balanced in-plane stiffness



- Sandwich panels

  -- honeycomb core between two facing sheets
    - benefits: low density, large bending stiffness

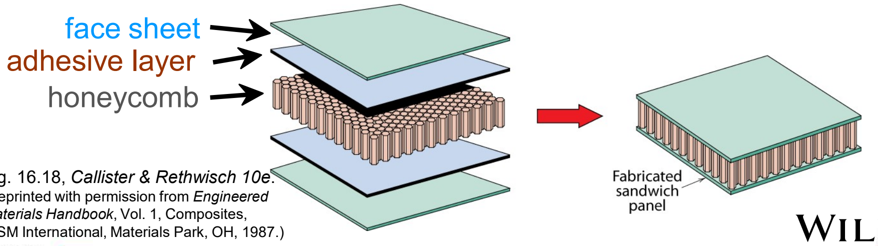
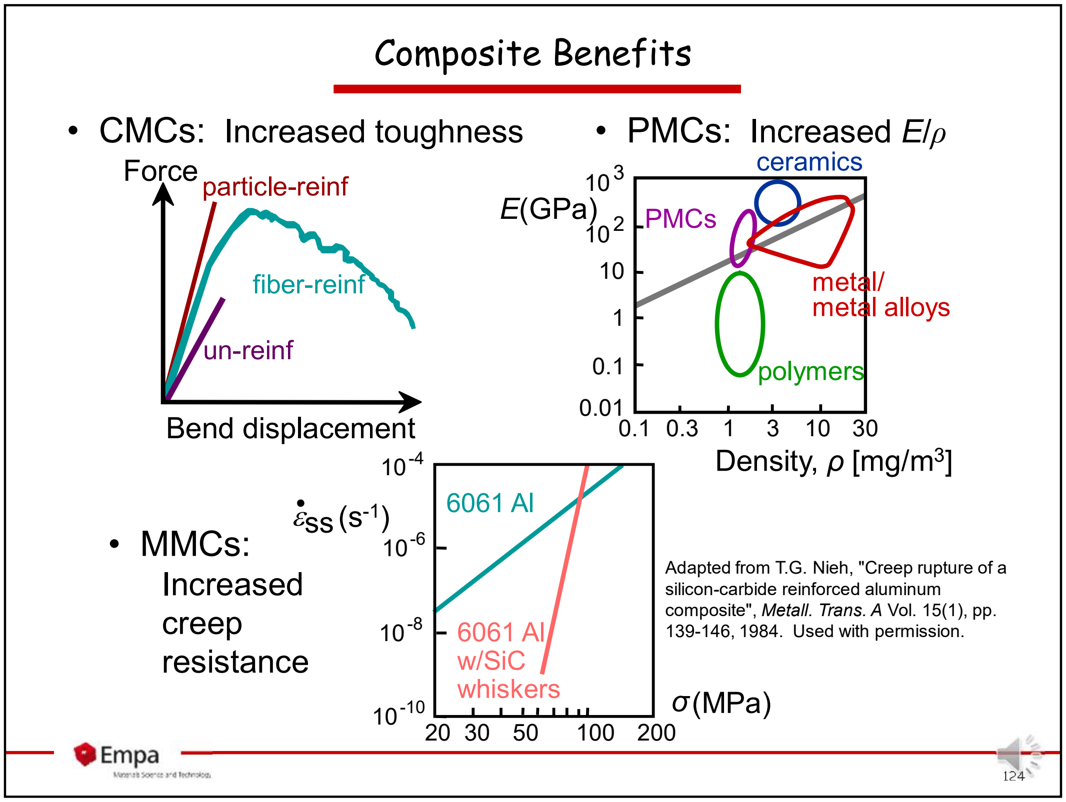


Fig. 16.18, *Callister & Rethwisch 10e*.
(Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, Composites, ASM International, Materials Park, OH, 1987.)



Composite Benefits

- CMCs: Increased toughness

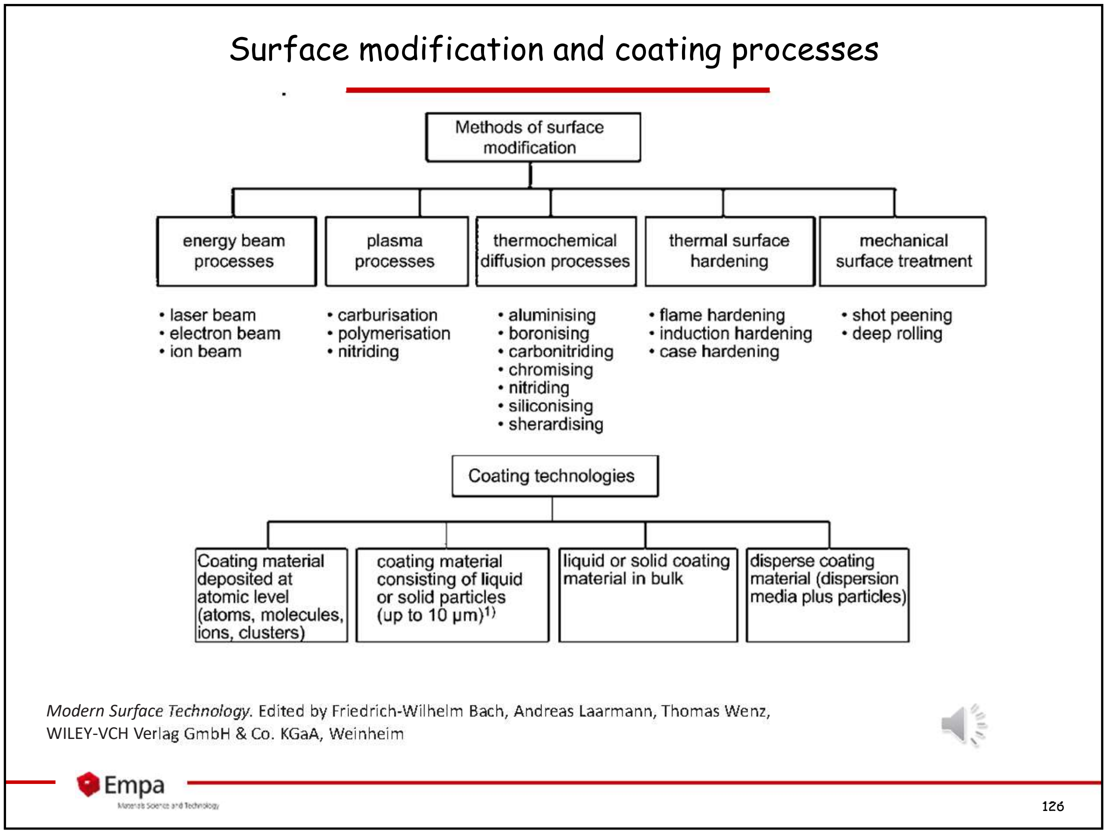
- PMCs: Increased E/ρ

- MMCs:
  Increased
  creep
  resistance

Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

Summary

- Composites types are designated by:
  - -- the matrix material (CMC, MMC, PMC)
  - -- the reinforcement (particles, fibers, structural)
- Composite property benefits:
  - -- MMC: enhanced E, σ^*, creep performance
  - -- CMC: enhanced K_{Ic}
  - -- PMC: enhanced E/ρ, σ_y, TS/ρ
- Particulate-reinforced:
  - -- Types: large-particle and dispersion-strengthened
  - -- Properties are isotropic
- Fiber-reinforced:
  - -- Types: continuous (aligned)
    discontinuous (aligned or random)
  - -- Properties can be isotropic or anisotropic
- Structural:
  - -- Laminates and sandwich panels



Surface modification and coating processes

Methods of surface modification

energy beam processes
- laser beam
- electron beam
- ion beam

plasma processes
- carburisation
- polymerisation
- nitriding

thermochemical diffusion processes
- aluminising
- boronising
- carbonitriding
- chromising
- nitriding
- siliconising
- sherardising

thermal surface hardening
- flame hardening
- induction hardening
- case hardening

mechanical surface treatment
- shot peening
- deep rolling

Coating technologies

- Coating material deposited at atomic level (atoms, molecules, ions, clusters)
- coating material consisting of liquid or solid particles (up to 10 µm)[1)]
- liquid or solid coating material in bulk
- disperse coating material (dispersion media plus particles)

Modern Surface Technology. Edited by Friedrich-Wilhelm Bach, Andreas Laarmann, Thomas Wenz, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

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Abgerundet?

Surface Treatments

- Aluminizing
- Boriding, Nitriding
- Carburizing and Carbonitriding (movie)
- Chromizing and Plasma Chromizing
- Induction and flame hardening (movie)
- Laser hardening & cladding
- Anodizing
- Chromating and Phosphating

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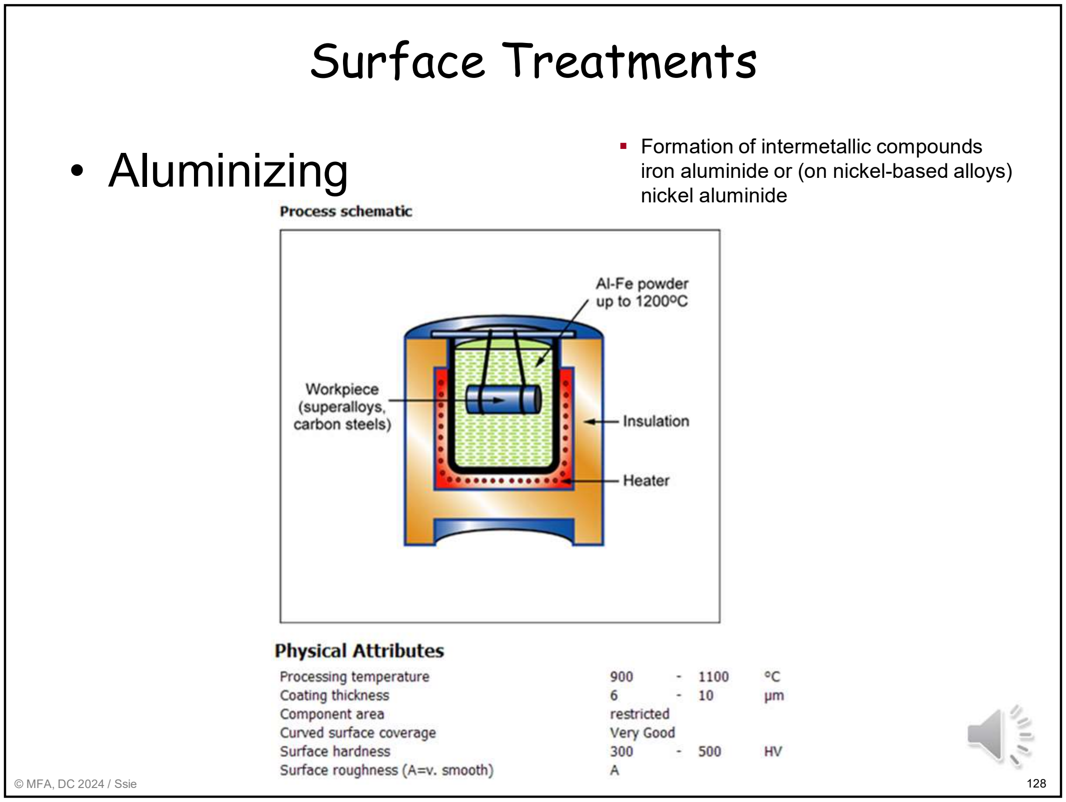

Surface Treatments

- Aluminizing

- Formation of intermetallic compounds iron aluminide or (on nickel-based alloys) nickel aluminide

Process schematic

Physical Attributes

Processing temperature	900	-	1100	°C
Coating thickness	6	-	10	µm
Component area	restricted			
Curved surface coverage	Very Good			
Surface hardness	300	-	500	HV
Surface roughness (A=v. smooth)	A			

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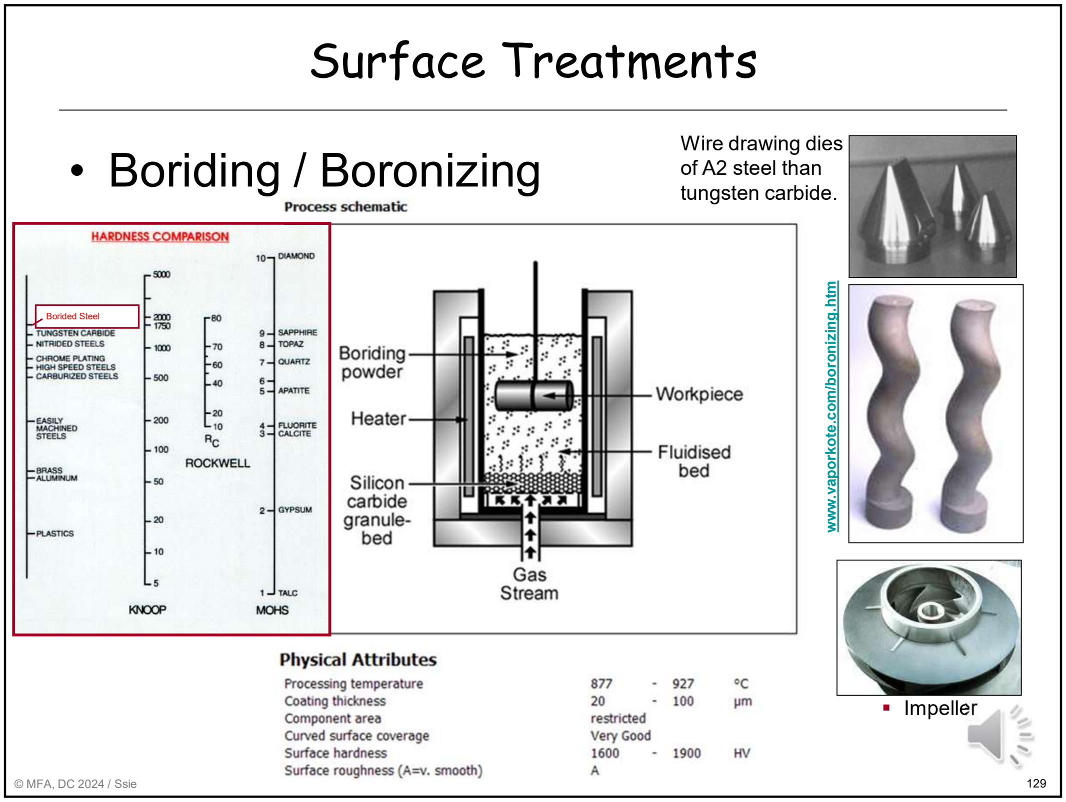
The process

Aluminizing, or aluminum diffusion, is an economical process for giving corrosion protection to steels, stainless steels and nickel alloy components that must operate in high temperature gases. There are several variants of the process. In one, the component is immersed in an Al-Fe powder mixture at about 1200 centigrade; In another, an aluminum halide (fluoride, chloride or bromide) is used as an activator. In all cases aluminum vapor is formed, which diffuses into the surface of the component forming a layer of the intermetallic compound iron aluminide or (on nickel-based alloys) nickel aluminide. The coating is uniform, even when the shape is complex.

e.g. **Patent 4655852**

… layer of the intermetallic **Al-Fe** alloy for improved corrosion resistance



Surface Treatments

- Boriding / Boronizing

Wire drawing dies of A2 steel than tungsten carbide.

Physical Attributes

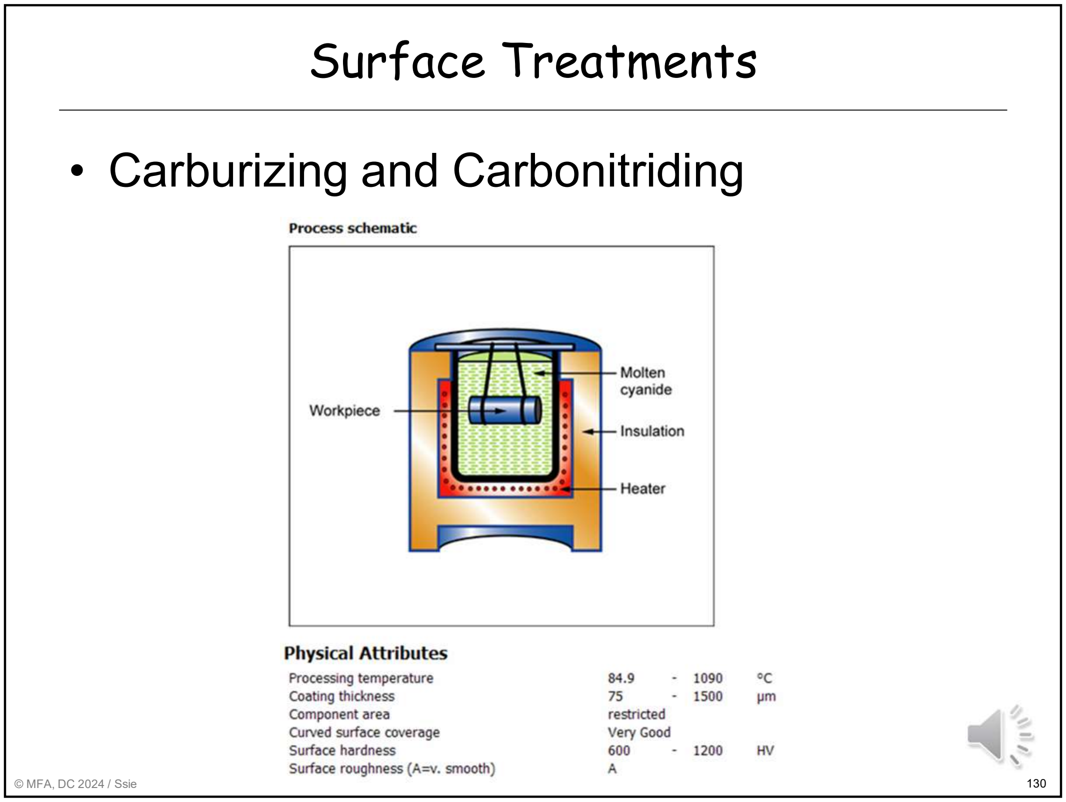
Processing temperature	877	-	927	°C
Coating thickness	20	-	100	µm
Component area	restricted			
Curved surface coverage	Very Good			
Surface hardness	1600	-	1900	HV
Surface roughness (A=v. smooth)	A			

- Impeller

The process

Boriding is a high-temperature CVD process whereby boron atoms **diffuse** from a vapor at 900 centigrade **into** the base metal of the component (usually steel), giving an exceptionally hard surface layer. The layer, typically 100 microns deep, imparts **excellent wear cavitation and erosion resistance**, a low coefficient to friction, and good **high temperature corrosion temperature up to 600 centigrade**. Boriding gives a uniform coating even when the component has a complex shape. It is possible to boride less costly steels to give a product that out performs more expensive, untreated steels. Welding is still possible and masking before treated leaves untreated areas for later machining. The process is economic for small and large parts.

Harder than tungsten carbide! (~ 79-80 Rockwell C)



Surface Treatments

- Carburizing and Carbonitriding

Process schematic

Physical Attributes

Processing temperature	84.9	-	1090	°C
Coating thickness	75	-	1500	µm
Component area	restricted			
Curved surface coverage	Very Good			
Surface hardness	600	-	1200	HV
Surface roughness (A=v. smooth)	A			

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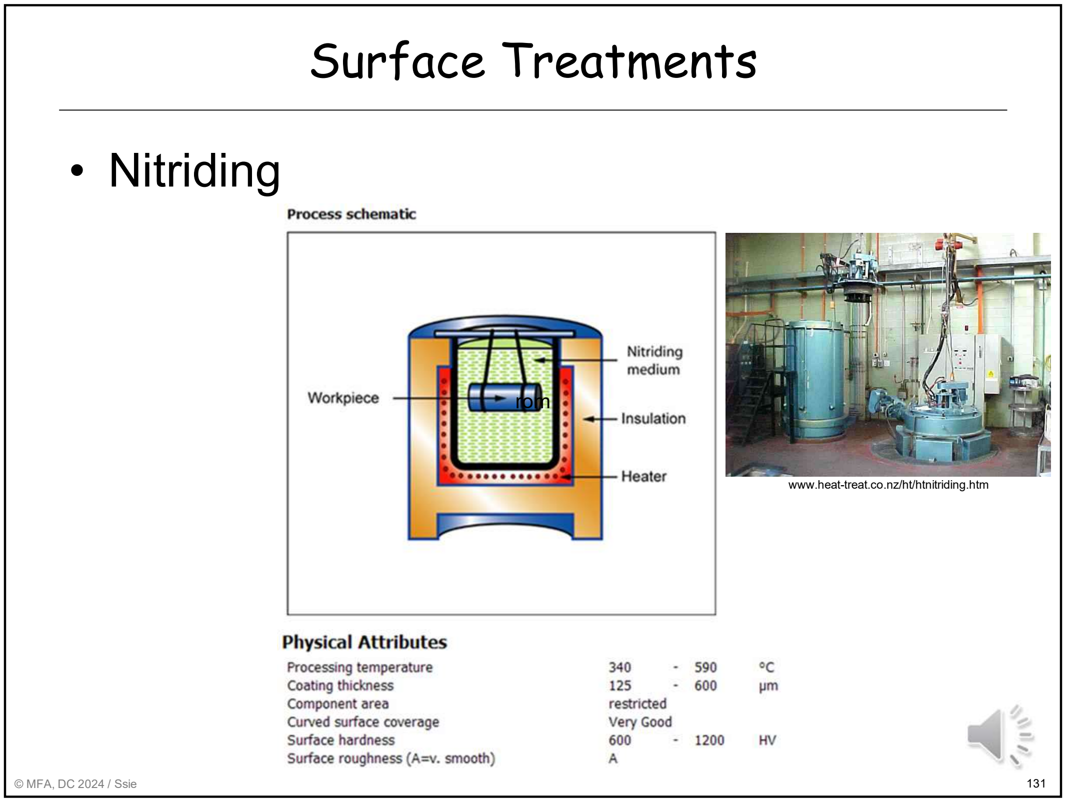
The process

In carburizing, additional carbon is diffused into the surface of a low-carbon steel to give a high-carbon surface layer. When this is quenched, the layer transforms to a hard, brittle, martensite, which can subsequently be tempered to obtain the required balance of hardness and toughness. There are three broad classes of carburizing equipment; all require temperatures of about 900 centigrade. The first uses a powder pack that releases carbon monoxide (CO); this decomposes on the surface of the steel to give atomic carbon and CO2. It is best for small parts. The second uses a fused salt bath containing sodium cyanide (NaCN>25%), barium chloride, sodium chloride and accelerators; it is very versatile and has a low capital cost. The last uses gas - methane, butane or pentane - as the source of carbon in a special muffle furnace that allows the gas to flow freely round the parts to be carburized; it lends itself to large-quantity production.

Carbo-nitriding is a variant of gas carburizing in which ammonia (NH3) is added to the carburizing gas. Nitrogen, released from the ammonia, and carbon from the carburizing gas, diffuse into the component at the same time, precipitating nitrides as well as increasing the surface carbon content. It generally requires a lower temperature and shorter time than plain carburizing. The process produces a thinner layer, but one that retains its hardness to higher temperatures.

Both processes give components with hard, wear resistant surfaces on a tough, ductile core. Carburizing gives better impact resistance than carbo-nitriding, but it causes more distortion and is slower, making it more expensive.



Surface Treatments

- Nitriding

Process schematic

www.heat-treat.co.nz/ht/htnitriding.htm

Physical Attributes

Processing temperature	340	-	590	°C
Coating thickness	125	-	600	μm
Component area	restricted			
Curved surface coverage	Very Good			
Surface hardness	600	-	1200	HV
Surface roughness (A=v. smooth)	A			

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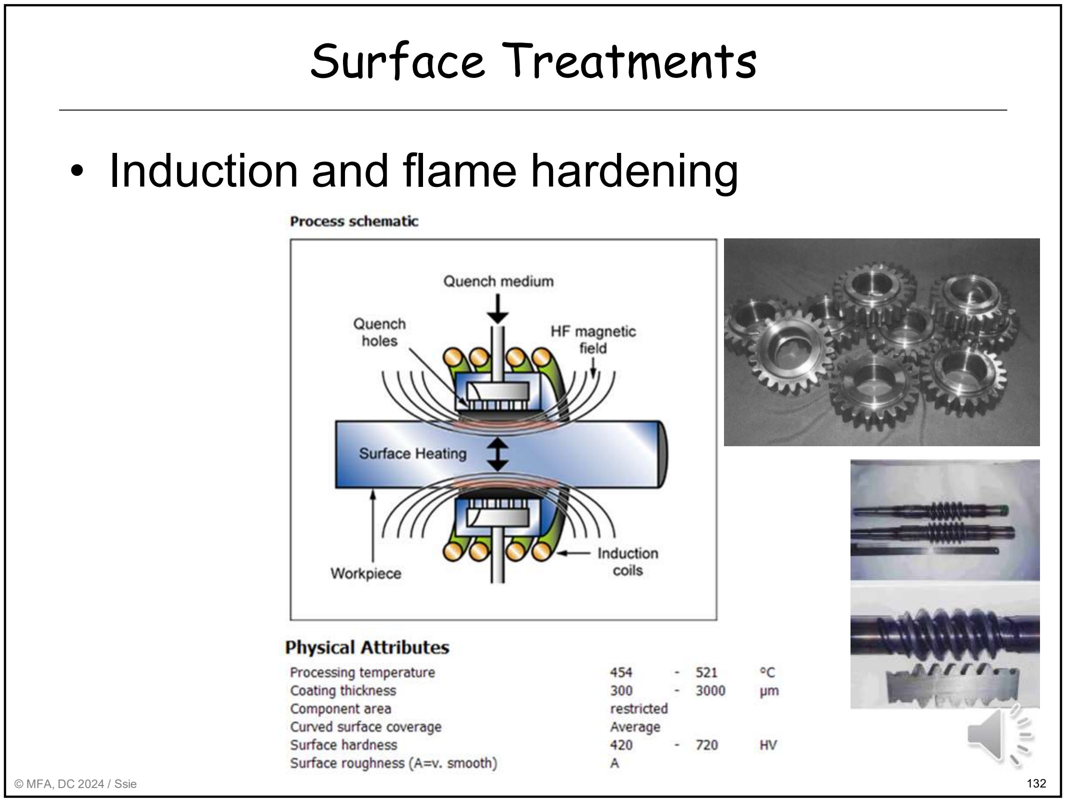
The process

In nitriding, nitrogen is introduced into the surface of a steel component by heating it in a fused salt bath containing nitrogen-baring salts (typically, sodium cyanide, NaCN) or in a gas stream containing cracked ammonia (NH3). Steels suitable for nitriding contain aluminum, vanadium, tungsten or molybdenum; These form stable nitride precipitates that harden the surface to a depth of about 500 microns. The temperature (495 to 565 centigrade) is lower than that for carburizing, giving less distortion, and the surface does not require later heat treatment (as carburizing does (to acquire its hardness)). Nitriding gives a high surface hardness, retained to high temperatures, increased wear resistance, improved fatigue life, and enhanced corrosion resistance.



Surface Treatments

- Induction and flame hardening

Process schematic

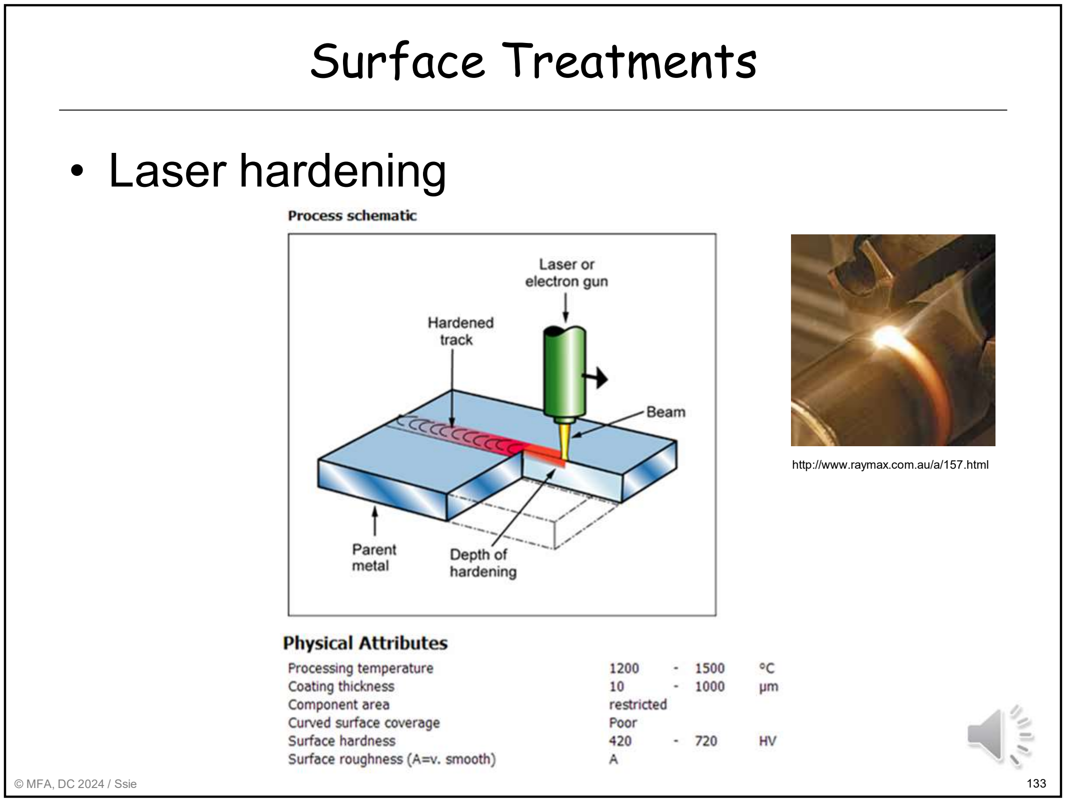
Physical Attributes

Processing temperature	454	-	521	°C
Coating thickness	300	-	3000	μm
Component area	restricted			
Curved surface coverage	Average			
Surface hardness	420	-	720	HV
Surface roughness (A=v. smooth)	A			

The process

Induction hardening allows the surface of carbon steels to be hardened with minimum distortion or oxidation. A high frequency (up to 50 kHz) electromagnetic field induces eddy-currents in the surface of the work-piece; these currents heat the surface into the austenitic phase-region, from which it is rapidly cooled from a gas or liquid jet, giving a martensitic surface layer. The depth of hardening depends on the frequency of the electromagnetic field. In flame hardening, heat is applied instead by means of one or more high-temperature gas burners, followed, as before, by rapid cooling. Both processes are versatile and can be applied to work pieces that cannot readily be furnace treated or case hardened in the normal way.

Induction and flame hardening allow selective hardening of particular areas of the work piece. Both give a surface layer with a hardness that is lower than that of diffusion-based processes like carburizing and nitriding, but the depth is greater. The hardened surface layer carries internal stresses that can lead to micro cracking if the process conditions are incorrect.



Surface Treatments

- Laser hardening

Process schematic

http://www.raymax.com.au/a/157.html

Physical Attributes

Processing temperature	1200	-	1500	°C
Coating thickness	10	-	1000	µm
Component area	restricted			
Curved surface coverage	Poor			
Surface hardness	420	-	720	HV
Surface roughness (A=v. smooth)	A			

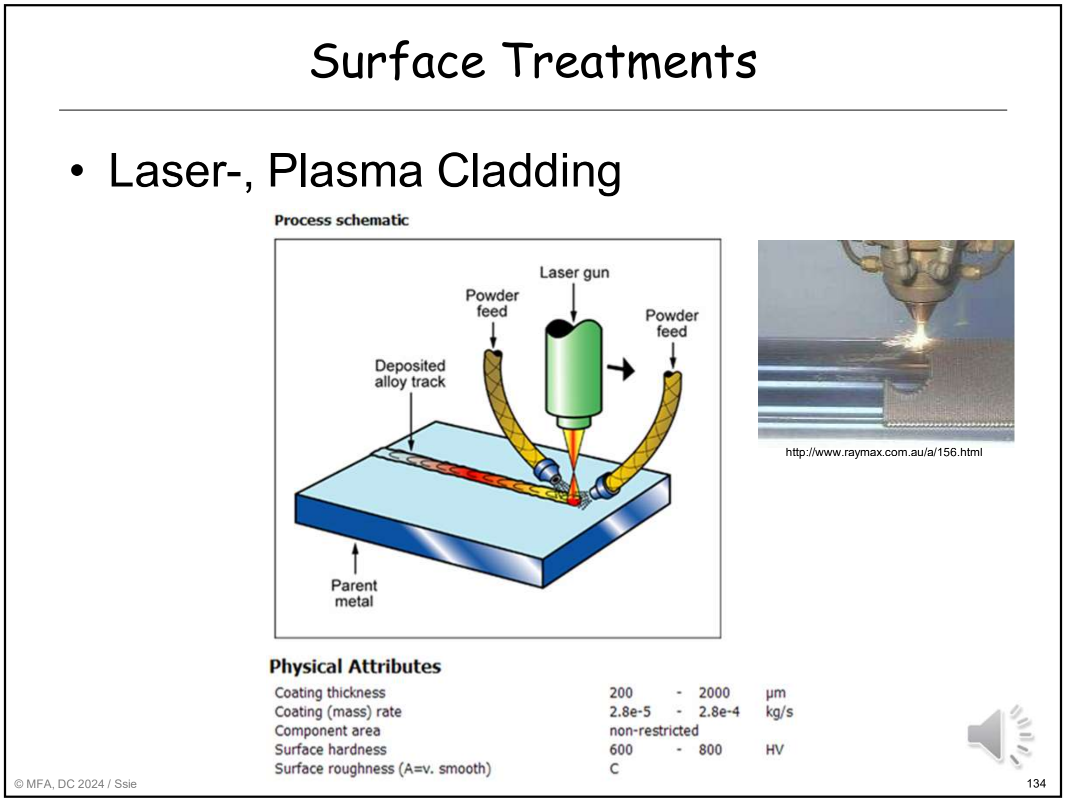
The process

Lasers can be used as a clean, controllable heat source for surface treatment and welding (see also the record for laser welding). The laser beam scans the surface of a component to cause a phase change for localized heat treatment, or to melt it for localized structure-change. There are three classes of laser surface engineering: Surface transformation hardening, surface shocking, and surface melting and glazing. Each requires a particular set of process conditions, detailed below. All allow local treatment of selected areas of the surface.

In surface transformation hardening (limited to carbon and alloy steels) the beam heats a spot on the surface to a temperature above that for the transmission to austenite. As the beam moves on, the hotspot is quenched by conduction of heat into the massive, cold interior of the component, transforming a thin surface layer to martensite. Single, separated tracks give a surface with good wear resistance - the alternating the hard and soft bands contribute to this. Overlapping tracks give a more uniform hardening of the entire surface.

Laser shock hardening uses a pulsed, high energy beam to violently vaporize a minute amount of surface material, creating a shock wave that locally deforms the underlying solid, while hardening it like shock peening (see record).

Laser surface melting involves the use of a high intensity beam to scan the surface, protected by a shielded gas atmosphere. Rapid melting and subsequent rapid quenching of the molten metal produces a track with a refined and homogenized microstructure. Laser glazing is a melting process carried out at a high processing speed such as the cooling rates between 10’000 and 1’000’000 °C/sec can be achieved. At this cooling rate, metallic glass formation is possible if the alloy composition has a high glass-forming tendency.



Surface Treatments

- Laser-, Plasma Cladding

Process schematic

http://www.raymax.com.au/a/156.html

Physical Attributes

Coating thickness	200	-	2000	µm
Coating (mass) rate	2.8e-5	-	2.8e-4	kg/s
Component area	non-restricted			
Surface hardness	600	-	800	HV
Surface roughness (A=v. smooth)	C			

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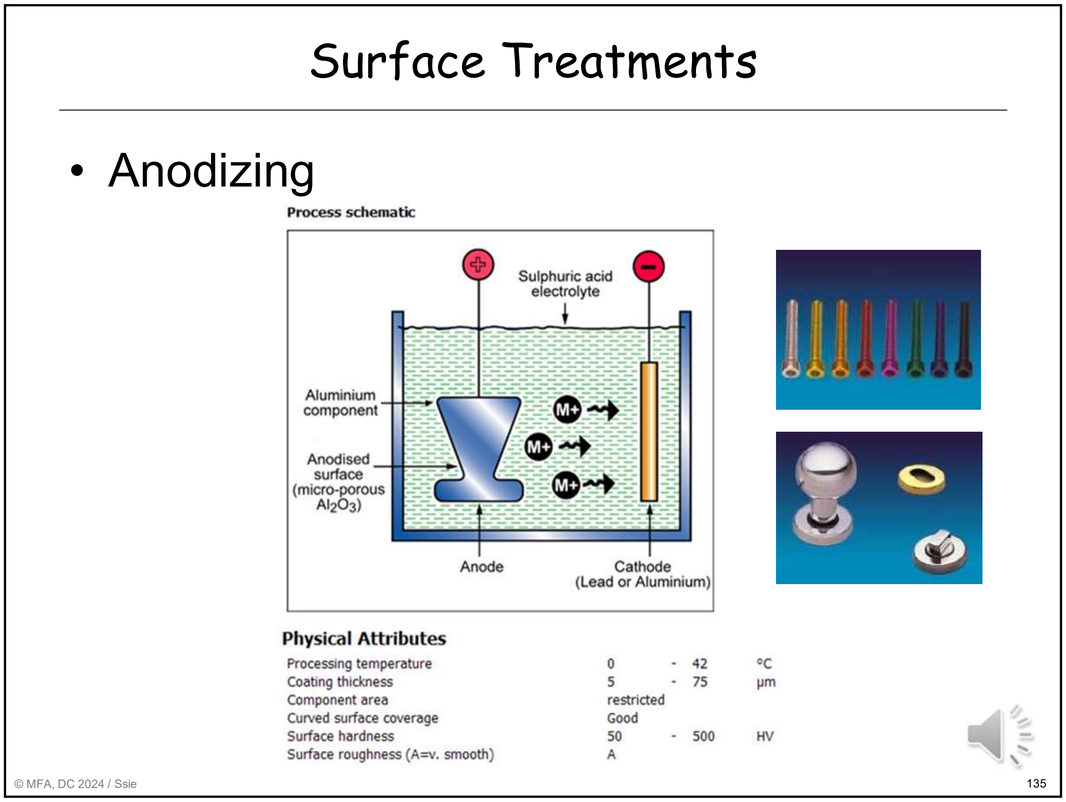
The process

Cladding is the application of a thick coating (generally above 1 mm), which melts or bonds by diffusion or cold welding to the substrate. In laser and plasma-arc cladding, the coating material is fed as a powder in a gas stream into the laser beam or plasma-arc, where it melts and bonds to the surface of the part to be coated. Both methods produce dense, metallurgically bonded coatings with minimal effect on the underlying surface.

Laser and plasma-arc coatings are used to give corrosion resistance, particularly from hot gases (as in gas turbines), to give abrasion and wear resistance and to create thermal barrier coatings. Both processes can also be used to restore and repair worn surfaces.



Surface Treatments

- Anodizing

Process schematic

Physical Attributes

Processing temperature	0	-	42	°C
Coating thickness	5	-	75	µm
Component area	restricted			
Curved surface coverage	Good			
Surface hardness	50	-	500	HV
Surface roughness (A=v. smooth)	A			

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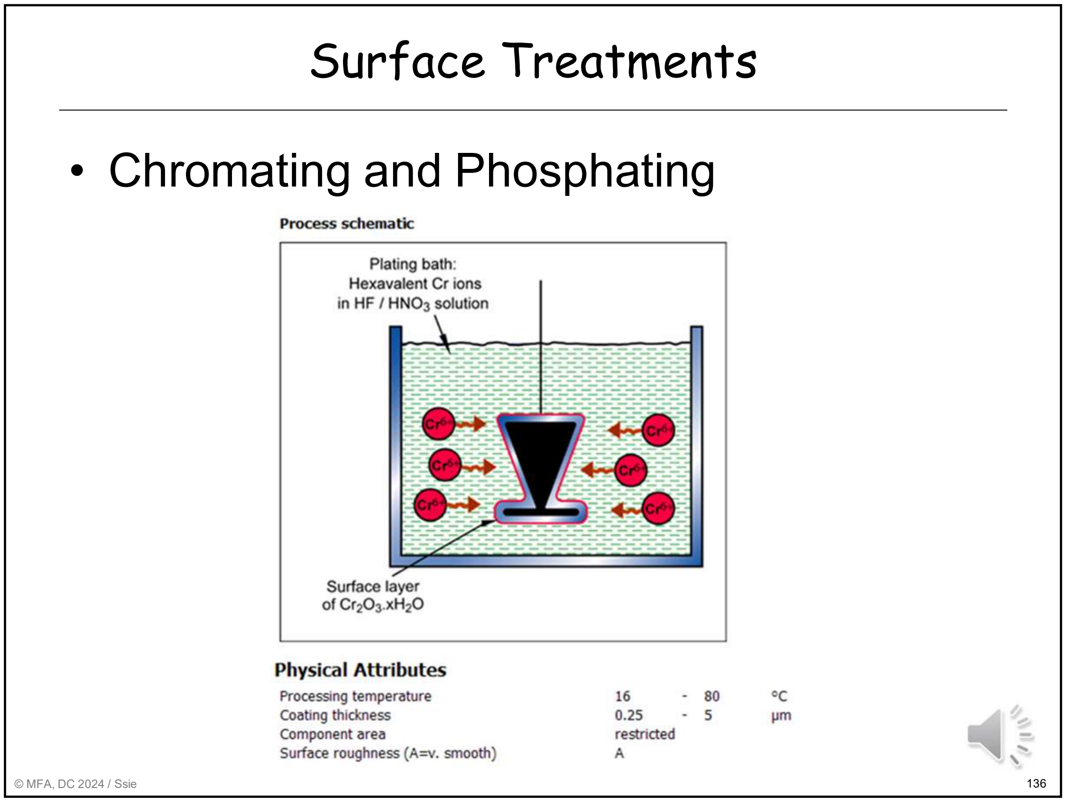
The process

Aluminum is a reactive metal, yet in everyday objects it does not corrode or discolor. That is because of a thin oxide film - Al2O3 - that forms spontaneously on its surface, and this film, though invisible, is highly protective. The film can be thickened and its structure controlled by the process of anodizing. The process is electrolytic; The electrolyte, typically, is dilute (15%) sulfuric acid. Anodizing is most generally applied to aluminum, but magnesium, titanium, zirconium and zinc can all be treated in this way.

The oxide formed by anodizing is hard, abrasion resistant and resists corrosion well. The film-surface is micro-porous, allowing it to absorb dyes, giving metallic reflectivity with an attractive gold, viridian, azure or rose-colored sheen; and it can be patterned. The process is cheap, and imparts both corrosion and wear resistance to the surface.



Surface Treatments

- Chromating and Phosphating

Process schematic

Physical Attributes

Processing temperature	16	-	80	°C
Coating thickness	0.25	-	5	µm
Component area	restricted			
Surface roughness (A=v. smooth)	A			

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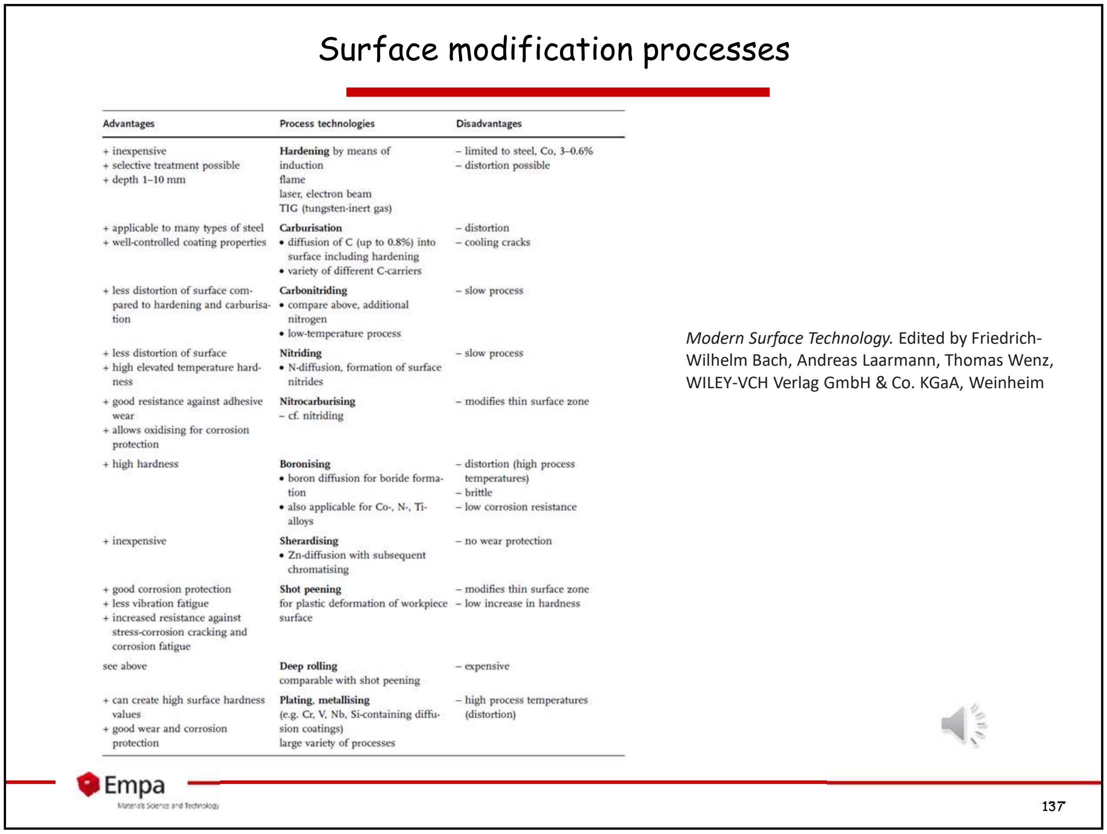
The process

chromating and phosphating are surface-coating processes that enhance the corrosion resistance of metals. Both involve soaking the component in a heated bath based on chromic or phosphoric acids. The acid reacts with the surface, dissolving some of the surface metal and depositing a thin protective layer of complex chromium or phosphorous compounds. It is essential that the surfaces are clean before treatment. Chromating is applied to steel and is used as a post-treatment for cadmium, zinc and aluminum coatings. Phosphating for corrosion resistance is limited to steel surfaces, but the process is also used as an undercoat for paint to improve bonding on aluminum, cadmium and zinc,

Chromated surfaces have an attractive gold, olive or black color, depending on the film thickness and composition.

Phosphating gives a porous coating of zinc or magnesium phosphate, and is generally applied to steel structures. Zinc phosphate holds oil well and gives a base to which paints adhere well. Manganese phosphate is used primarily on friction and bearing surfaces to reduce wear. Both processes are cheap to apply.



Surface modification processes

Advantages	Process technologies	Disadvantages
+ inexpensive + selective treatment possible + depth 1–10 mm	**Hardening** by means of induction flame laser, electron beam TIG (tungsten-inert gas)	– limited to steel, Co, 3–0.6% – distortion possible
+ applicable to many types of steel + well-controlled coating properties	**Carburisation** • diffusion of C (up to 0.8%) into surface including hardening • variety of different C-carriers	– distortion – cooling cracks
+ less distortion of surface compared to hardening and carburisation	**Carbonitriding** • compare above, additional nitrogen • low-temperature process	– slow process
+ less distortion of surface + high elevated temperature hardness	**Nitriding** • N-diffusion, formation of surface nitrides	– slow process
+ good resistance against adhesive wear + allows oxidising for corrosion protection	**Nitrocarburising** – cf. nitriding	– modifies thin surface zone
+ high hardness	**Boronising** • boron diffusion for boride formation • also applicable for Co-, N-, Ti-alloys	– distortion (high process temperatures) – brittle – low corrosion resistance
+ inexpensive	**Sherardising** • Zn-diffusion with subsequent chromatising	– no wear protection
+ good corrosion protection + less vibration fatigue + increased resistance against stress-corrosion cracking and corrosion fatigue	**Shot peening** for plastic deformation of workpiece surface	– modifies thin surface zone – low increase in hardness
see above	**Deep rolling** comparable with shot peening	– expensive
+ can create high surface hardness values + good wear and corrosion protection	**Plating, metallising** (e.g. Cr, V, Nb, Si-containing diffusion coatings) large variety of processes	– high process temperatures (distortion)

Modern Surface Technology. Edited by Friedrich-Wilhelm Bach, Andreas Laarmann, Thomas Wenz, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Abgerundet?

Coatings and Thin Films

- Electroless- and Electroplating
- Hot-dip Coatings
- Chemical Vapour Deposition (CVD)
- Physical Vapour Deposition (PVD)
- Thermal Spray Methods (movie)

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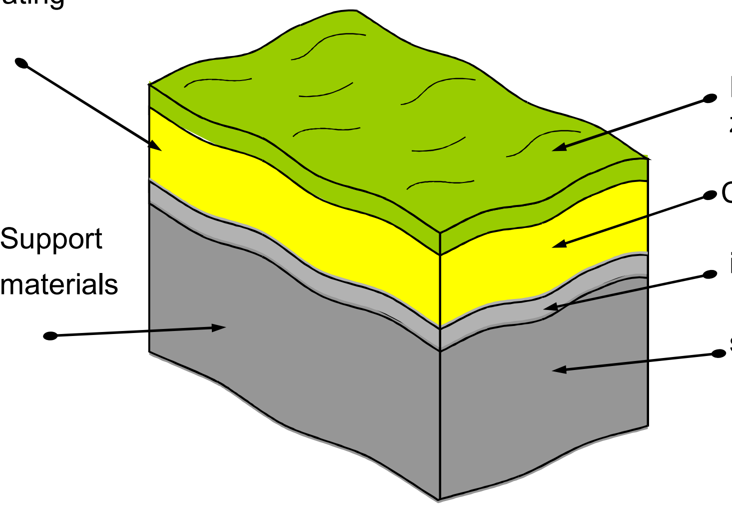
Coatings – A system



Functional Coating

Environmental zone

Coating material

interface

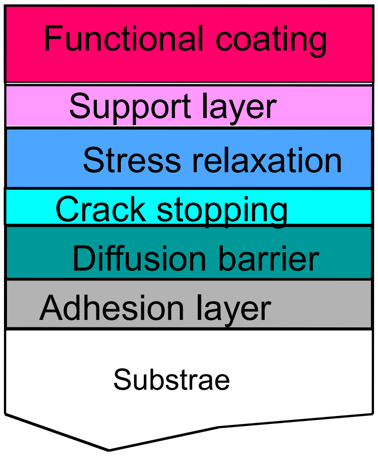
substrate

Support materials

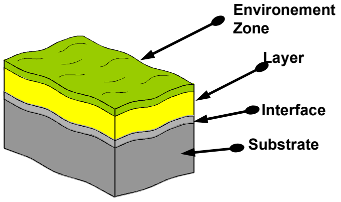
Multilayer concept

Advantages

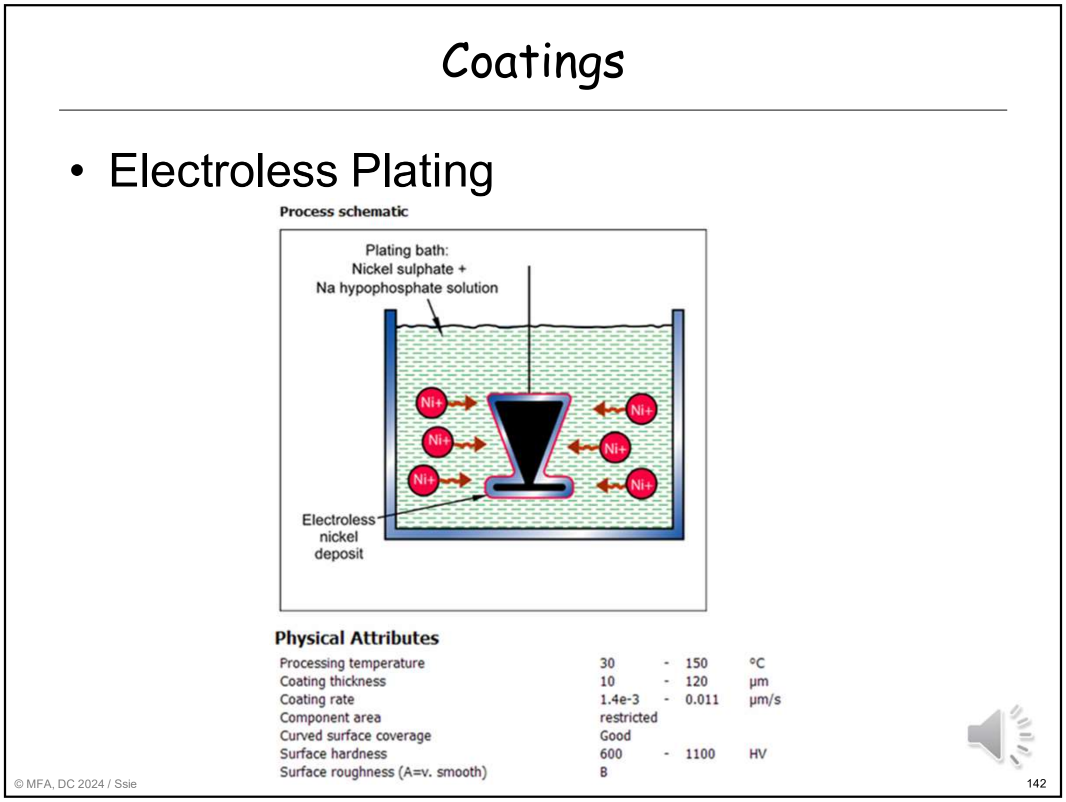
- Specific coating for specific use case/substrate
- Deformation under load
- Use on soft substrates
- Multifuctional coatings



Film properties of interest



- geometry (thickness, …)
- topography (roughness, sub-mirco structures, grain size)
- chemistry (elements, composition, bonds)
- crystallography (structure, texture, defects)
- mechanical prop. (stress, hardness, density)
- optical prop. (color, refr. index, scattering)
- electrical prop. (conductivity, permittivity, …)



Coatings

- Electroless Plating

Process schematic

Physical Attributes

Processing temperature	30	-	150	°C
Coating thickness	10	-	120	µm
Coating rate	1.4e-3	-	0.011	µm/s
Component area	restricted			
Curved surface coverage	Good			
Surface hardness	600	-	1100	HV
Surface roughness (A=v. smooth)	B			

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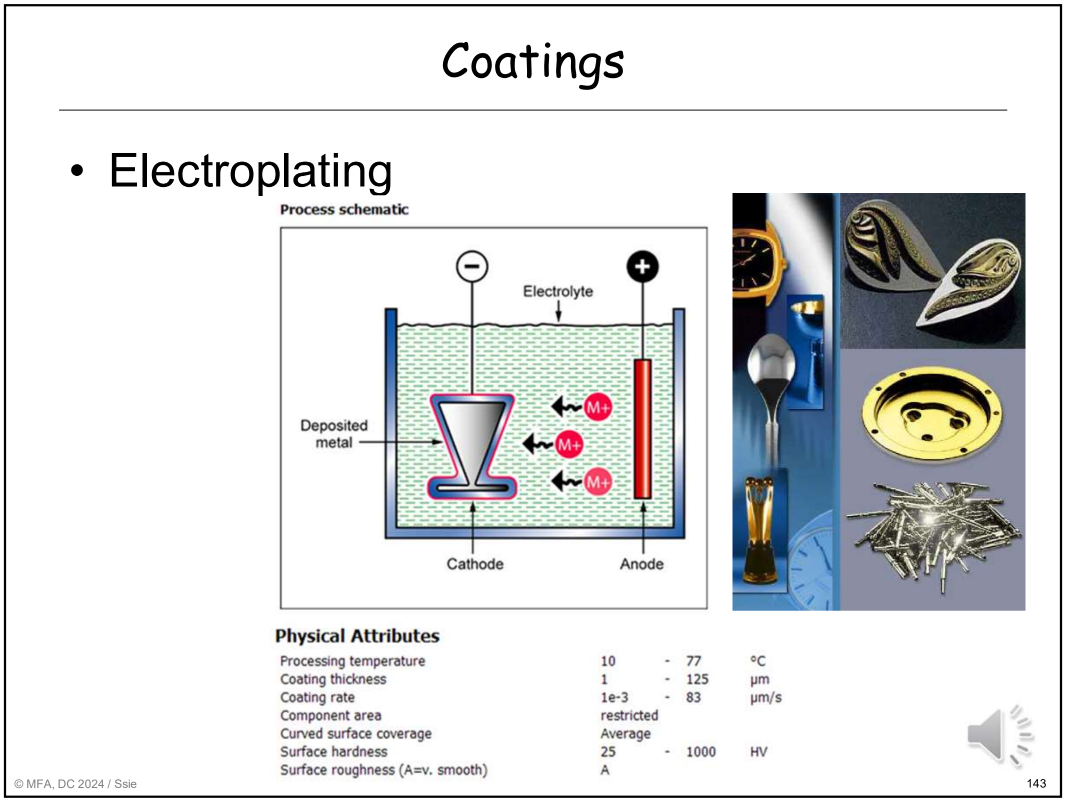
The process

In auto-catalyst or electroless plating, no external current is used. Metal is deposited on a catalytic surface of the workpiece by the action of a chemical reducing agent present in a metallic salt solution. In the case of electroless plating of nickel (the most significant commercial application of the process), the salt is nickel chloride and the reducing agent is sodium hypophosphate. Once started the reaction can continue (auto-catalyst, contrary to immersion plating) and there is no theoretical limit to the thickness of the coating.

Electro-less plating is used when it is either not possible or impractical to use normal electroplating (because of physical factors or special properties needed). For example, electro-less plating should be specified if dimensional accuracy of the part is critical. The processes gives a very uniform coating, with good corrosion resistance.



Coatings

- Electroplating

Process schematic

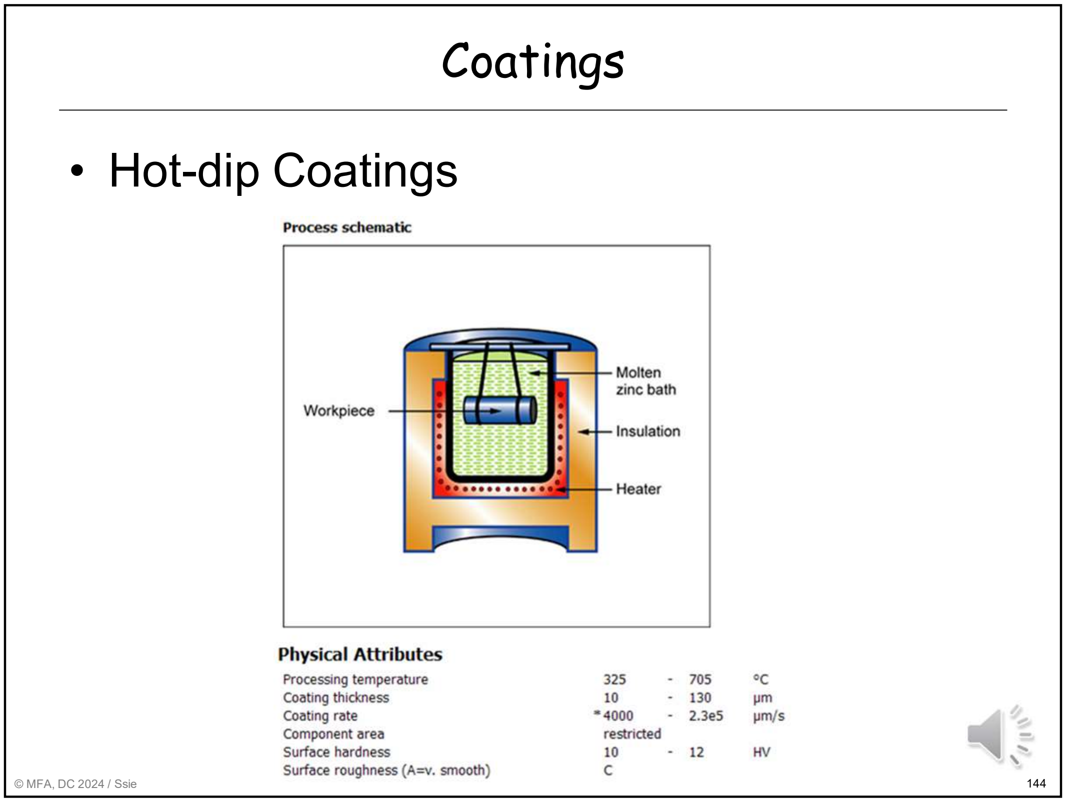
Physical Attributes

Processing temperature	10	-	77	°C
Coating thickness	1	-	125	µm
Coating rate	1e-3	-	83	µm/s
Component area	restricted			
Curved surface coverage	Average			
Surface hardness	25	-	1000	HV
Surface roughness (A=v. smooth)	A			

The process

Metal coating process wherein a thin metallic coat is deposited on the workpiece by means of an ionized electrolytic solution. The workpiece (cathode) and the metallizing source material (anode) are submerged in the solution where a direct electrical current causes the metallic ions to migrate from the source material to the workpiece. The workpiece and source metal are suspended in the ionized electrolytic solution by insulated rods. Thorough surface cleaning precedes the plating operation.

Plating is carried out for many reasons, corrosion resistance, improved appearance, wear resistance, higher electrical conductivity, better electrical contact, greater surface smoothness and better light reflectance.



Coatings

- Hot-dip Coatings

Process schematic

Physical Attributes

Processing temperature	325	-	705	°C
Coating thickness	10	-	130	µm
Coating rate	*4000	-	2.3e5	µm/s
Component area	restricted			
Surface hardness	10	-	12	HV
Surface roughness (A=v. smooth)	C			

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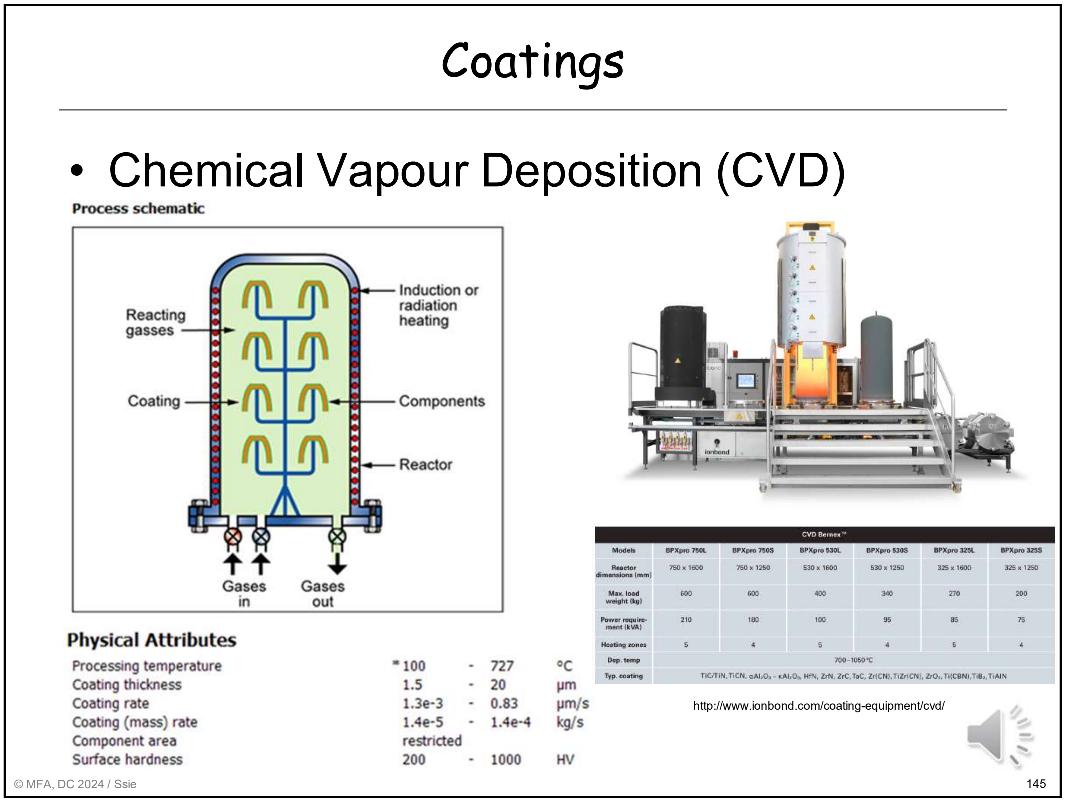
The process

Hot dipping is a process for coating a metal, mainly ferrous metals, with low melting point metals usually zinc and its alloys. The component is first degreased in a caustic bath, then pickled (to remove rust and scale) in a sulfuric acid bath, immersed (dipped) in the liquid metal and, after lifting out it is cooled in a cold air stream. The molten metal alloys with the surface of the component, forming a continuous thin coating. When the coating is zinc and the component is steel, the process is known as galvanizing.

The process is very versatile and can be applied to components of any shape, and sizes up to 30 m x 2 m x 4 m. The cost is comparable with that of painting, but the protection offered by galvanizing is much greater, because if the coating is scratched it is the zinc not the underlying steel that corrodes (“galvanic protection"). Properly galvanized steel will survive outdoors for 30-40 years without further treatment.



Coatings

- Chemical Vapour Deposition (CVD)

Process schematic

Physical Attributes

Processing temperature	*100	- 727	°C
Coating thickness	1.5	- 20	µm
Coating rate	1.3e-3	- 0.83	µm/s
Coating (mass) rate	1.4e-5	- 1.4e-4	kg/s
Component area	restricted		
Surface hardness	200	- 1000	HV

CVD Bernex™

Models	BPXpro 750L	BPXpro 750S	BPXpro 530L	BPXpro 530S	BPXpro 325L	BPXpro 325S
Reactor dimensions (mm)	750 x 1600	750 x 1250	530 x 1600	530 x 1250	325 x 1600	325 x 1250
Max. load weight (kg)	600	600	400	340	270	200
Power requirement (kVA)	210	180	100	95	85	75
Heating zones	5	4	5	4	5	4
Dep. temp	700–1050 °C					
Typ. coating	TiC/TiN, TiCN, αAl_2O_3 – κAl_2O_3, HfN, ZrN, ZrC, TaC, Zr(CN), TiZr(CN), ZrO_2, Ti(CBN), TiB_2, TiAlN					

http://www.ionbond.com/coating-equipment/cvd/

The process

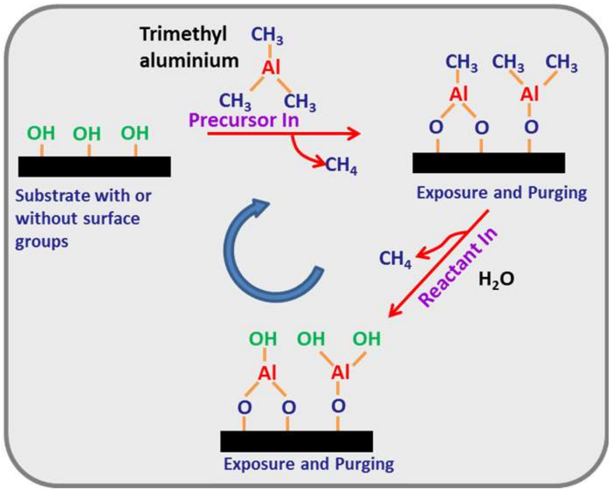
In CVD processing, a reactant gas mixture comes in contact with the surfaces to be coated, where it decomposes, depositing a dense pure layer of a metal or compound. The deposit can be formed by a reaction between precursor gases in the vapor phase or by a reaction between a constituent of the vapor phase and the surface of the substrate.

In a variation of conventional CVD, called Moderate temperature CVD (MTCVD), metal organic precursors are used (hence, it is also referred to as metal organic MOCVD). As they decompose at relatively lower temperature, the reaction temperature is typically in the range of 723 K to 1123 K. The chemical reactions in the vapor phase can be activated by the creation of a plasma in the gas phase or by shining a laser beam into the gas mixture. These techniques are called Plasma-assisted (or plasma-enhanced) CVD (PACVD or PECVD) and laser CVD (LCVD). They permit deposition at very low temperature.

Coatings formed with PCVD are typically amorphous because their formation is no longer dependent upon equilibrium thermodynamics constraints.

Laser CVD can be thermal (pyrolitic) or photochemical (photolytic).

Coatings - Atomic Layer Deposition (ALD) of Al_2O_3



TMA + Water is strongly exothermic reaction

TMA starts spontaneously @ RT to react with humidity and produces powder

Was used as rocket fuel

TMA refill only in dry glovebox under inert atmosphere

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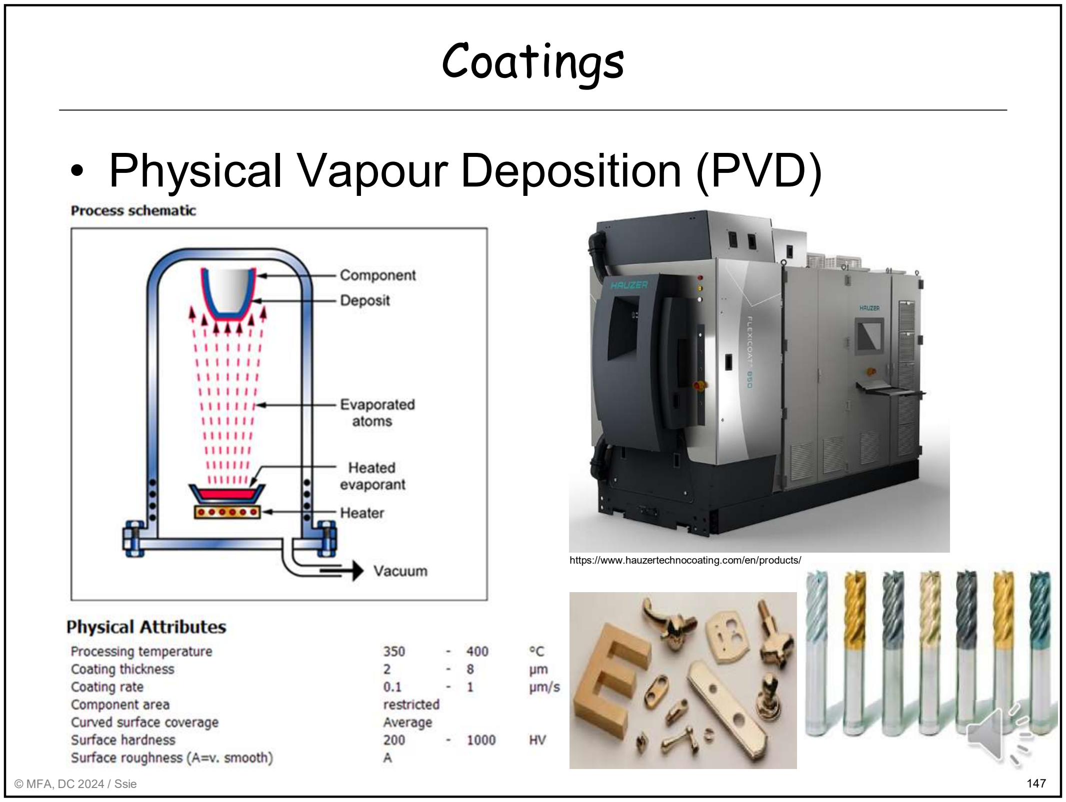

Coatings

- Physical Vapour Deposition (PVD)

Process schematic

https://www.hauzertechnocoating.com/en/products/

Physical Attributes

Processing temperature	350	-	400	°C
Coating thickness	2	-	8	µm
Coating rate	0.1	-	1	µm/s
Component area	restricted			
Curved surface coverage	Average			
Surface hardness	200	-	1000	HV
Surface roughness (A=v. smooth)	A			

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The process

In PVD plating, a thin coating of metal - usually aluminum - is deposited from a vapor onto the object to be coated. The vapor is created in a vacuum chamber by direct heating or electron beam heating of the metal, from which it condenses onto the cold workpiece, much like steam from a hot bath condensing on a bathroom mirror.

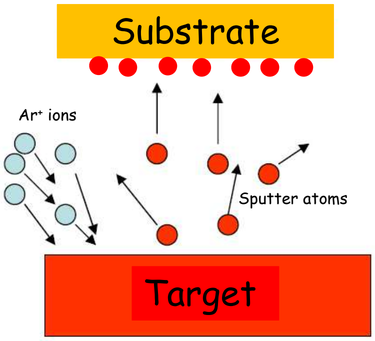
In PVD metallizing there is no potential difference between bath and workpiece. In ion plating the vapor is ionized and accelerated by an electric field (the workpiece is the cathode, and the metallizing source material is the anode).

In sputtering, argon ions are accelerated by the electric field onto a metal target, ejecting ions onto the component surface. By introducing a reactive gas, compounds can be formed (Ti sputtering in an atmosphere of N_2, which gives a coating of hard TiN, for instance).

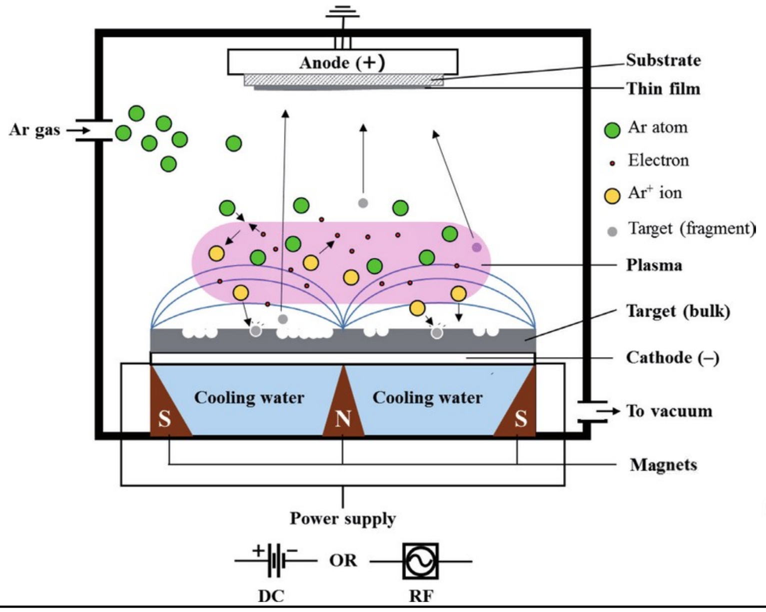
Clean surfaces are essential. Aluminum, copper, nickel, zirconium and other metals can be deposited. The process can be applied to plastics, metals, ceramics or glass.

Coatings - Sputtering

- **Instead of using heat** to eject material from a source, we can **bombard them with high speed particles**.
- The **momentum transfer** from the **particles to the surface** atoms can impart enough energy to allow the surface atoms to escape.
- Once ejected, these **atoms** (or molecules) **can travel to a substrate and deposit as a film**.
- There are several considerations here:
  - ❖ Creating, **controlling** and directing a **high speed particle stream**.
  - ❖ Interaction of these particles **with the source surface and emission yields**.
  - ❖ **Deposition** of the emitted atoms on the substrate and **film quality**.

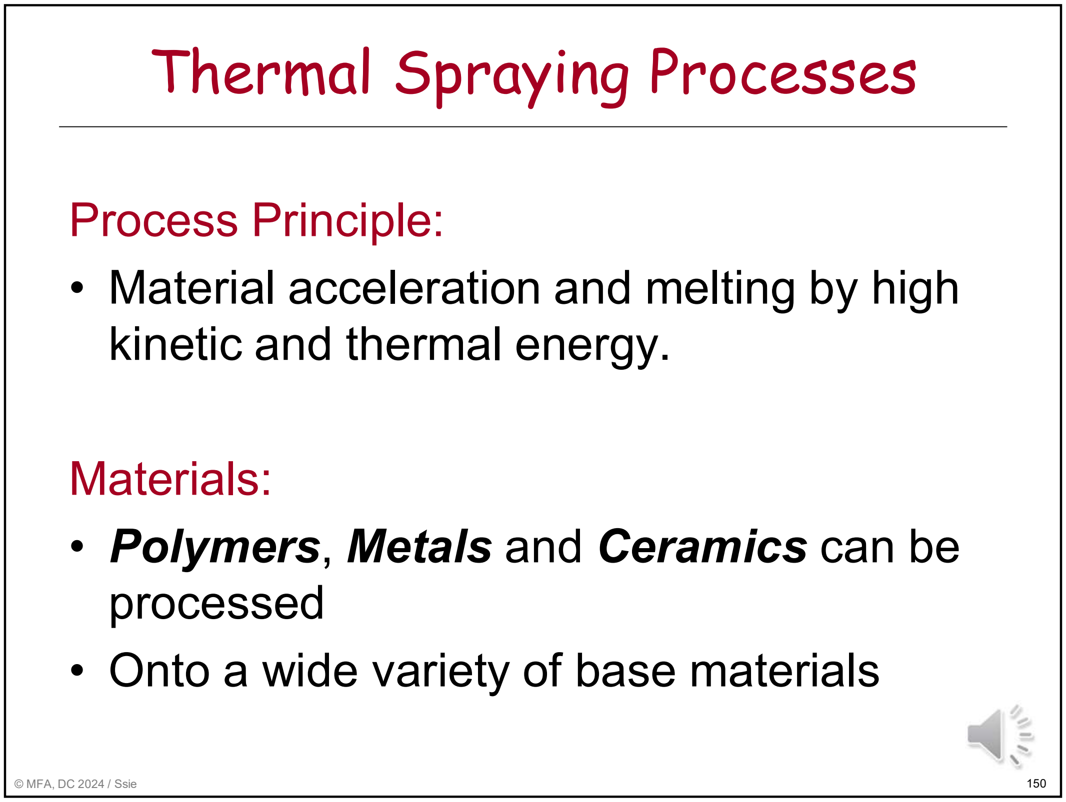


Coatings - Physical vapor deposition (PVD)
II - Sputtering



The process

In sputtering, a vapor of metal is created by bombarding a target (the coating material) with ions, accelerated by a potential difference of 100 to 10’000 volts. A d.c. or r.f. power source is applied between the target (the cathode) and inert anodes, creating a glow discharge. Within the discharge, gas atoms are ionized and accelerated towards the target where they knock out atoms of the target material, which condense on all cool surfaces that are in line-of-sight of the target. Almost any metal or compound that doesn't decompose chemically can be sputtered, making this a very flexible (though expensive) process. Targets can be changed during the process, allowing multilayers to be built up.



Thermal Spraying Processes

Process Principle:

- Material acceleration and melting by high kinetic and thermal energy.

Materials:

- ***Polymers***, ***Metals*** and ***Ceramics*** can be processed
- Onto a wide variety of base materials

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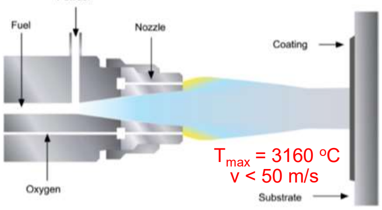
Introduction to history and possibilities of TS processes.

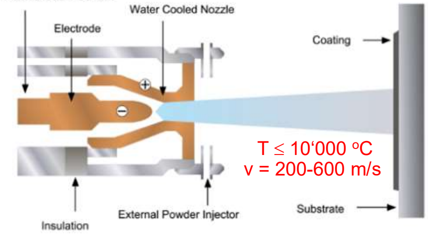
Working principles of different torches

- Flame spraying



T_{max} = 3160 °C
v < 50 m/s

- Plasma spraying

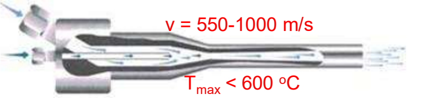


T ≤ 10‘000 °C
v = 200-600 m/s

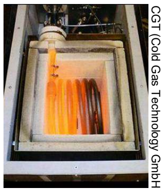
- HVOF

T_{max} = 3160 °C
v ≈ 500 m/s

- Cold gas deposition

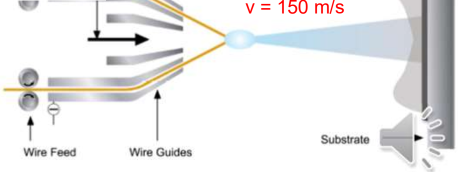


v = 550-1000 m/s
T_{max} < 600 °C



CGT (Cold Gas Technology GmbH

- Wire arc spraying



T ≈ 4‘000 °C
v = 150 m/s

Ref: K.E. Schneider, V. Belashchenko, M. Dratwinski, St. Siegmann, A. Zagorski; ***Thermal Spraying for Power Generation Components***, Wiley-VCH

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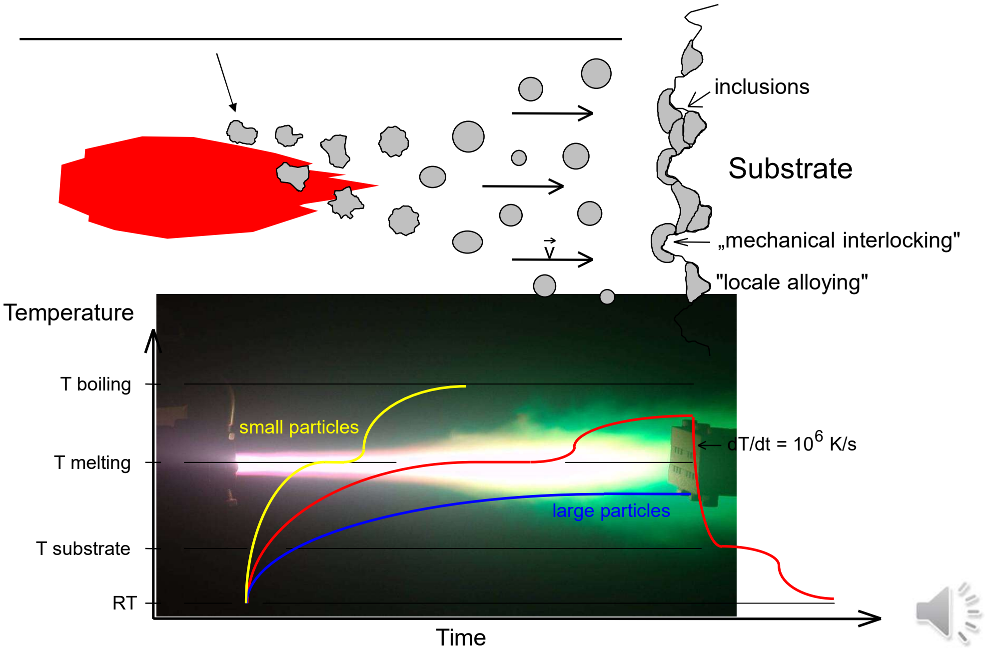
The processes are different, but the principle remains the same



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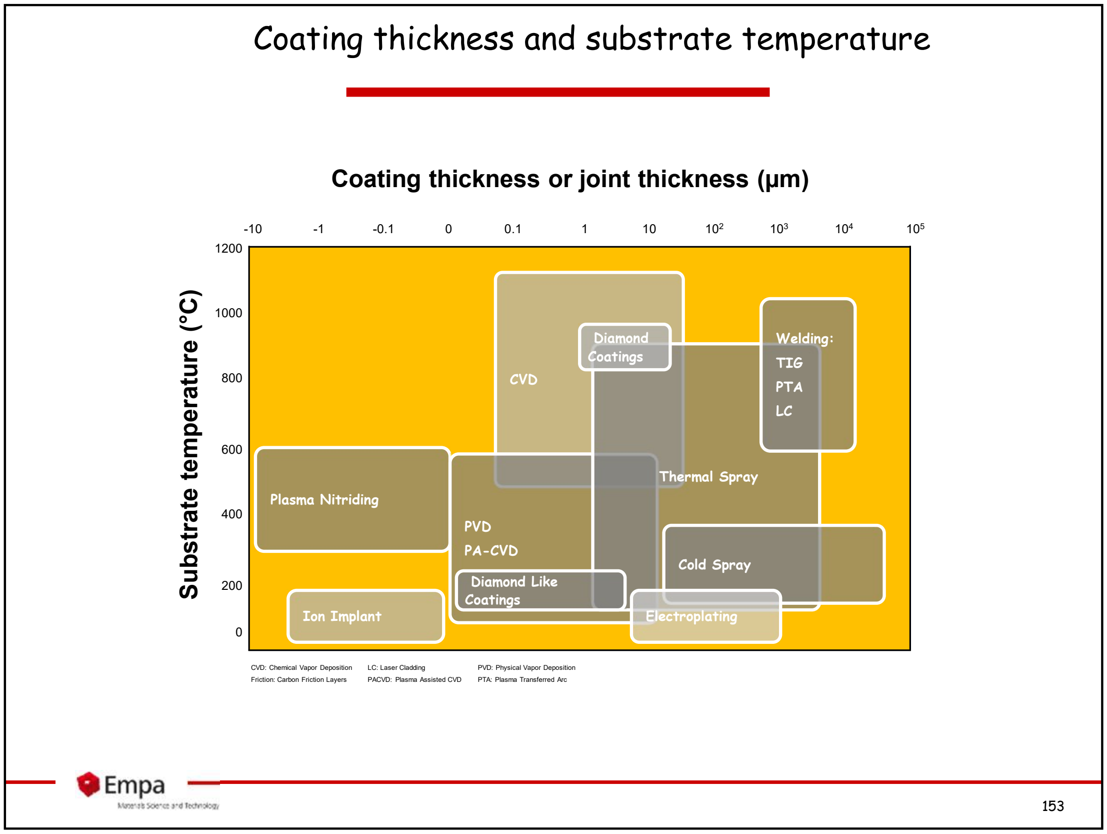

Coating thickness and substrate temperature

CVD: Chemical Vapor Deposition
Friction: Carbon Friction Layers
LC: Laser Cladding
PACVD: Plasma Assisted CVD
PVD: Physical Vapor Deposition
PTA: Plasma Transferred Arc

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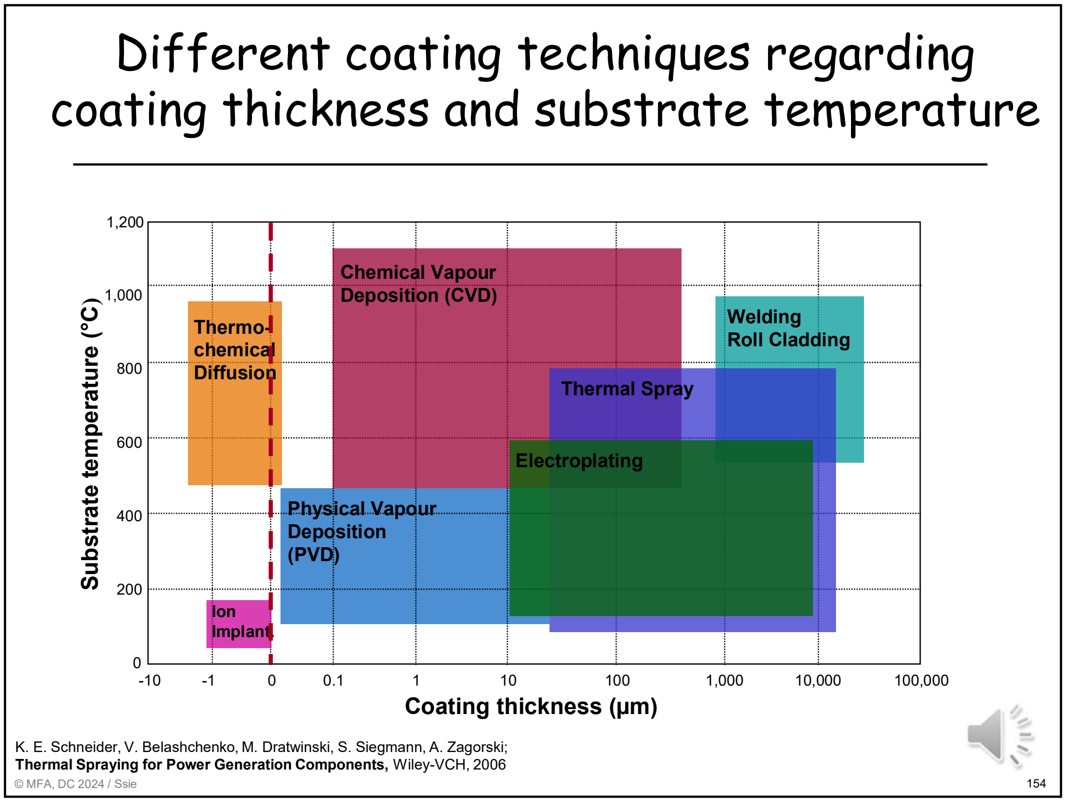
Abgerundet?



Different coating techniques regarding coating thickness and substrate temperature

K. E. Schneider, V. Belashchenko, M. Dratwinski, S. Siegmann, A. Zagorski;
Thermal Spraying for Power Generation Components, Wiley-VCH, 2006

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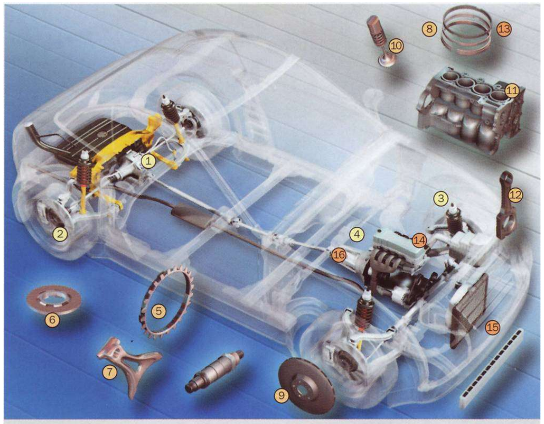
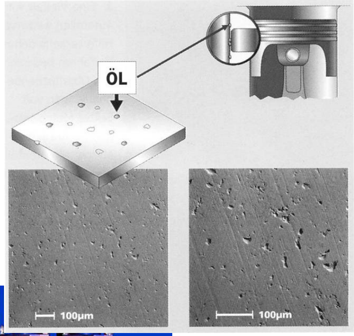
Examples of coated parts from car industry

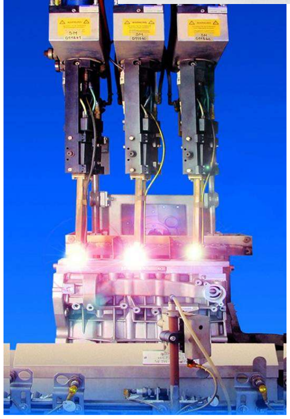


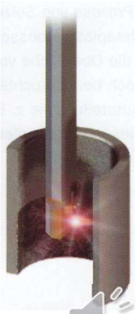
Ionit Ox
- ① Welle für Differenzialgetriebe
- ② Bremsen
- ③ Kugelzapfen
- ④ Schalthebel

Thermisches Spritzen
- ⑤ Synchronringe
- ⑥ Kupplungsscheibe
- ⑦ Schaltgabeln
- ⑧ Kolbenringe
- ⑨ Bremsscheiben (in Entwicklung)
- ⑩ Ventilsitze und -federn
- ⑪ Zylinderbohrungen
- ⑫ Pleuel

PVD
- ⑬ Kolbenringe
- ⑭ Kraftstoffeinspritzung
- ⑮ Embleme (dekorativ)
- ⑯ Zahnräder (in Entwicklung)







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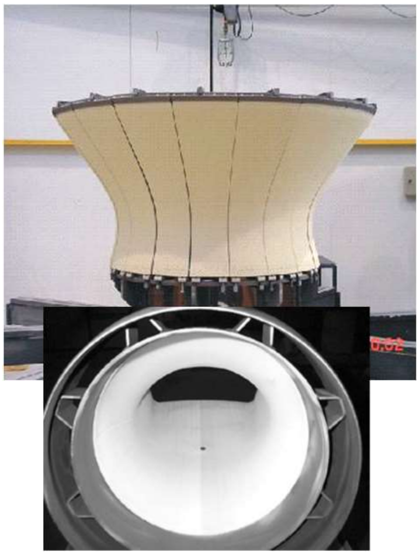
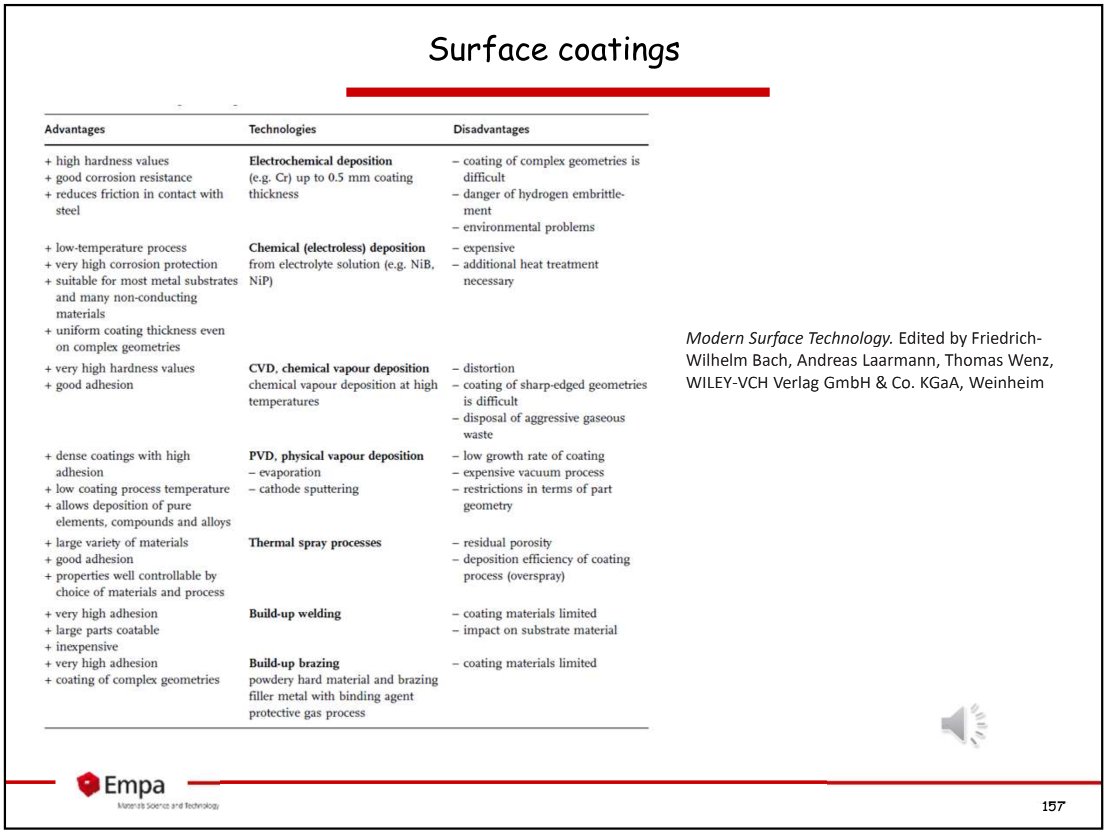
Examples of TBCs (ZrO_2) coated metallic turbine parts



- Courtesy by Alstom

K. E. Schneider, V. Belashchenko, M. Dratwinski, S. Siegmann, A. Zagorski; **Thermal Spraying for Power Generation Components,** Wiley-VCH, 2006



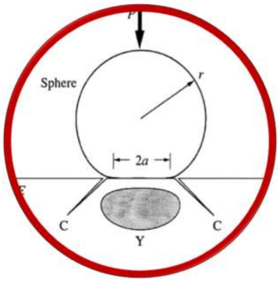
Surface coatings

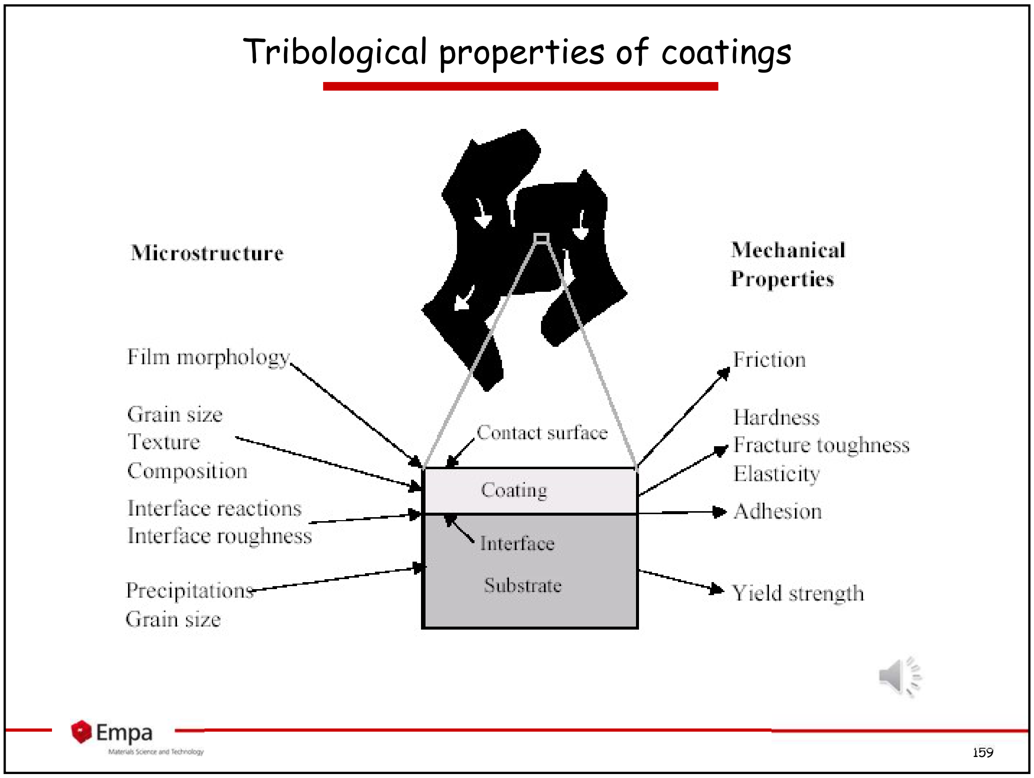
Advantages	Technologies	Disadvantages
+ high hardness values + good corrosion resistance + reduces friction in contact with steel	**Electrochemical deposition** (e.g. Cr) up to 0.5 mm coating thickness	– coating of complex geometries is difficult – danger of hydrogen embrittlement – environmental problems
+ low-temperature process + very high corrosion protection + suitable for most metal substrates and many non-conducting materials + uniform coating thickness even on complex geometries	**Chemical (electroless) deposition** from electrolyte solution (e.g. NiB, NiP)	– expensive – additional heat treatment necessary
+ very high hardness values + good adhesion	**CVD, chemical vapour deposition** chemical vapour deposition at high temperatures	– distortion – coating of sharp-edged geometries is difficult – disposal of aggressive gaseous waste
+ dense coatings with high adhesion + low coating process temperature + allows deposition of pure elements, compounds and alloys	**PVD, physical vapour deposition** – evaporation – cathode sputtering	– low growth rate of coating – expensive vacuum process – restrictions in terms of part geometry
+ large variety of materials + good adhesion + properties well controllable by choice of materials and process	**Thermal spray processes**	– residual porosity – deposition efficiency of coating process (overspray)
+ very high adhesion + large parts coatable + inexpensive	**Build-up welding**	– coating materials limited – impact on substrate material
+ very high adhesion + coating of complex geometries	**Build-up brazing** powdery hard material and brazing filler metal with binding agent protective gas process	– coating materials limited

Modern Surface Technology. Edited by Friedrich-Wilhelm Bach, Andreas Laarmann, Thomas Wenz, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Abgerundet?

Materials Index Case study: tribology of thin films





Tribological properties of coatings

Microstructure

Film morphology

Grain size
Texture
Composition

Interface reactions
Interface roughness

Precipitations
Grain size

Contact surface
Coating
Interface
Substrate

Mechanical Properties

Friction

Hardness
Fracture toughness
Elasticity

Adhesion

Yield strength

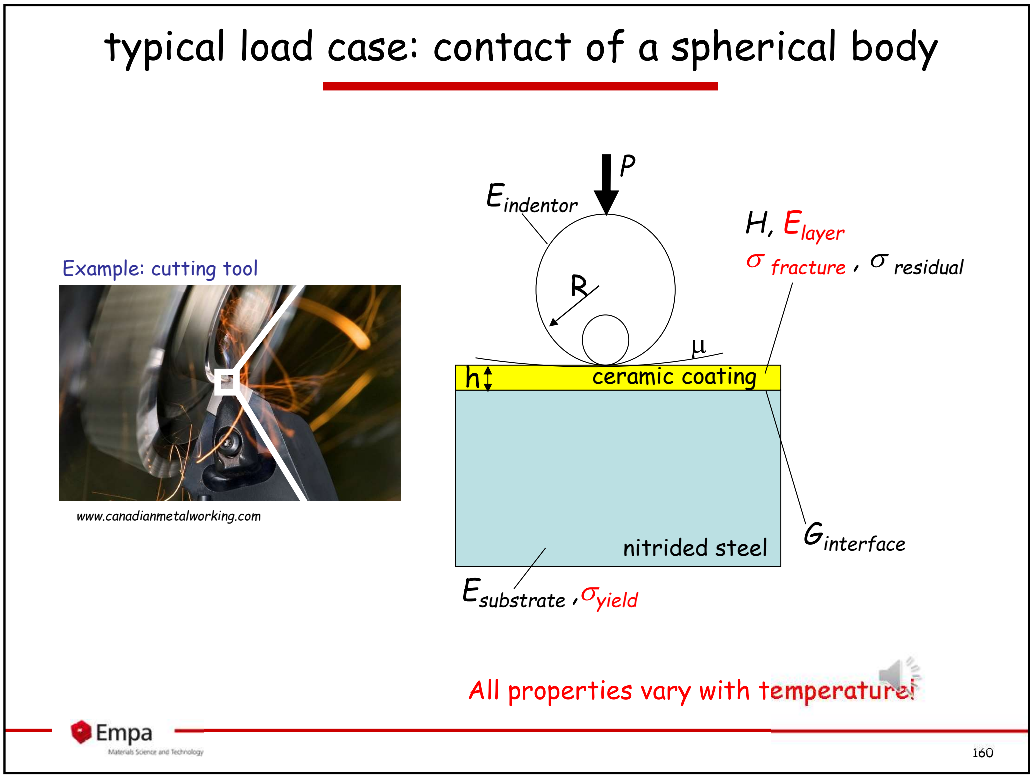
Thin films are often used to protect the substrate from outside influence, e.g. corrosion or mechanical wear. When the coating comes into contact with another body, ist tribological properties are very important.

These include friction, which means how much resistance is offered to relative motion in a sliding contact under normal load. This depends on the materials in contact as well as the morphology and roughness of the coating as well as the counterbody.

The hardness and fracture toughness of the material are measures how strong and tough the coating is and allow predictions about strength and wear properties. The elastic properties are also important when determining e.g. contact stresses in the system. These properties are influenced by the composition of the film, but also other factors like texture, grain size, or porosity.

The interface between the coating and the substrate plays a very important role. The strength of this interface is characterized by the adhesion. It depends on the morphology and roughness of the interface and what chemical reactions can occur between the substrate and film material.

Finally, the yield stress of the substrate is important, as under some circumstances the substrate can yield when the coating is loaded, which can also lead to failure of the coated component.



typical load case: contact of a spherical body

Example: cutting tool

www.canadianmetalworking.com

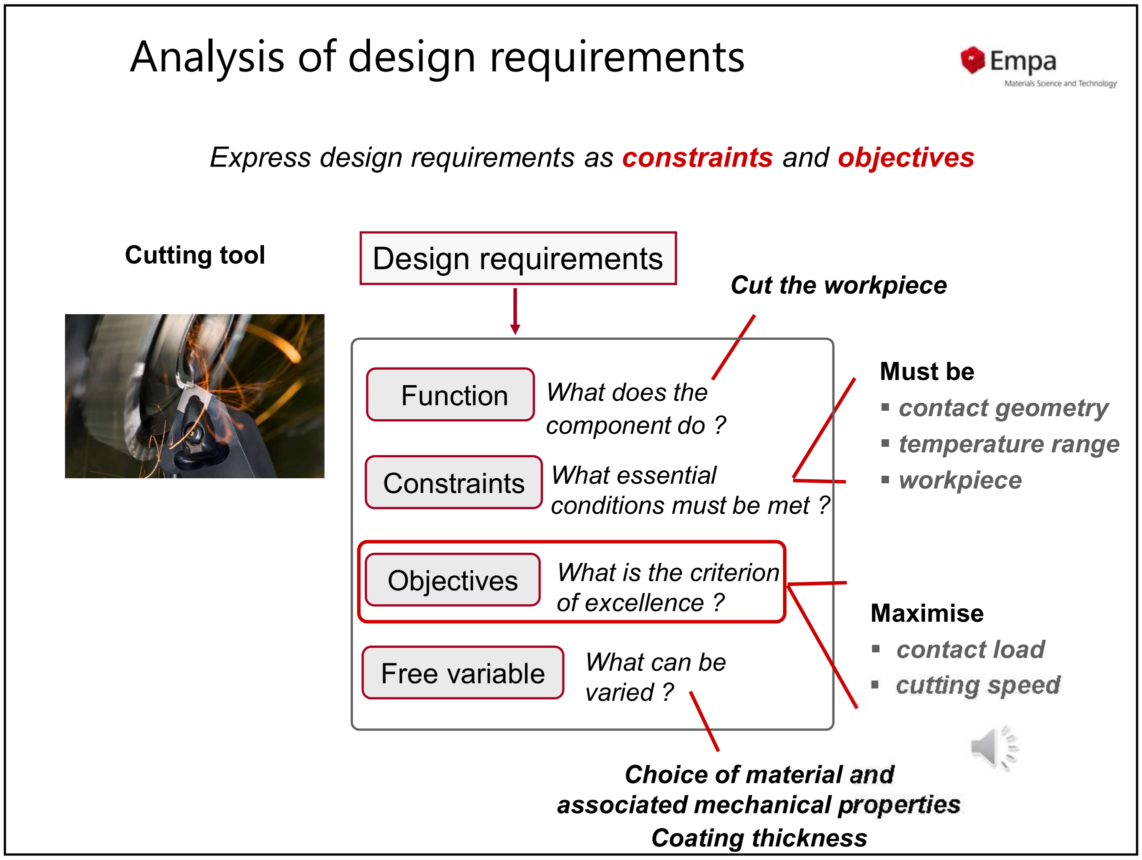
All properties vary with temperature!

Before we do nanomechanical measurements for an industrial application it is a good idea to think about objectives of the measurement. Which mechanical properties do we want to measure and how do these properties relate to the application performance. This brings us to the field of materials indices

In general, the first step is that of **translating** the design requirements into a specification for materials selection. The steps are summarized here:

- Identify the **function** of the component for which the material is sought.
- Identify and list the **constraints** it must meet: its ability to carry loads safely, satisfy limits on thermal or electrical properties and so forth.
- Finally, identify the **free variables** – those that the designer is free to change: usually dimensions or shape, and, of course, the choice of material.

An objective is a criterion by which the excellence of choice is to be judged. Thus the most desirable choice from among those materials that meet all the constraints might be the cheapest one – the objective is that of minimizing cost. It might be the lightest one – the objective is then that of minimizing mass.



Analysis of design requirements

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Express design requirements as ***constraints*** *and* ***objectives***

Cutting tool

Design requirements

Function — *What does the component do ?*

Constraints — *What essential conditions must be met ?*

Objectives — *What is the criterion of excellence ?*

Free variable — *What can be varied ?*

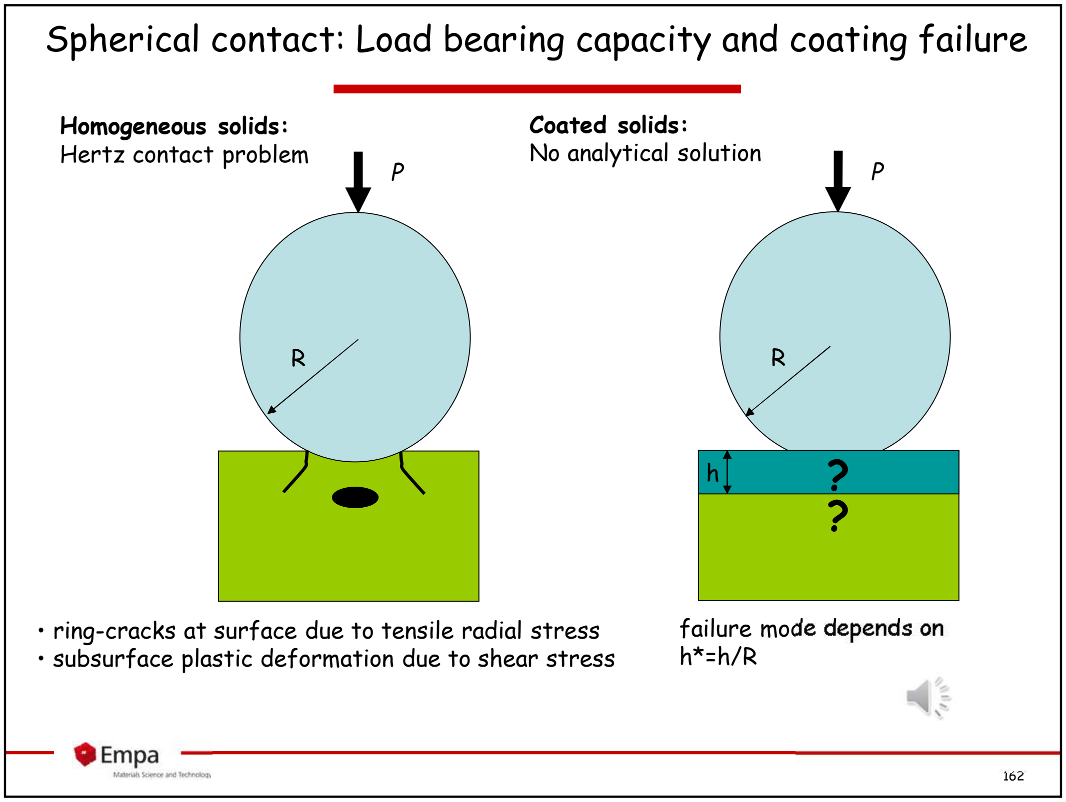
Cut the workpiece

Must be
- ***contact geometry***
- ***temperature range***
- ***workpiece***

Maximise
- ***contact load***
- ***cutting speed***

Choice of material and
associated mechanical properties
Coating thickness

Lets image we have to design a coating for a cutting tool. The objective is a criterion by which the excellence of choice is to be judged.



Spherical contact: Load bearing capacity and coating failure

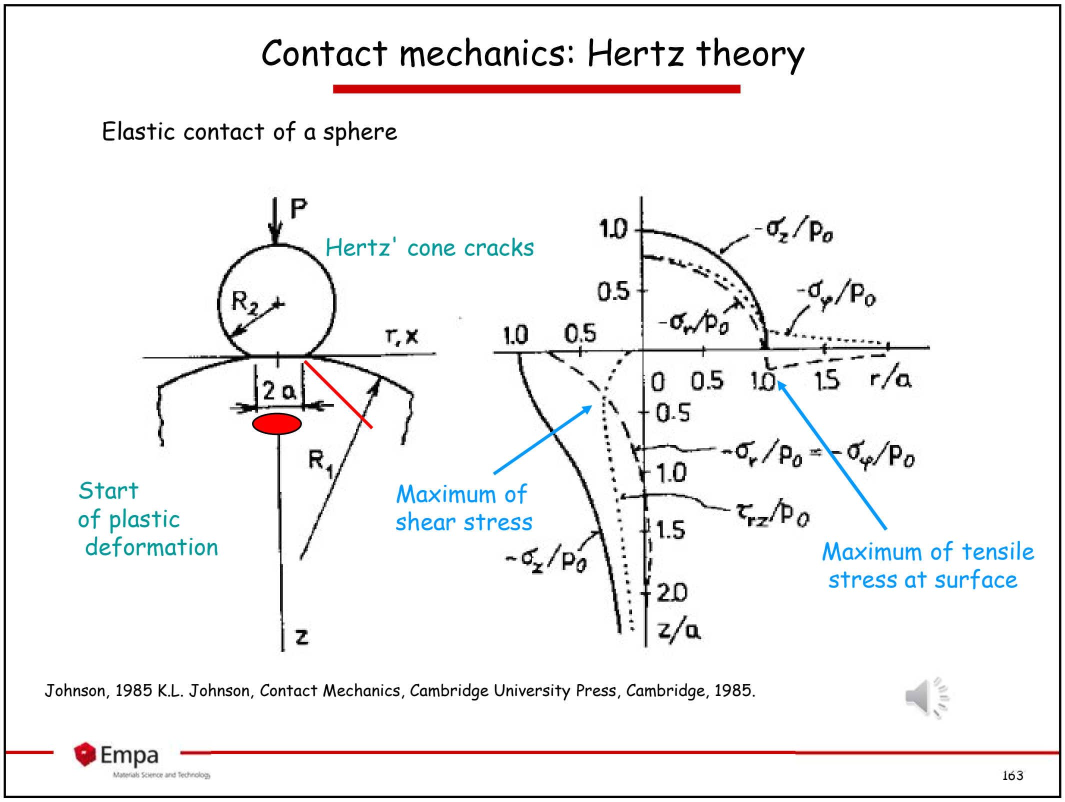
Homogeneous solids:
Hertz contact problem

Coated solids:
No analytical solution

- ring-cracks at surface due to tensile radial stress
- subsurface plastic deformation due to shear stress

failure mode depends on
$h^*=h/R$

A commonly encountered load case is the indentation of spherical bodies into a layered surface, which is, for example, representative of the mechanics in a bearing or for wear debris penetrating a layered surface. Owing to the difference in the elastic and plastic properties between the coating and the substrate, a general and simple analytical solution of the contact problem is not available. A design catalogue should include the failure mode for a particular geometry and load case, the critical load for failure to occur and how this load depends on materials and geometry parameters.



Contact mechanics: Hertz theory

Elastic contact of a sphere

Hertz' cone cracks

Start of plastic deformation

Maximum of shear stress

Maximum of tensile stress at surface

Johnson, 1985 K.L. Johnson, Contact Mechanics, Cambridge University Press, Cambridge, 1985.

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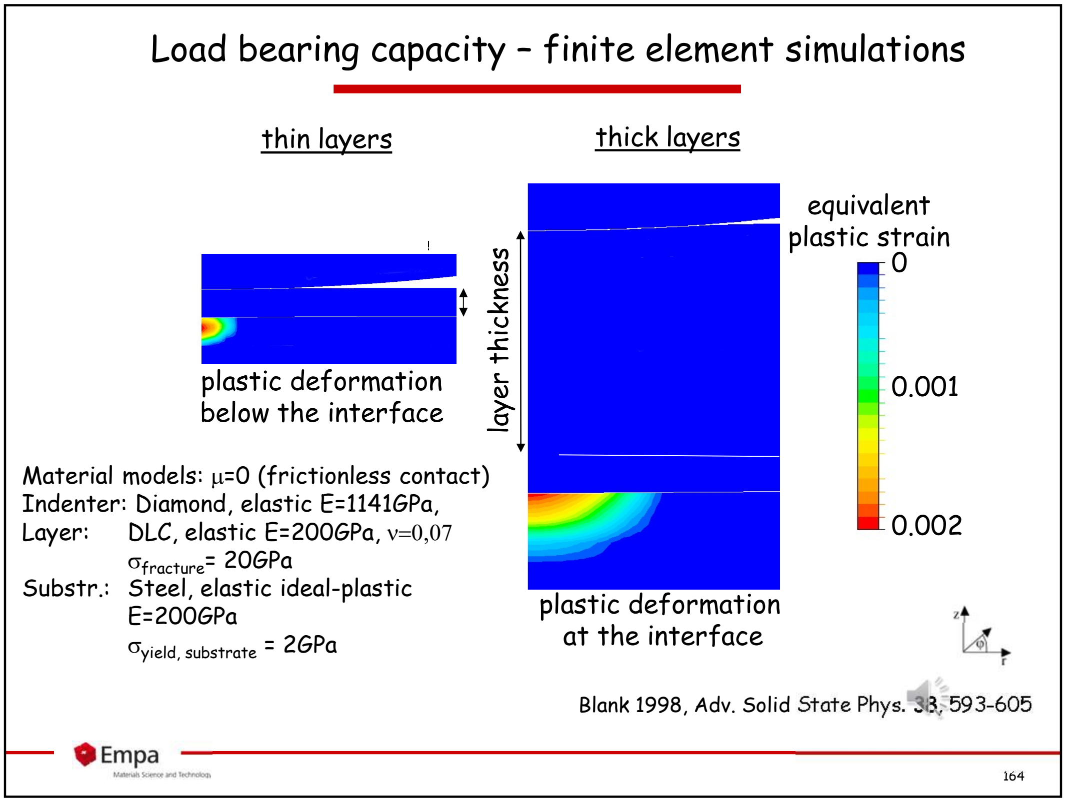
Note that the maximum shear and Von Mises stress are reached below the contact area and that radial tensile stress reaches a maximum at the surface at the edge of contact.

A homogeneous solid indented by a hard sphere can be damaged with increasing load in two different ways. A ductile material begins to deform plastically, if the maximum shear stress or the von Mises stress below the contact surface reaches the yield strength. A brittle material fails by the formation of Hertzian ring cracks, if the radial tensile stress at the edge of the contact area reaches the fracture strength of the material. In the case of a hard and brittle coating on a ductile substrate, both substrate plasticity and coating fracture are possible.

If the coating thickness is much larger than the indentor radius, the coating is expected to fail with increasing load like a homogeneous brittle solid before the substrate is plastified. If the coating thickness is comparable to the indentor radius or smaller, the substrate can deform plastically before coating

fracture. Both the critical load for the onset of plastic deformation and the critical load for coating fracture can differ from the case of a homogeneous solid. The stress distribution in the layer is different, leading to different modes of failure, i.e. different locations for the onset of plastic deformation or crack initiation and crack propagation.



Load bearing capacity – finite element simulations

Material models: μ=0 (frictionless contact)
Indenter: Diamond, elastic E=1141GPa,
Layer: DLC, elastic E=200GPa, ν=0,07
$\sigma_{fracture}$= 20GPa
Substr.: Steel, elastic ideal-plastic
E=200GPa
$\sigma_{yield, substrate}$ = 2GPa

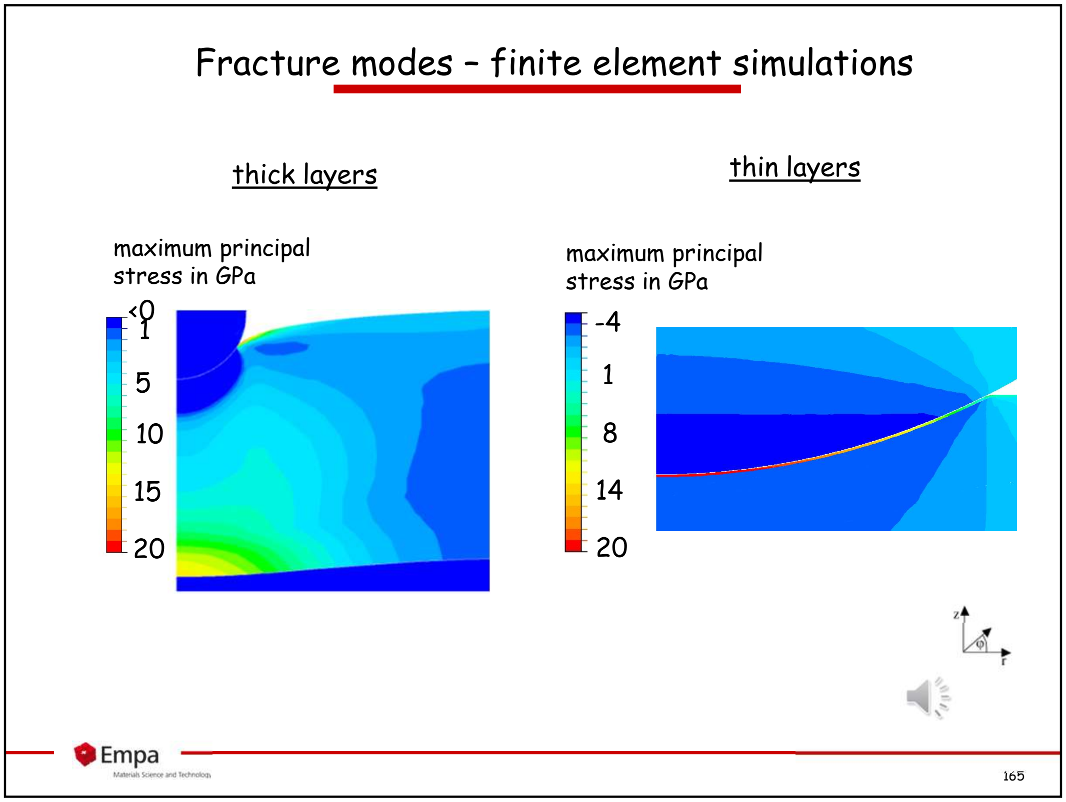
Blank 1998, Adv. Solid State Phys. 38, 593-605

There is no simple analytical solution for contact loading of a layered solid, but we can perform finite element simulations to assess the stress and strain tensors. The simulation was performed using the large strain elasto-plastic feature of the ABAQUS finite element code. The force-controlled procedure was used: a normal load *P* was applied, pushing the indentor into the surface. The automatic depth increment scheme was used to determine the appropriate size of the load increments and the simulation was stopped once the critical load was achieved that induces plastic deformation of the substrate.

If the composite fails first by plastic substrate deformation, two different yield locations for the point of the first yield are possible, which depends,

among others, on the ratio of coating thickness *h* to indentor ratio *R*. In cases where the coating thickness is significantly smaller, than the depth, at which the maximum shear stress reaches the yield stress in a homogeneous solid, then the substrate yields first in the substrate below the interface see the figure on the left. In the other case, the maximum shear stress lies within the layer and the onset of plastic yield in the substrate occurrs at higher loads, compared to the uncoated case.

J. Michler, E. Blank, Thin Solid Films 381 (2001) 119-134



Fracture modes – finite element simulations

thick layers

maximum principal stress in GPa

thin layers

maximum principal stress in GPa

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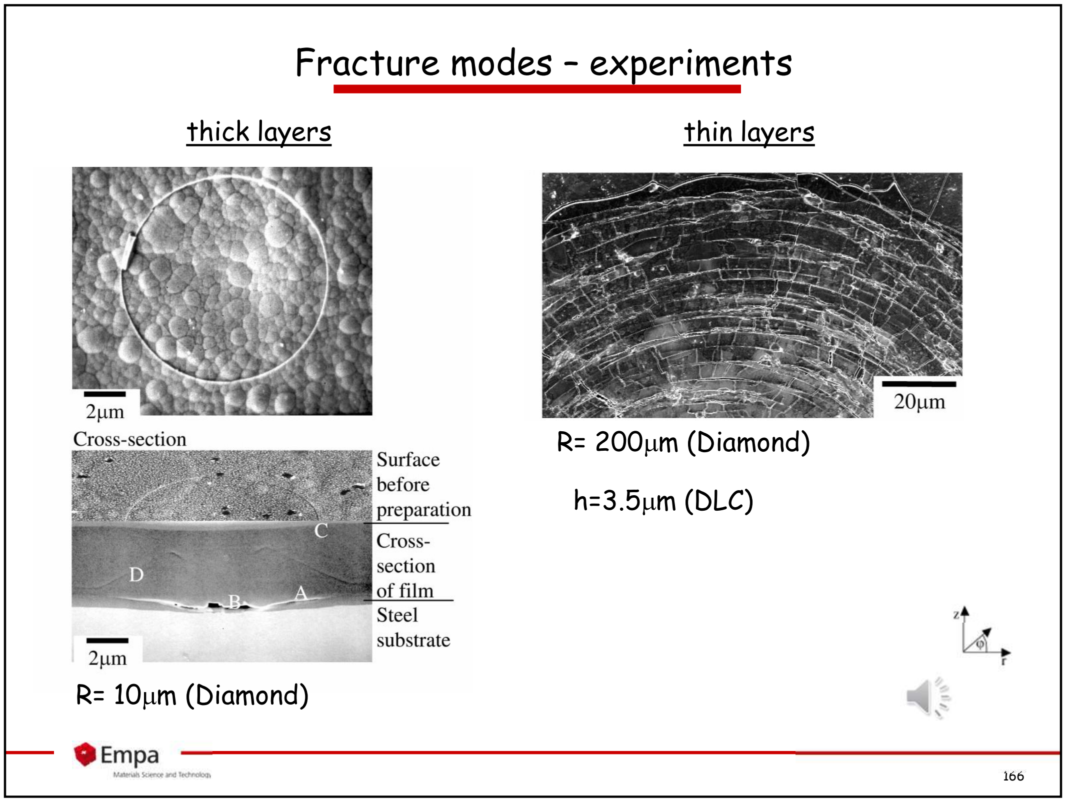
The coating is assumed to fail by fracture if the maximum principal stress reaches the fracture strength somewhere in the layer. Various different locations of fracture are possible, depending on the layer thickness and the extent of the possible foregoing plastic deformation in the substrate. To explore these fracture modes, the layer thickness in the calculations was varied over several orders of magnitude. Concerning the stress tensor in the layer, radial tensile is stresses were responsible for the initiation of circumferential cracks, and circumferential tensile stresses are responsible for radial cracks.

The maximum principal stress, a common measure for brittle fracture, is thus supposed to act perpendicularly to *z* and to be dominated by sigma_*rr* , and sigma_phiphi. Only the critical stress for crack initiation is considered here.

For very thick coatings the substrate will not plastify before the coating fracture, and a situation similar to the indentation of a homogeneous solid is encountered. For thick a situation as shown on the left may be encountered. The maximum principal stress attained a maximum at the interface and at the surface near the contact edge. The layer could fail by the formation of Hertzian cone cracks similar to the elastic case and due to cracks initiated at the interface.

For very thin layers like in the figure on the right the interface and surface stresses are nearly identical and tensile in the contact zone with a maximum at the symmetry axis. The stress distribution is similar to a thin circular membrane under pressure, promoting radial and circumferential cracks. The bending of the layer around the contact edge was less severe in the case of a thin layer, because the bending stiffness of the layer decreased with the layer thickness.



Fracture modes – experiments

thick layers

thin layers

R= 10µm (Diamond)

R= 200µm (Diamond)

h=3.5µm (DLC)

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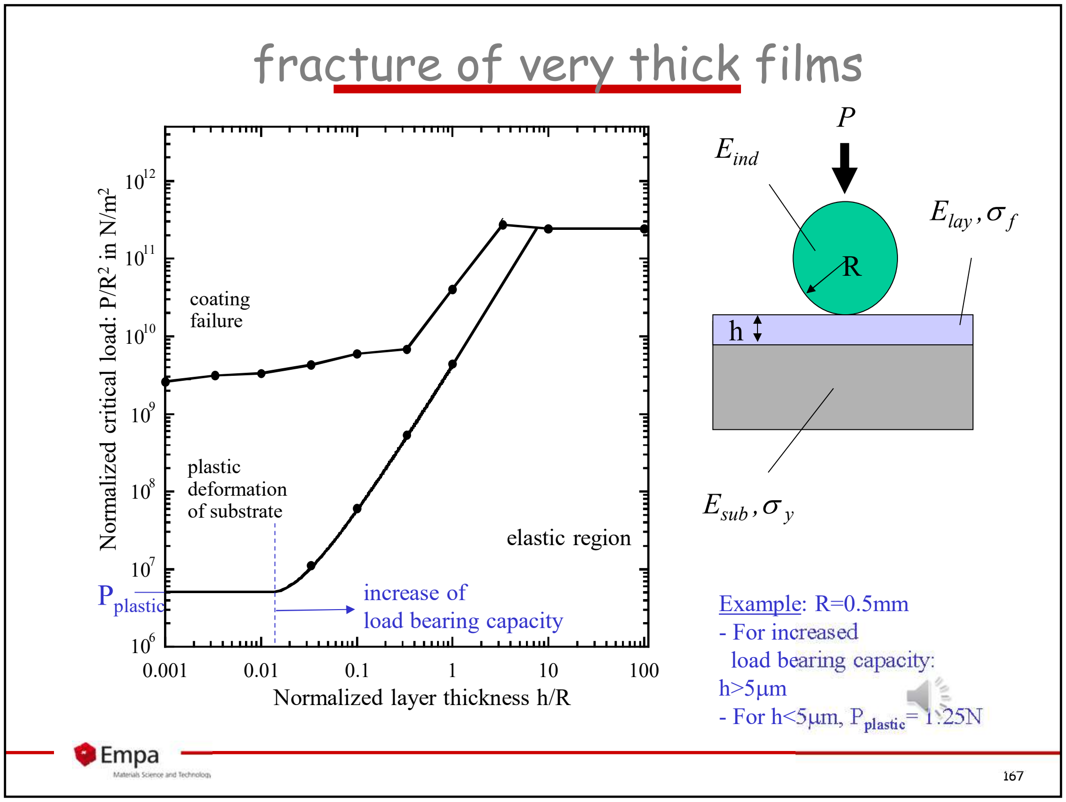
Formation of radial and circumferential cracks. Indentation of a DLC coated steel substrate with a diamond indentor.

Left: Crack formation at the surface and interface for nano-indentation of a 3.5 micro thick DLC coating on steel with a 10micro diamond indenter.

Right: Radial and circumferential crack formation for Rockwell C indentation with 200micron tip radius into the same DLC layer.

J. Michler, E. Blank, Thin Solid Films 381 (2001) 119-134



fracture of very thick films

Example: R=0.5mm
- For increased load bearing capacity: h>5μm
- For h<5μm, $P_{plastic}$= 1.25N

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Failure map for DLC on steel. A substrate yield strength of 2 GPa and a coating fracture strength of 20GPa is assumed. FEM calculations are represented by points, connected with solid lines.

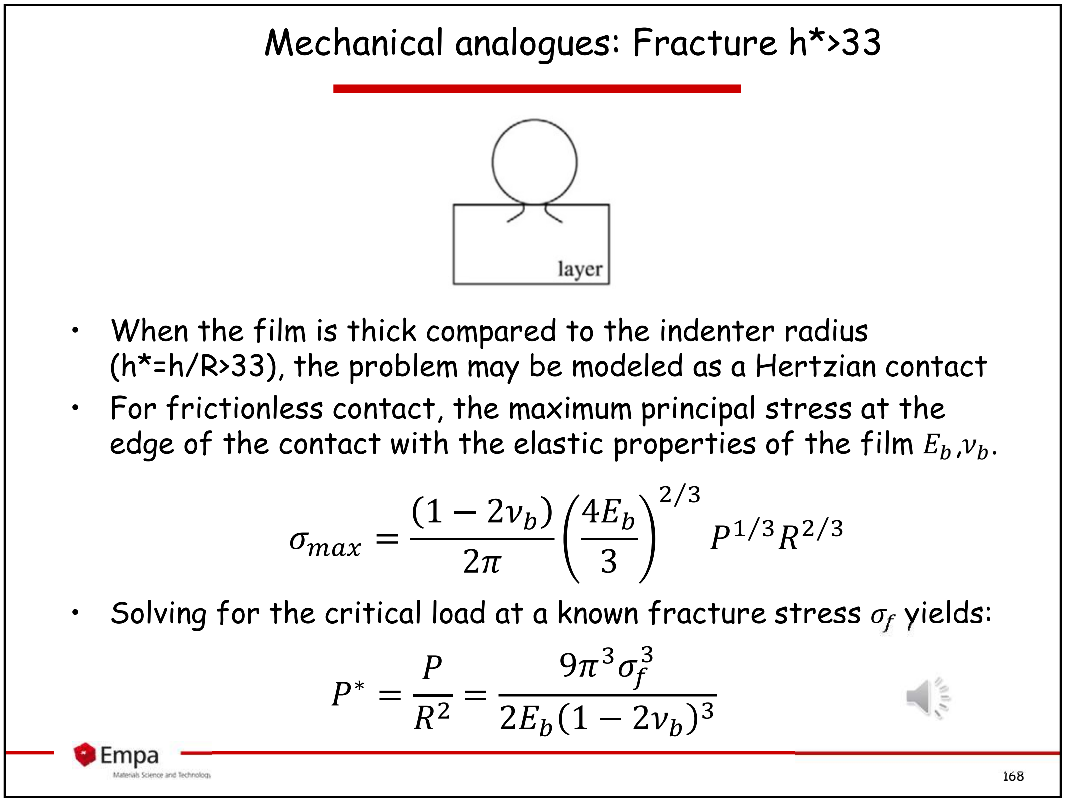
A failure map is supposed to allow the prediction of whether a coated component fails or not under a specific loading condition, which here refers to the penetration of a spherical body into the layered surface, and it should indicate the expected failure mode. Failure mode mapping requires suitable normalisation of the relevant coating design parameters in order to be valid for a wide range of different substrate / layer combinations and load cases. For a given combination of substrate/coating/indentor materials, the three important

application design parameters are the load *P*, the indentor radius *R* and the coating thickness *h*. The often-used contact radius *a* is an inconvenient normalisation factor because it is hardly known in practice.

Using the normalisation *P*=P/R^2 and h*=h/R* a normalised failure map can be established over the whole thickness range. The finite element calculations allow us to construct a failure map, which only depends on *P** and *h** and a

special combination of materials. From a *P**-h*map, the critical force for substrate plastification or coating fracture can be estimated if the layer thickness and the indentor radius are known. Analytical approximations

for *P3-h**, based on the stress distributions which are typical for the different failure modes encountered in the preceding chapters, are developed in the following.



Mechanical analogues: Fracture h*>33

- When the film is thick compared to the indenter radius (h*=h/R>33), the problem may be modeled as a Hertzian contact
- For frictionless contact, the maximum principal stress at the edge of the contact with the elastic properties of the film E_b,ν_b.

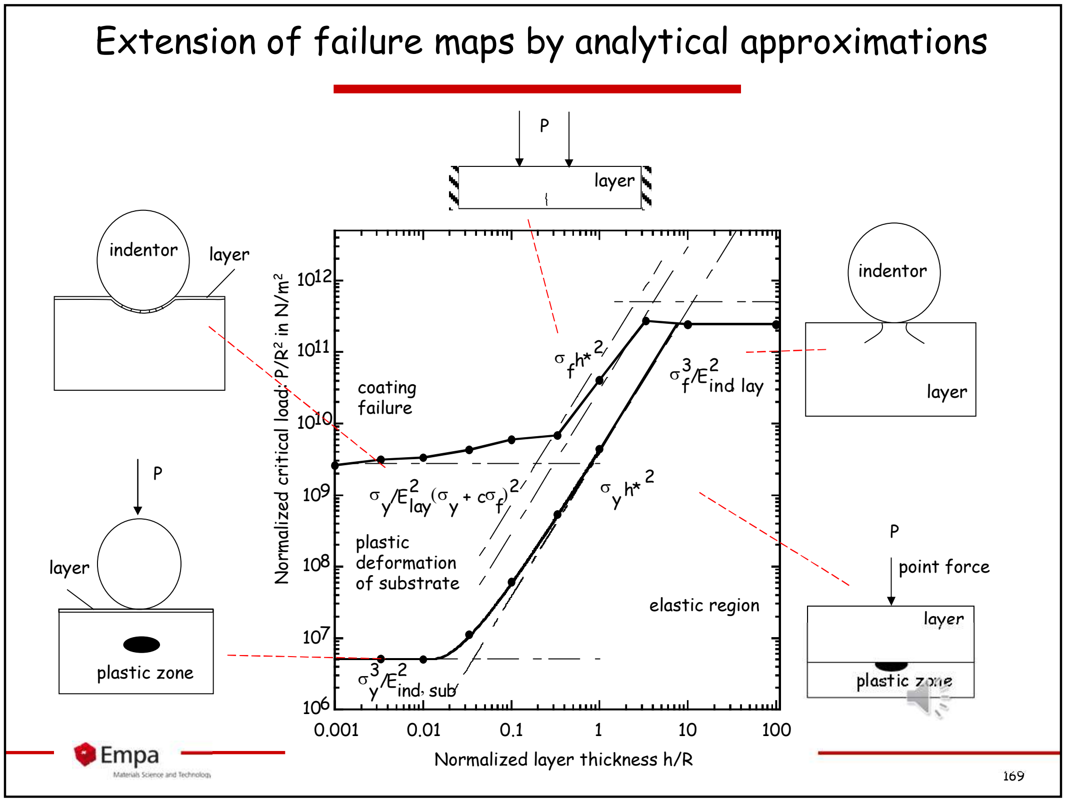
$$\sigma_{max} = \frac{(1-2\nu_b)}{2\pi}\left(\frac{4E_b}{3}\right)^{2/3} P^{1/3} R^{2/3}$$

- Solving for the critical load at a known fracture stress σ_f yields:

$$P^* = \frac{P}{R^2} = \frac{9\pi^3\sigma_f^3}{2E_b(1-2\nu_b)^3}$$

If the layer is very thick compared to the indenter radius, the effect of the substrate vanishes and the problem may be modeled as a Hertzian contact of a rigid sphere with an elastic halfspace. In the case of frictionless contact case, the maximum principal stress on the surface is at the edge of the contact and is given by

with the elastic properties of the film E_b,ν_b. Solving for the critical load at a known fracture stress σ_f yields the relation



Extension of failure maps by analytical approximations

Depending on the layer thickness, the substrate plastifies either below the interface or at the interface. Cracks in the layer were introduced at the surface outside the contact area, at the interface close to the symmetry axis, or within the contact area at the surface or interface. The analytical solutions described above, represented by dotted lines curves describe approximately the critical loads for these failure modes. They have been derived by identifying the stress components leading to substrate plasticity or layer fracture based on simple mechanical analogues for the five failure modes.

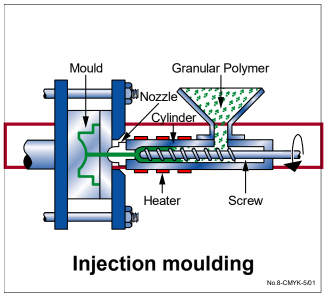
Concerning DLC coatings on tool steel, the critical force for the onset of substrate plasticity varies mainly with the third power of the yield stress for *h** below 0.01, but is proportional to the yield stress and the square of the

layer thickness *h* for larger *h**. Similarly the critical load for coating fracture is proportional to the square of *h* and the fracture strength in the thickness range

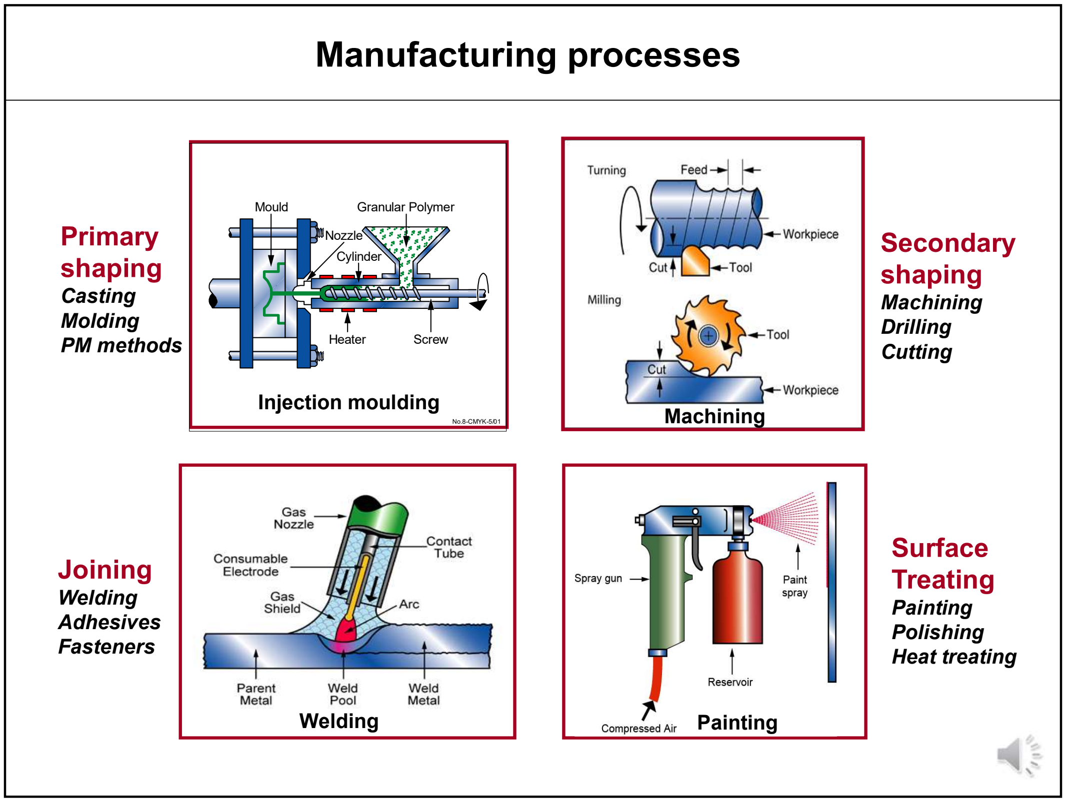
0.33-*h**-3.33; proportional to the third power of the layer fracture stress for larger *h** ratios; and a more complex function implicating substrate yield and coating fracture stress for smaller *h**. Failure modes, where the forces are proportional to the square of the layer thickness show little dependence on the elastic properties of the involved materials.

Selecting processes

shaping, joining and surface treatment



Injection moulding



Manufacturing processes

Primary shaping
Casting
Molding
PM methods

Injection moulding

Machining

Secondary shaping
Machining
Drilling
Cutting

Joining
Welding
Adhesives
Fasteners

Welding

Painting

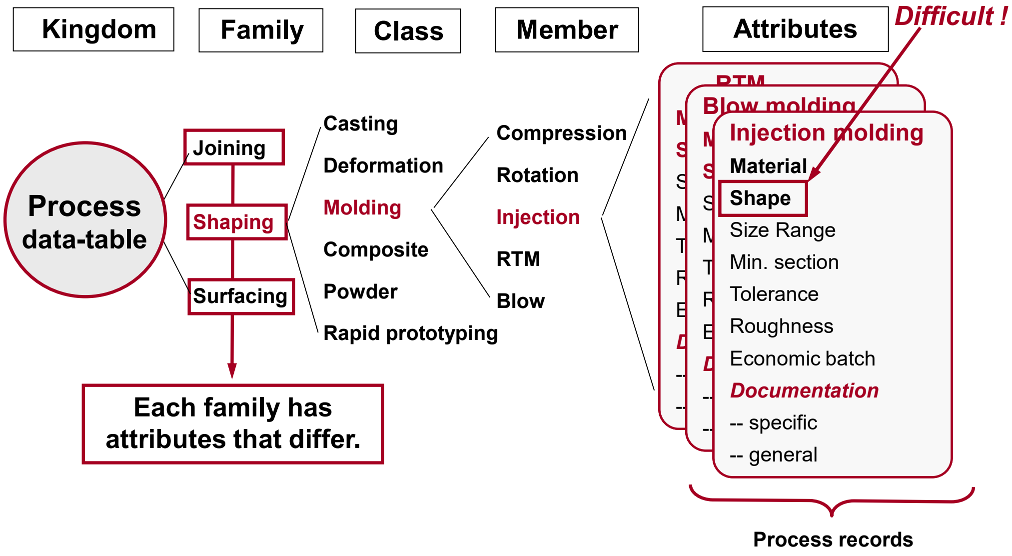
Surface Treating
Painting
Polishing
Heat treating

There are three broad **families of processes:**

- Those for **creating shapes** – subdivided into primary shaping processes (like casting) and secondary shaping processes (such as machining)
- Those for **joining** components
- Those for **surface-treating** components and structures.

The attributes of each family differ. Because of this, records for each are stored in separate folders. It is necessary, when using the CES software, to select the Level and the family before opening records or performing a selection exercise.

Data organisation: the PROCESS TREE



Kingdom
Family
Class
Member
Attributes
Difficult !

Process data-table

Joining
Shaping
Surfacing

Casting
Deformation
Molding
Composite
Powder
Rapid prototyping

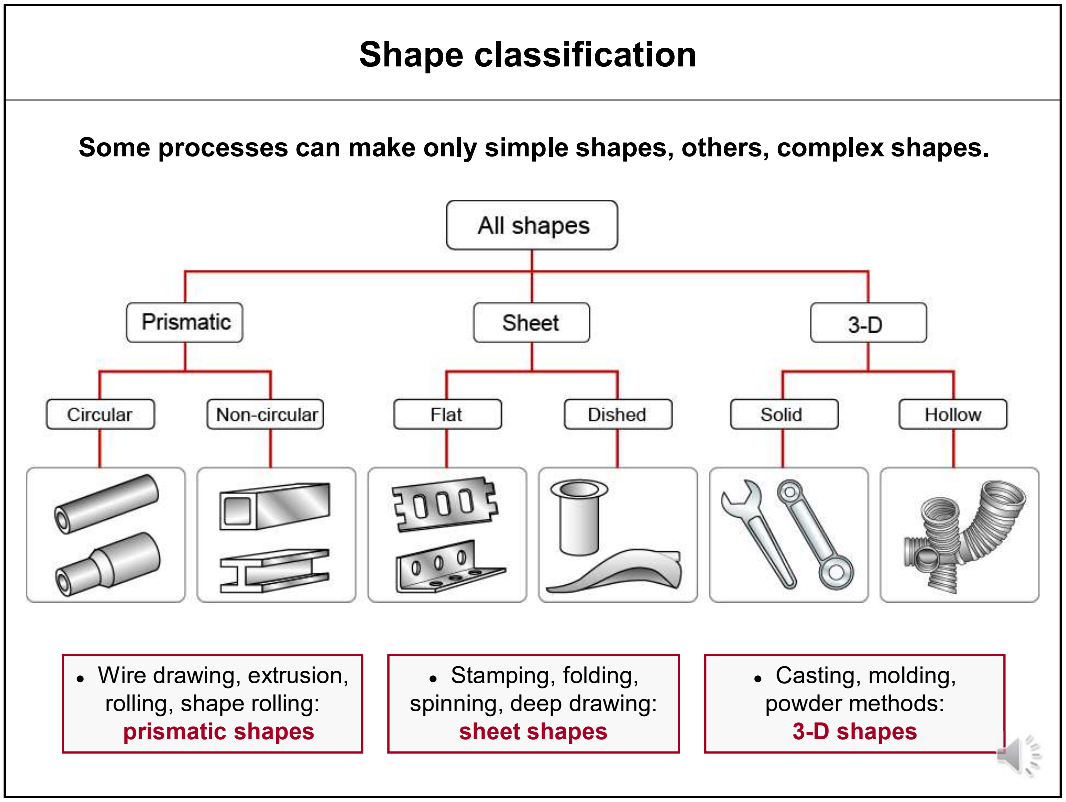
Compression
Rotation
Injection
RTM
Blow

RTM
Blow molding
Injection molding
Material
Shape
Size Range
Min. section
Tolerance
Roughness
Economic batch
Documentation
-- specific
-- general

Process records

Each family has attributes that differ.

If data for processes are to be stored in a database, an organizational structure is needed. This classification of processes allows information about them to be organized in a useful way, one that parallels that for materials in Unit 1. The three **families** – shaping, joining and surfacing – each contain a number of **classes**; that for shaping is expanded here. Each class has many **members**, as the expansion of molding in this frame suggests. And each member is characterized by a set of **attributes**, some numeric and able to be structured, some based on text and images that are stored as unstructured information. One of these – that of describing the **shapes** that a process can make – requires some explanation.



Shape classification

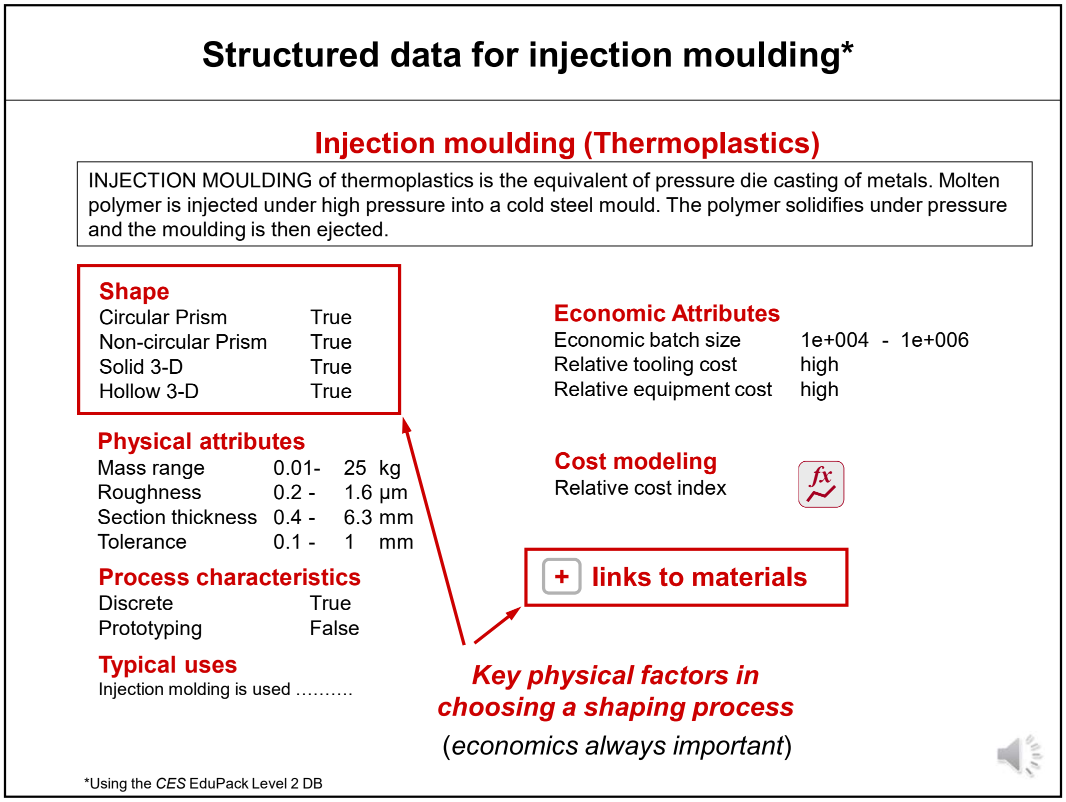
Some processes can make only simple shapes, others, complex shapes.

- Wire drawing, extrusion, rolling, shape rolling: **prismatic shapes**

- Stamping, folding, spinning, deep drawing: **sheet shapes**

- Casting, molding, powder methods: **3-D shapes**

Shape is the most difficult attribute to describe and quantify. Many texts on processing attempt a classification; none is wholly satisfactory. Here the primary distinctions are between **prismatic shapes** made by processes such as extrusion, rolling and wire-drawing; **shapes made from sheet** by stamping, deep drawing, spinning or folding; and **3-dimensional shapes** that involve change of section made by casting, molding and a host of more elaborate procedures.



Structured data for injection moulding*

Injection moulding (Thermoplastics)

INJECTION MOULDING of thermoplastics is the equivalent of pressure die casting of metals. Molten polymer is injected under high pressure into a cold steel mould. The polymer solidifies under pressure and the moulding is then ejected.

Shape

Circular Prism	True
Non-circular Prism	True
Solid 3-D	True
Hollow 3-D	True

Physical attributes

Mass range	0.01-	25	kg
Roughness	0.2 -	1.6	μm
Section thickness	0.4 -	6.3	mm
Tolerance	0.1 -	1	mm

Process characteristics

Discrete	True
Prototyping	False

Typical uses

Injection molding is used ……….

Economic Attributes

Economic batch size	1e+004 - 1e+006
Relative tooling cost	high
Relative equipment cost	high

Cost modeling

Relative cost index

+ links to materials

Key physical factors in choosing a shaping process

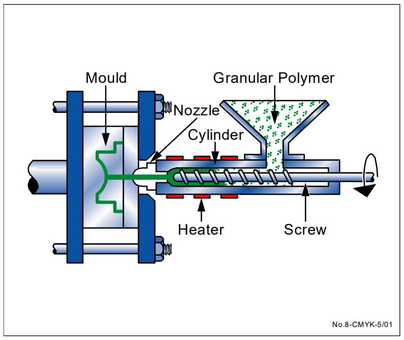
(*economics always important*)

*Using the *CES* EduPack Level 2 DB

We now return to the attributes.This is an example of **structured data** for a shaping process. The physical attributes include the size of part that can be made (the mass range), the surface roughness, the minimum thickness of section (often limited by the ability of material to flow into narrow channels) and the precision or tolerance of which it is capable. Structured information includes an identification of the process as discrete (like stamping) or continuous (like wire-drawing), the shapes it can make, and information about economics, most usefully, the economic batch size (the production run needed to justify the cost of the dies, molds or other tooling). A key attribute of a process is the portfolio of materials with which it is compatible. This is captured by the **links** to materials.

Unstructured data for injection moulding*

The process. **Most small, complex plastic parts you pick up – children's toys, CD cases, telephones – are injection moulded. Injection moulding of thermoplastics is the equivalent of pressure die casting of metals. Molten polymer is injected under high pressure into a cold steel mould. The polymer solidifies under pressure and the moulding is then ejected.**
Various types of injection moulding machines exist, but the most common in use today is the reciprocating screw machine, shown schematically here. Polymer granules are fed into a spiral press like a heated meat-mincer where they mix and soften to a putty-like goo that can be forced through one or more feed-channels ("sprues") into the die.



Design guidelines. Injection moulding is the best way to mass-produce small, precise, plastic parts with complex shapes. The surface finish is good; texture and pattern can be moulded in, and fine detail reproduces well. The only finishing operation is the removal of the sprue.

The economics. Capital cost are medium to high; tooling costs are high, making injection moulding economic only for large batch-sizes (typically 5000 to 1 million). Production rate can be high particularly for small mouldings. Multi-cavity moulds are often used. The process is used almost exclusively for large volume production. Prototype mouldings can be made using cheaper single cavity moulds of cheaper materials. Quality can be high but may be traded off against production rate. Process may also be used with thermosets and rubbers.

Typical uses. The applications, of great variety, include: housings, containers, covers, knobs, tool handles, plumbing fittings, lenses, etc.

The environment. Thermoplastic sprues can be recycled. Extraction may be required for volatile fumes. Significant dust exposures may occur in the formulation of the resins. Thermostatic controller malfunctions can be extremely hazardous.

*Using the *CES* EduPack Level 2 DB

Much information about processes is specialized and best recorded as text and images. It includes design guidelines, technical information, examples of uses, and a commentary guiding its economic use and identifying any environmental concerns that it raises. It is stored as **unstructured data,** as shown here.

Selection of processes

- **Process selection has the same 4 basic steps**

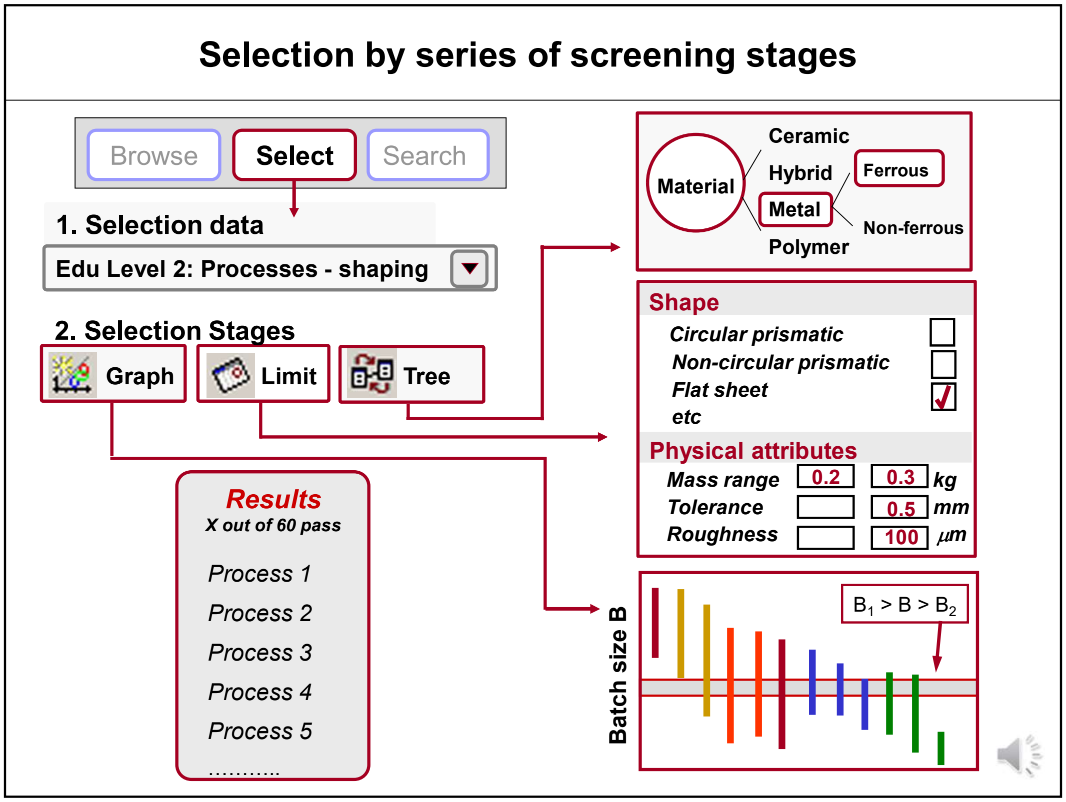
Step 1 **Translation:** *express design requirements as constraints & objectives*

Step 2 **Screening:** *eliminate processes that cannot do the job*

Step 3 **Ranking:** *find the processes that do the job most cheaply*

Step 4 **Documentation:** *explore pedigrees of top-ranked candidates*

The steps in selecting processes parallels that for selecting materials: **translation, screening, ranking** and **documentation**.



Selection by series of screening stages

1. Selection data

Edu Level 2: Processes - shaping ▼

2. Selection Stages

Results

X out of 60 pass

Process 1

Process 2

Process 3

Process 4

Process 5

....

Shape

Circular prismatic ☐

Non-circular prismatic ☐

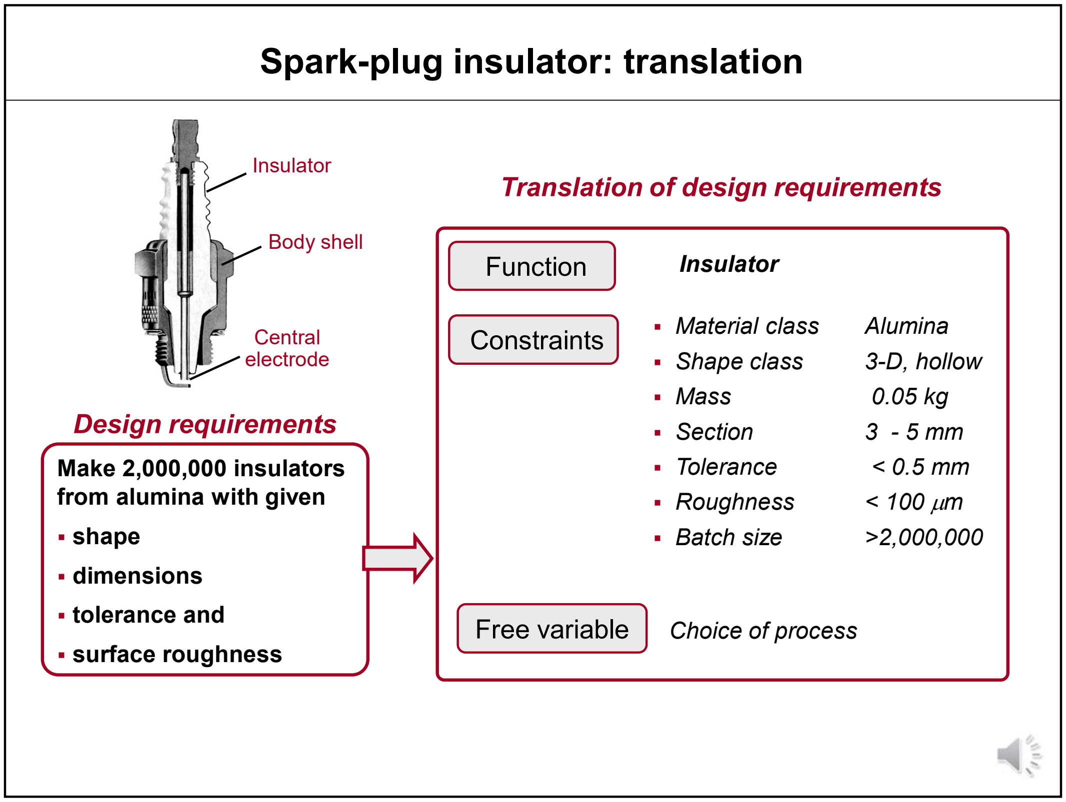
Flat sheet ☑

etc

Physical attributes

Mass range	0.2	0.3	*kg*
Tolerance		0.5	*mm*
Roughness		100	*µm*

Typical process selection exercises combine the use of **Graph, Limit** and **Tree stages.** Graph stages to plot bar charts work well. Graph stages to make bubble charts (charts with attributes on both the X-axis and the Y-axis) do not, because the range of process attributes are too wide. They should be avoided.



Spark-plug insulator: translation

Design requirements

Make 2,000,000 insulators from alumina with given

- **shape**
- **dimensions**
- **tolerance and**
- **surface roughness**

Translation of design requirements

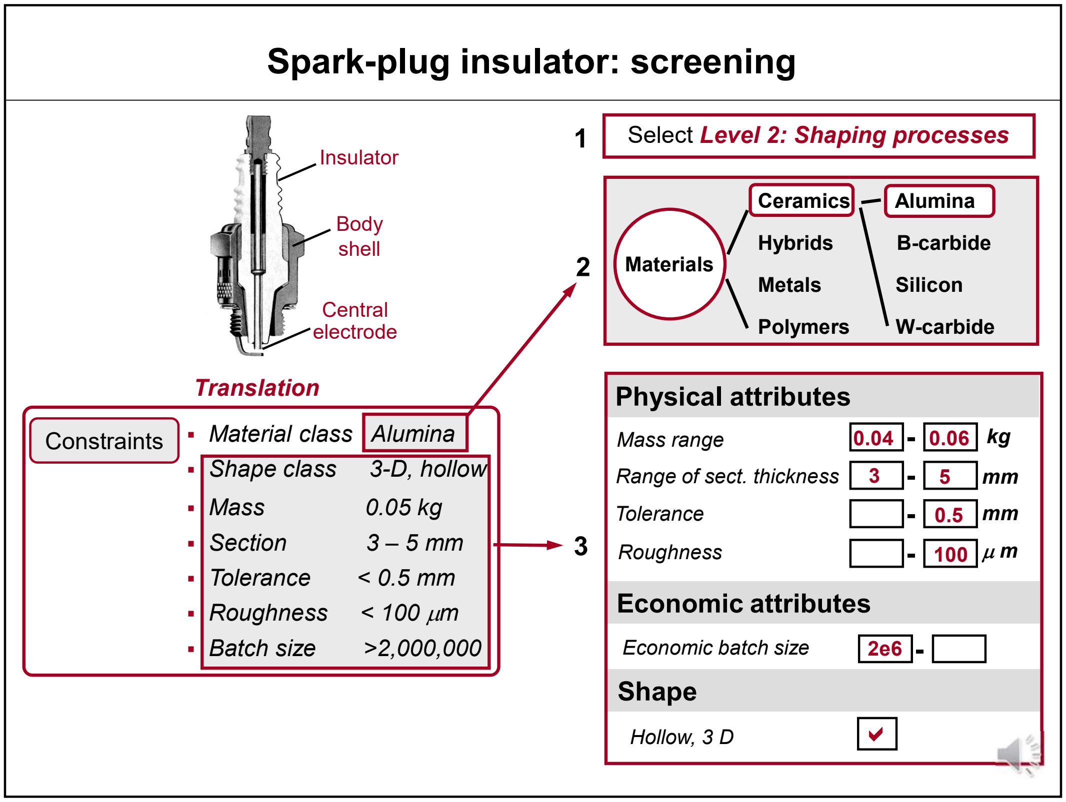
Function: ***Insulator***

Constraints

Material class	*Alumina*
Shape class	*3-D, hollow*
Mass	*0.05 kg*
Section	*3 - 5 mm*
Tolerance	*< 0.5 mm*
Roughness	*< 100 μm*
Batch size	*>2,000,000*

Free variable: *Choice of process*

Now an example: choosing a process to make a the **insulator of a spark plug**. It is to be made of the technical ceramic Alumina. How can it be shaped? The constraints (translated from the design requirements) are listed on this frame. They are the inputs to the selection exercise.



Spark-plug insulator: screening

Insulator

Body shell

Central electrode

Translation

Constraints

Material class	*Alumina*
Shape class	*3-D, hollow*
Mass	*0.05 kg*
Section	*3 – 5 mm*
Tolerance	*< 0.5 mm*
Roughness	*< 100 μm*
Batch size	*>2,000,000*

1 Select ***Level 2: Shaping processes***

2

Materials
- **Ceramics**
  - **Alumina**
  - **B-carbide**
  - **Silicon**
  - **W-carbide**
- **Hybrids**
- **Metals**
- **Polymers**

3

Physical attributes

Mass range	0.04	-	0.06	*kg*
Range of sect. thickness	3	-	5	*mm*
Tolerance		-	0.5	*mm*
Roughness		-	100	μ m

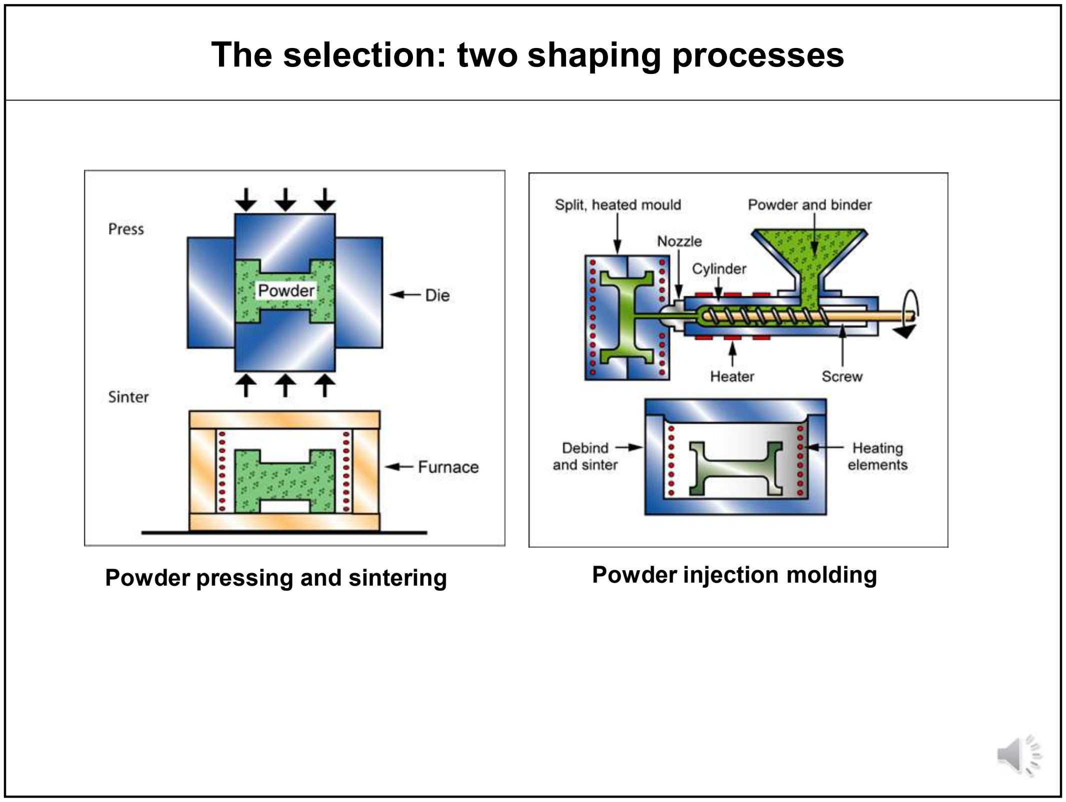
Economic attributes

Economic batch size	2e6	-	

Shape

Hollow, 3 D ☑

This frame shows an **implementation of the selection method**. The translated requirements are used as inputs to a Tree stage (for the material choice) and a Limit stage (for the limits on shape, mass, tolerance, batch size etc.)

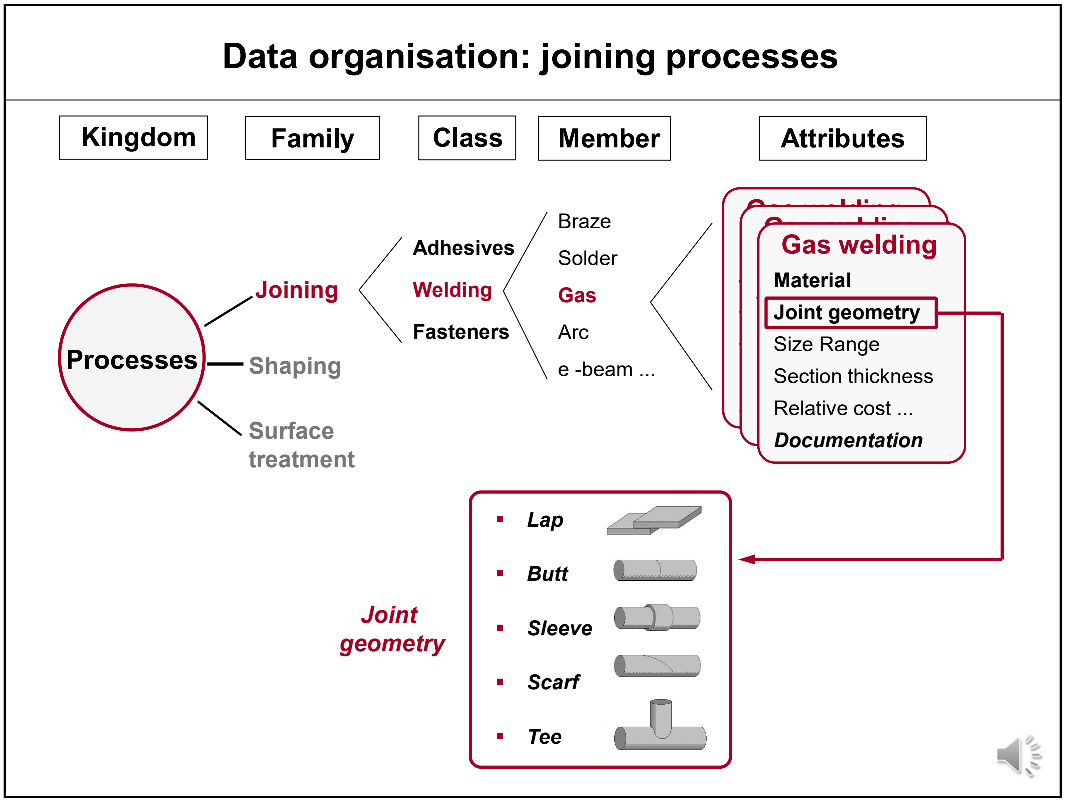


The selection: two shaping processes

Powder pressing and sintering

Powder injection molding

Applying the constraints, as in the previous frame, with CES set to Level 2 SHAPING gives two selections: powder pressing and sintering, and powder injection molding.



Data organisation: joining processes

Kingdom **Family** **Class** **Member** **Attributes**

Processes

- **Joining**
  - **Adhesives**
  - **Welding**
    - Braze
    - Solder
    - **Gas**
    - Arc
    - e -beam ...
  - **Fasteners**
- **Shaping**
- **Surface treatment**

Gas welding

Material

Joint geometry

Size Range

Section thickness

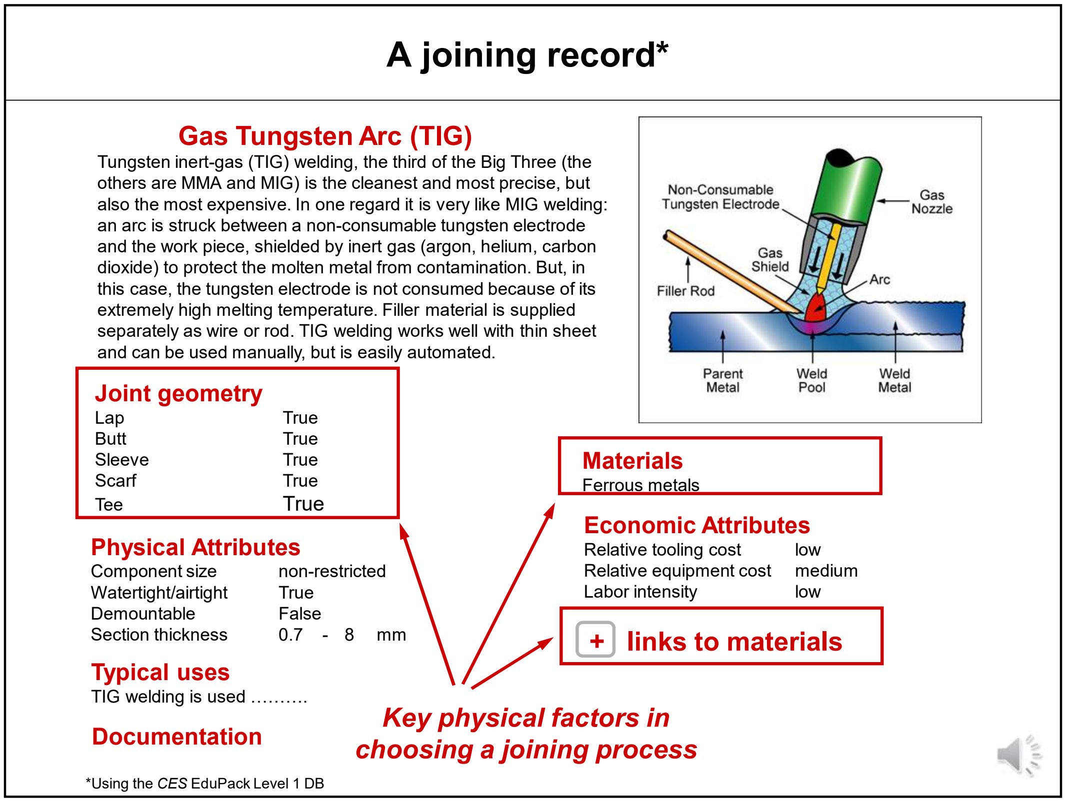
Relative cost ...

Documentation

Joint geometry

- ***Lap***
- ***Butt***
- ***Sleeve***
- ***Scarf***
- ***Tee***

So far we have discussed only shaping processes. The other two families – **joining** and **surface treatment** – can be structured and selected in similar ways. This frame shows the **joining** tree, with the class of **welding** expanded to show members and some of their attributes. The two most important attbributes when selecting a joining process are the **materials** to be joined and the **joint geometry**, shown here.



A joining record*

Gas Tungsten Arc (TIG)

Tungsten inert-gas (TIG) welding, the third of the Big Three (the others are MMA and MIG) is the cleanest and most precise, but also the most expensive. In one regard it is very like MIG welding: an arc is struck between a non-consumable tungsten electrode and the work piece, shielded by inert gas (argon, helium, carbon dioxide) to protect the molten metal from contamination. But, in this case, the tungsten electrode is not consumed because of its extremely high melting temperature. Filler material is supplied separately as wire or rod. TIG welding works well with thin sheet and can be used manually, but is easily automated.

Joint geometry

Lap	True
Butt	True
Sleeve	True
Scarf	True
Tee	True

Physical Attributes

Component size	non-restricted
Watertight/airtight	True
Demountable	False
Section thickness	0.7 - 8 mm

Typical uses

TIG welding is used ……….

Documentation

Materials

Ferrous metals

Economic Attributes

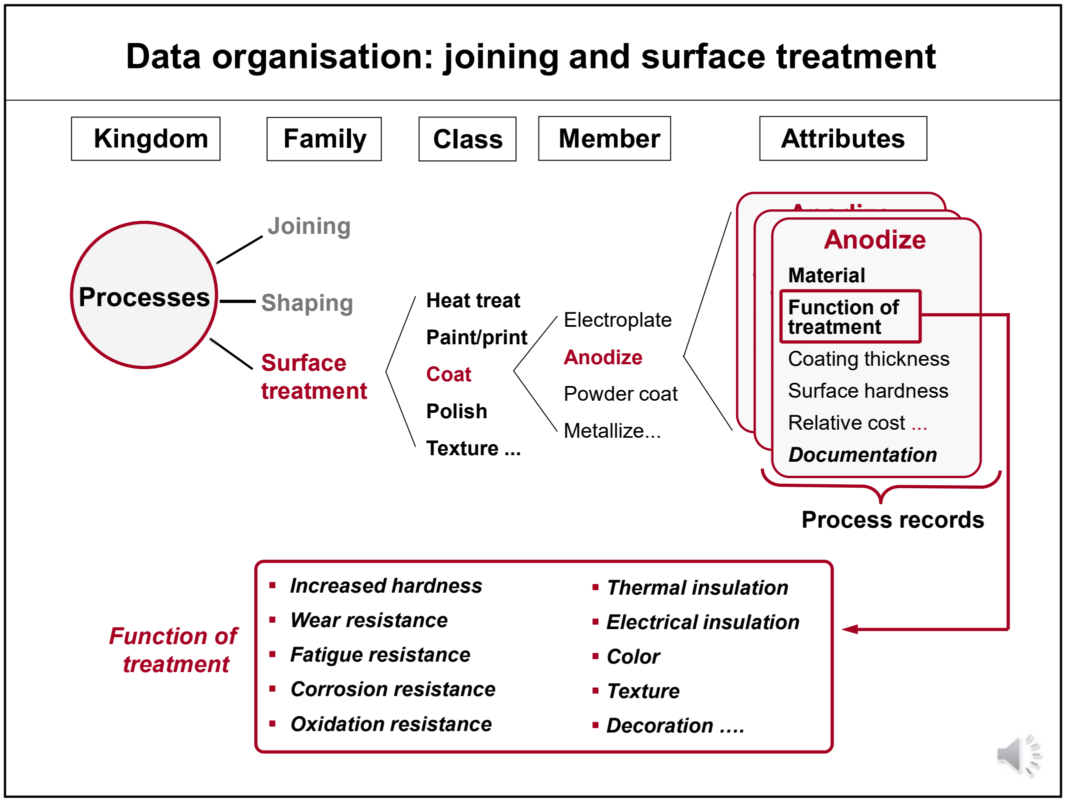
Relative tooling cost	low
Relative equipment cost	medium
Labor intensity	low

+ links to materials

Key physical factors in choosing a joining process

*Using the *CES* EduPack Level 1 DB

This frame show **structured** and **unstructured data** for a **joining process**. The attributes are those that engineers use to select a joining process. They differ in many ways (not unexpectedly) from those for shaping. Some attributes – material, size, and general economic information – are common to all processes. But the rest – the geometry of the joint, the ability to join dissimilar materials or to allow disassembly etc. – are specific to joining.



Data organisation: joining and surface treatment

Kingdom **Family** **Class** **Member** **Attributes**

Processes

Joining

Shaping

Surface treatment

- **Heat treat**
- **Paint/print**
- **Coat**
- **Polish**
- **Texture ...**

- Electroplate
- **Anodize**
- Powder coat
- Metallize...

Anodize

Material

Function of treatment

Coating thickness

Surface hardness

Relative cost ...

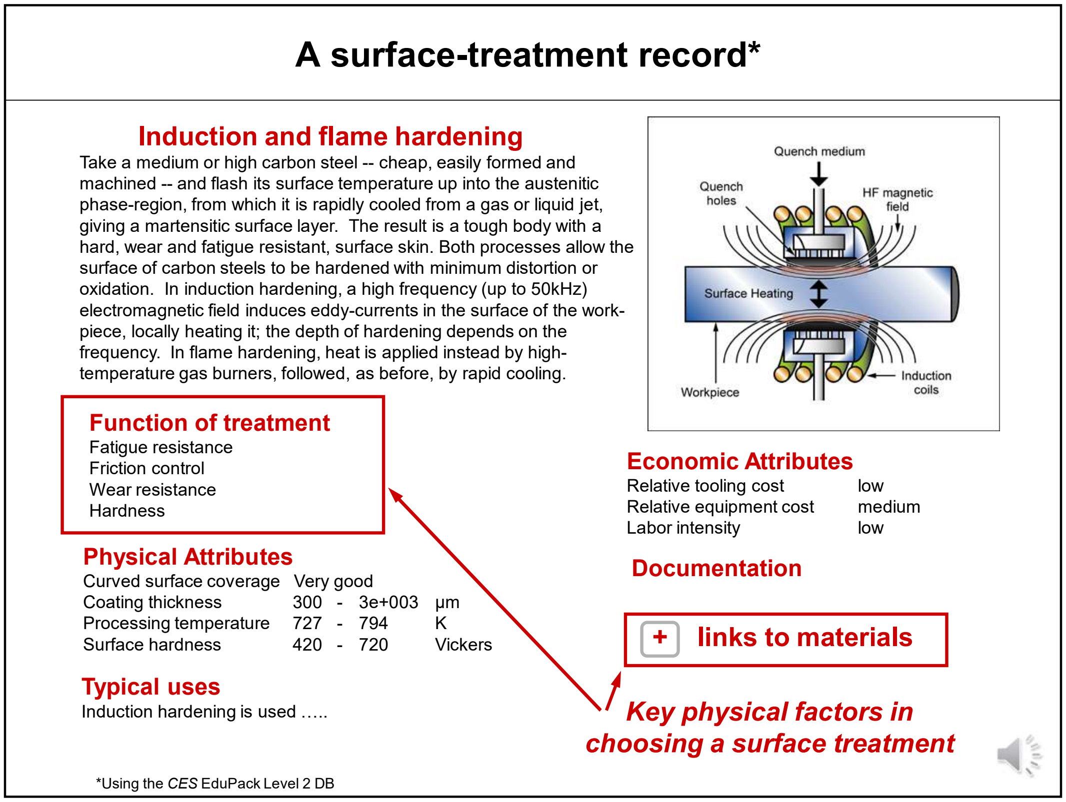
Documentation

Process records

Function of treatment

- ***Increased hardness***
- ***Wear resistance***
- ***Fatigue resistance***
- ***Corrosion resistance***
- ***Oxidation resistance***
- ***Thermal insulation***
- ***Electrical insulation***
- ***Color***
- ***Texture***
- ***Decoration ....***

So far we have discussed shaping and joining processes. The remaining family – **surface treatment** – can be structured and selected in similar ways. This frame shows the **surface treatment** tree, with the class of **coating** expanded to show members and some of their attributes. The most discriminating attributes when selecting a surface treatment process are the **material** to be treated and the **function of the treatment**. The frame shows typical functions of treatments.



A surface-treatment record*

Induction and flame hardening

Take a medium or high carbon steel -- cheap, easily formed and machined -- and flash its surface temperature up into the austenitic phase-region, from which it is rapidly cooled from a gas or liquid jet, giving a martensitic surface layer. The result is a tough body with a hard, wear and fatigue resistant, surface skin. Both processes allow the surface of carbon steels to be hardened with minimum distortion or oxidation. In induction hardening, a high frequency (up to 50kHz) electromagnetic field induces eddy-currents in the surface of the work-piece, locally heating it; the depth of hardening depends on the frequency. In flame hardening, heat is applied instead by high-temperature gas burners, followed, as before, by rapid cooling.

Function of treatment

Fatigue resistance
Friction control
Wear resistance
Hardness

Physical Attributes

Curved surface coverage	Very good			
Coating thickness	300	-	3e+003	μm
Processing temperature	727	-	794	K
Surface hardness	420	-	720	Vickers

Typical uses

Induction hardening is used …..

Economic Attributes

Relative tooling cost	low
Relative equipment cost	medium
Labor intensity	low

Documentation

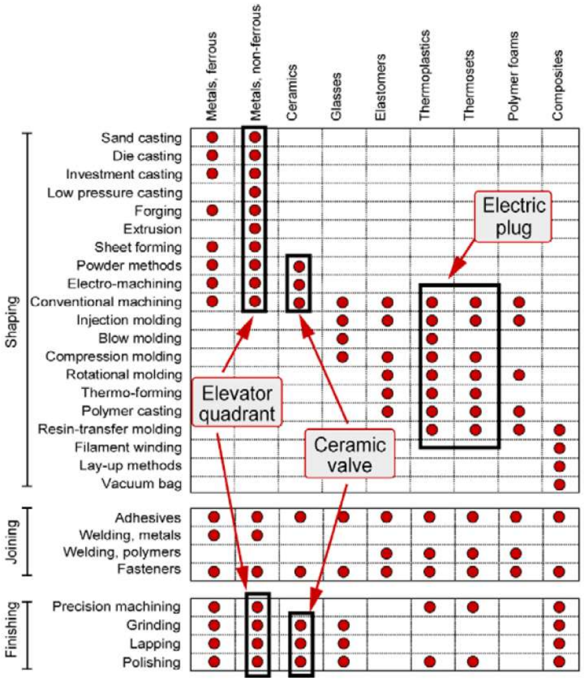
+ **links to materials**

Key physical factors in choosing a surface treatment

*Using the *CES* EduPack Level 2 DB

This frame show **structured** and **unstructured data** for a **surface treatment process**. The most critical attributes are the function that the treatment is required to provide and the materials to which it will be applied, accessed via the links.

The Process-Material Matrix



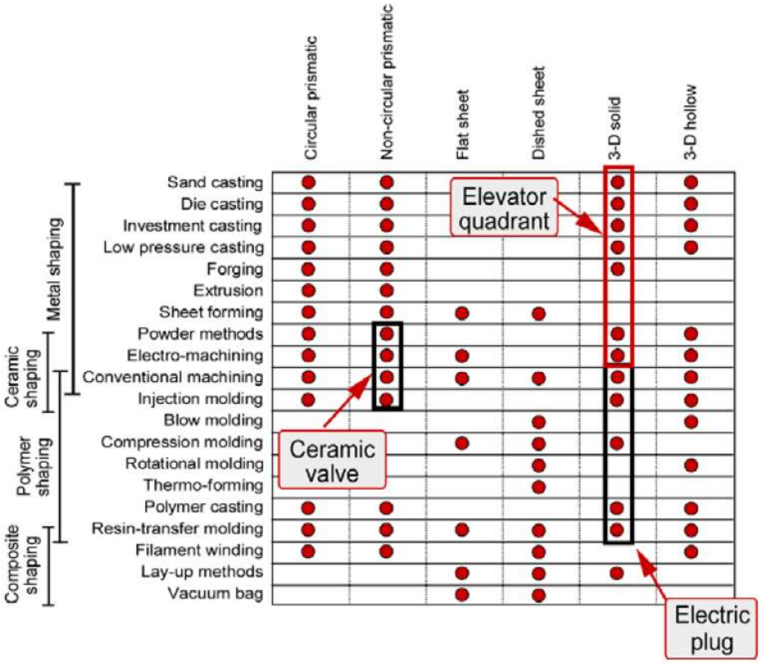
		Metals, ferrous	Metals, non-ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	●	●							
	Die casting	●	●							
	Investment casting	●	●							
	Low pressure casting		●							
	Forging	●	●							
	Extrusion		●							
	Sheet forming	●	●							
	Powder methods	●	●	●						
	Electro-machining	●	●	●						
	Conventional machining	●	●	●	●	●	●	●	●	
	Injection molding				●	●	●	●	●	
	Blow molding				●		●			
	Compression molding				●	●	●	●		
	Rotational molding					●	●	●	●	
	Thermo-forming					●	●	●		
	Polymer casting					●	●	●	●	
	Resin-transfer molding						●	●	●	●
	Filament winding									●
	Lay-up methods									●
	Vacuum bag									●
Joining	Adhesives	●	●	●	●	●	●	●	●	●
	Welding, metals	●	●							
	Welding, polymers					●	●	●	●	
	Fasteners	●	●	●	●	●	●	●	●	●
Finishing	Precision machining	●	●				●	●		●
	Grinding	●	●	●	●					●
	Lapping	●	●	●	●					●
	Polishing	●	●	●	●		●	●		●

Electric plug

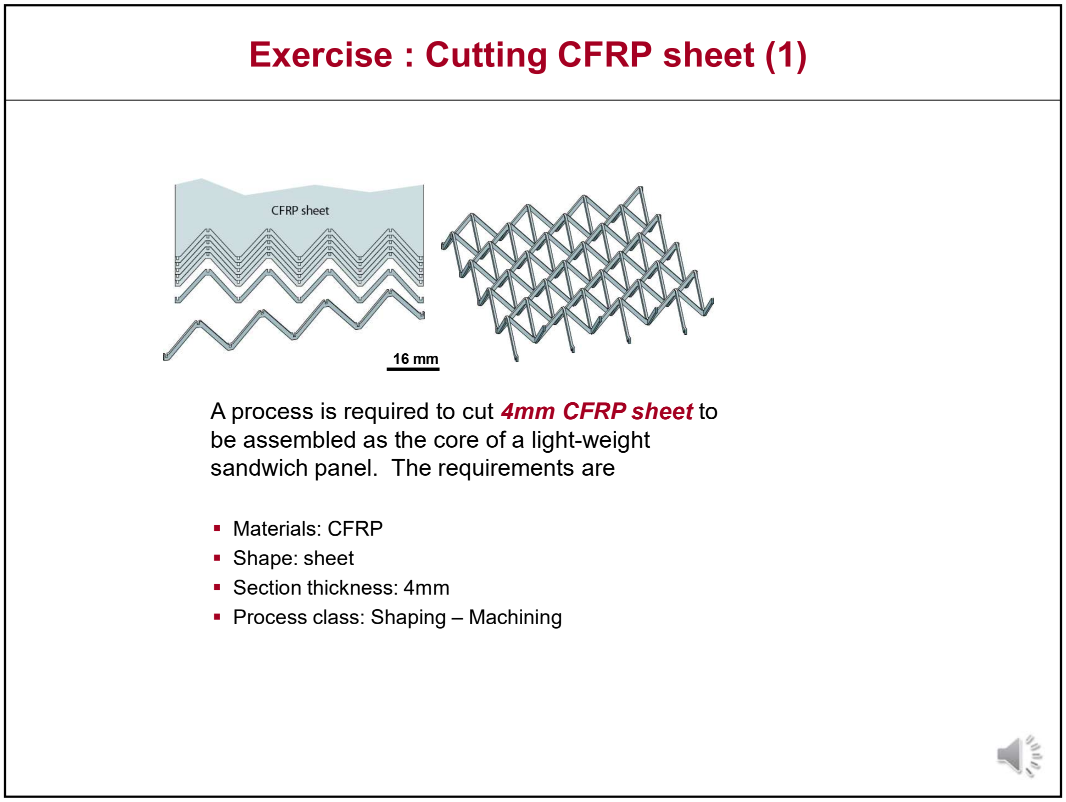
Elevator quadrant

Ceramic valve

The Process-Shape Matrix



	Circular prismatic	Non-circular prismatic	Flat sheet	Dished sheet	3-D solid	3-D hollow
Sand casting	●	●			●	●
Die casting	●	●			●	●
Investment casting	●	●			●	●
Low pressure casting	●	●			●	●
Forging	●	●			●	
Extrusion	●	●				
Sheet forming	●	●	●	●		
Powder methods	●	●			●	●
Electro-machining	●	●	●		●	●
Conventional machining	●	●	●	●	●	●
Injection molding	●	●			●	●
Blow molding				●		●
Compression molding			●	●	●	
Rotational molding				●		●
Thermo-forming				●		
Polymer casting	●	●			●	●
Resin-transfer molding	●	●	●	●	●	●
Filament winding	●	●		●		●
Lay-up methods			●	●	●	
Vacuum bag			●	●		

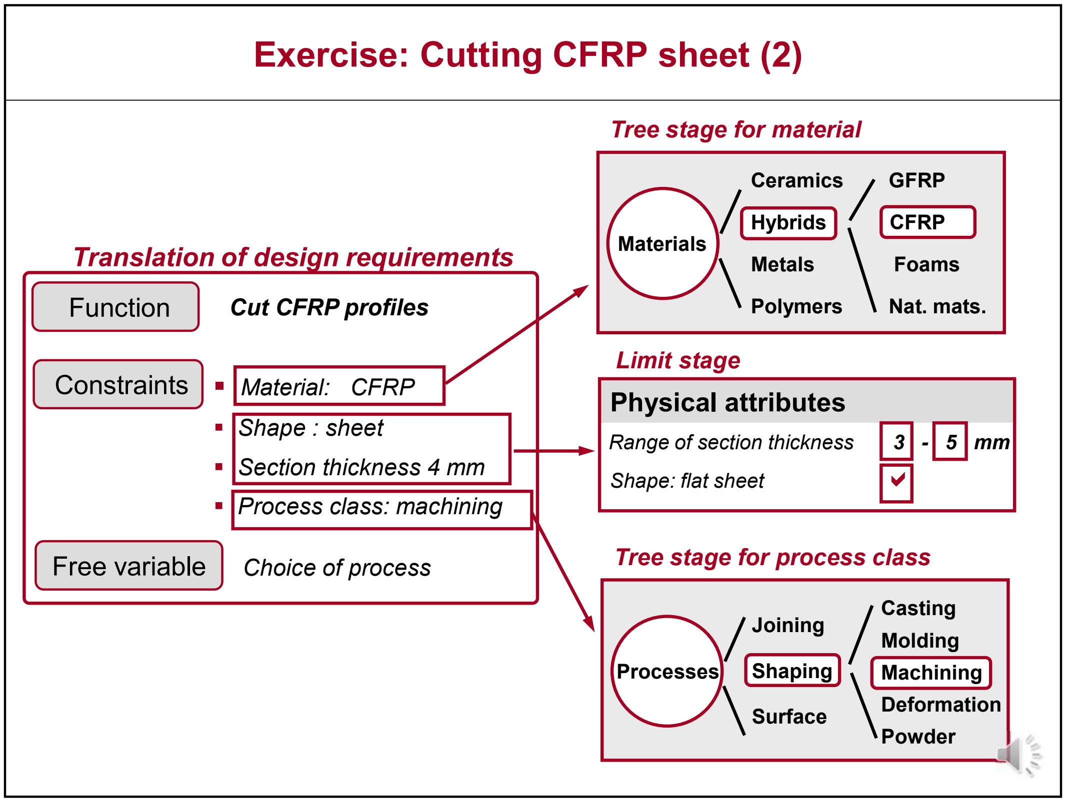


Exercise : Cutting CFRP sheet (1)

A process is required to cut ***4mm CFRP sheet*** to be assembled as the core of a light-weight sandwich panel. The requirements are

- Materials: CFRP
- Shape: sheet
- Section thickness: 4mm
- Process class: Shaping – Machining

This is the first of three **exercises** in process selection. Each has frames presenting the problem, implementing the selection and listing the results. This exercise is to select a **shaping process**. The ultra lightweight sandwich core is to be made by cutting 3 mm CFRP sheet to the profile shown on the left; the lay-up of the sheet is such that fibers in alternate layers lie parallel to the arms of the profile. The cut profiles slot together and are epoxy-bonded at the nodes. The task is to select a process for cutting the profiles from the sheet.



Exercise: Cutting CFRP sheet (2)

Translation of design requirements

Function — ***Cut CFRP profiles***

Constraints
- *Material: CFRP*
- *Shape : sheet*
- *Section thickness 4 mm*
- *Process class: machining*

Free variable — *Choice of process*

Tree stage for material

Limit stage

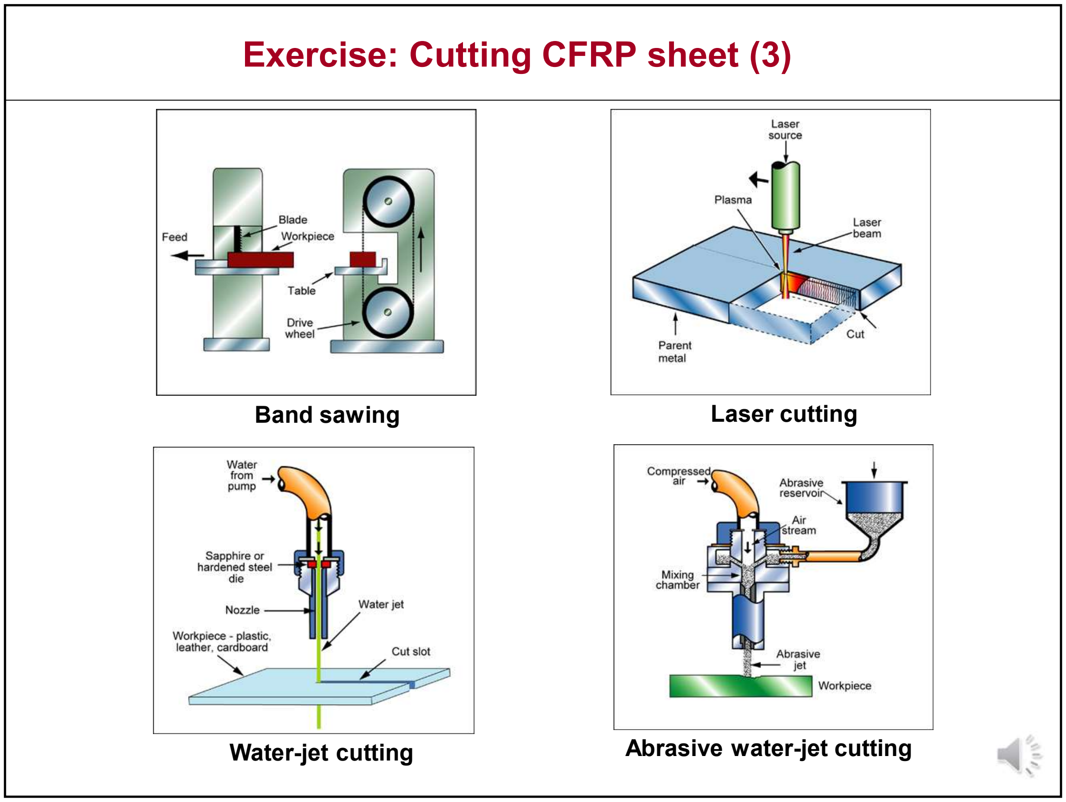
Physical attributes

Range of section thickness 3 - 5 *mm*

Shape: flat sheet ☑

Tree stage for process class

The selection is done by applying a constraint on thickness, a tree stage to isolated processes that can shape CFRP and a second tree stage to limit the choice to the Machining class of the Shaping family. The results are shown in the next frame.



Exercise: Cutting CFRP sheet (3)

Band sawing

Laser cutting

Water-jet cutting

Abrasive water-jet cutting

Applying the constraints listed on the previous frame gives the four cutting processes shown here. In practice, water-jet cutting was used to cut the profiles.

The main points

- Processes can be organised into a tree structure containing records for structured data and supporting information
- The structure allows easy searching for process data
- Select first on primary constraints
  - **Shaping:** *material, shape and batch size*
  - **Joining:** *material(s) and joint geometry*
  - **Surface treatment**: *material and function of treatment*
- Then add secondary constraints as needed.
- **Documentation** in CES, and other data bases

Processes can be classified and information about them stored and manipulated in ways that parallel those for materials. In this Unit we have explored:

- How information for processes can be **organized** in a hierarchical structure
- How to **find** information for shaping, joining and surface treatment, and
- How processes are **selected** to meet a set of constraints by using simple screening stages.

The final choice of process is guided by the insight derived from the search for **Documentation**, and by a more detailed analysis of costs.

Exercise: Material & Surface Treatment

1.) Find a ***coating material*** with the following properties **and** appropriate ***application techniques***:

- Material with high hardness: > 1900 HV
- Fracture toughness: > 7 MPa.m^1/2
- Excellent oxidation resistance up to 500 ^oC
- Thermal conductivity: > 100 W/mK
- Thermal expansion coefficient: > 2 µstrain/^oC

→

2.) Find a ***coating material*** with the following properties and appropriate ***application techniques***:

- Material with high hardness: > 1100 HV
- Fracture toughness: > 5 MPa.m^1/2
- Very good wear resistance
- Exellent oxidation resistance up to 500 ^oC
- Thermal conductivity < 2 W/mK

→

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Exercise: Material & Surface Treatment

3.) Find ***coating materials*** with the following properties **and** appropriate ***application techniques***:

- Material with high hardness: > 3000 HV
- Melting Point: > 3500 ^{o}C
- Very good wear resistance
- Very good oxidation resistance up to 500 ^{o}C

→

4.) Find a ***material*** with the following properties and appropriate ***Joining techniques***:

- Density: < 30 kg/m^3
- Service Temperature: at least 80 ^{o}C
- Thermal conductivity < 0.03 W/mK
- Strong acids resistance: Excellent →
- Joining methods: All geometries, discrete and continuous, all loadings, short set up time (<0.2hr)
- Low labour intensity →

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Exercise: Material & Surface Treatment

5.) Find an appropriate ***coating application technique***:

- For materials with good wear resistance
- Smooth surfaces not required: C
- Relative equipment cost: medium
- Labor intensity: medium →

6.) Find coating **materials** with the following properties and appropriate **application techniques**:

- Elongation: 2-10%
- Hardness: 280-340 HV
- Melting Point: > 1900 ^{o}C
- Thermal conductivity: > 140 W/mK
- Excellent against strong acids
- Can be recycled: Yes

→

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Appendix

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