Ceramics and glasses for biomedical applications

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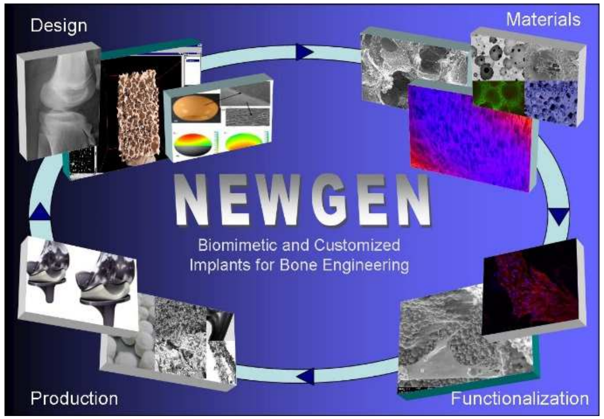

2nd Training School
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Outline

Introduction

- What are ceramics?
- Main characteristics
- Classification

Manufacturing

- Batch preparation of powdery materials
- Shaping
- Densification

Structural ceramics materials

- Area of applications
- Properties comparison of some particular ceramics
- Coatings/Porous ceramics

Bioceramics

- Bio-inert
- Bio-active

Bioglasses

INTRODUCTION

Introduction

What are ceramics?

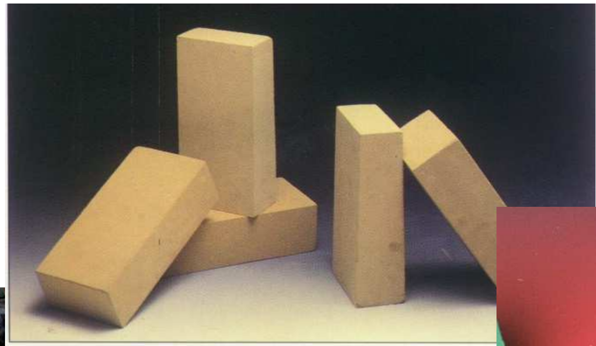
→ Inorganic and non-metallic materials, having high melting points and therefore requires high temperatures for their processing

→ Ionic/covalent bond between metallic and non metallic elements (O, N, C, B)

- Al_2O_3, ZrO_2, MgO
- SiC, Si_3N_4, WC, ZrB_2

→ This includes : tiles, bricks, cements, concretes, refractories, advanced ceramics, … and glasses





Introduction

Main characteristics

- Brittle (poor ductility, poor tensile strength)
- Chemically inert, stable
- Hard
- Wear-resistant
- A variety of electrical and thermal properties
- Refractory
- Non-magnetic

Some exceptions

- « YBaCuO » → Superconductor
- (Ba, Sr)O.6Fe_2O_3 → Hard magnet
- Partially Stabilized Zirconia → High toughness

Introduction

Classification?

- Variety of materials, variety of properties… → how to classify them?

Traditional Ceramics

Advanced Ceramics

Introduction

Classification?

- Variety of materials, variety of properties… → how to classify them?

Traditional Ceramics

- **Clay products**
- **Refractories**
- **Cements**
- **Abrasives**

Advanced Ceramics

Introduction

Classification?

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Traditional Ceramics

- Clay products
- **Refractories**
- Cements
- Abrasives

Advanced Ceramics

Introduction

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Traditional Ceramics

- Clay products
- Refractories
- **Cements/Castables**
- Abrasives

Advanced Ceramics

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Advanced Ceramics

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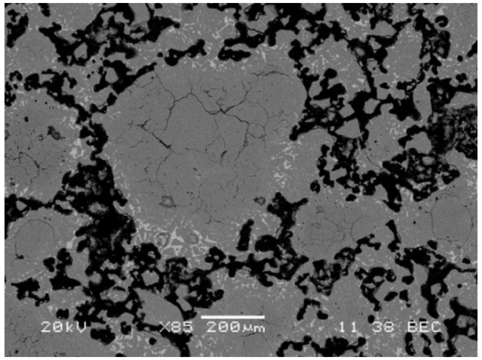
Traditional Ceramics

- **Clay products**
- **Refractories**
- **Cements/Castables**
- **Abrasives**

Advanced Ceramics

- **Raw materials :** clay, feldspath, sand, etc.
- **Physical transformation :** grinding, milling, filtration, etc.
- **Grain size :** from several μm to several mm



Introduction

Classification?

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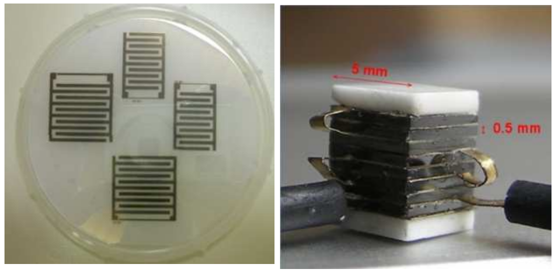
Traditional Ceramics

Advanced Ceramics

- **Electro-ceramics**
- Magnetic ceramics
- Optical ceramics
- Structural ceramics

Electronic substrates (AlN)

Piezo-electric ceramics ($BaTiO_3$, PZT, etc.)



(Semi-)conducting ceramics (SiC, ZnO, etc.) → Varistors, gas sensors, etc.

Introduction

Classification?

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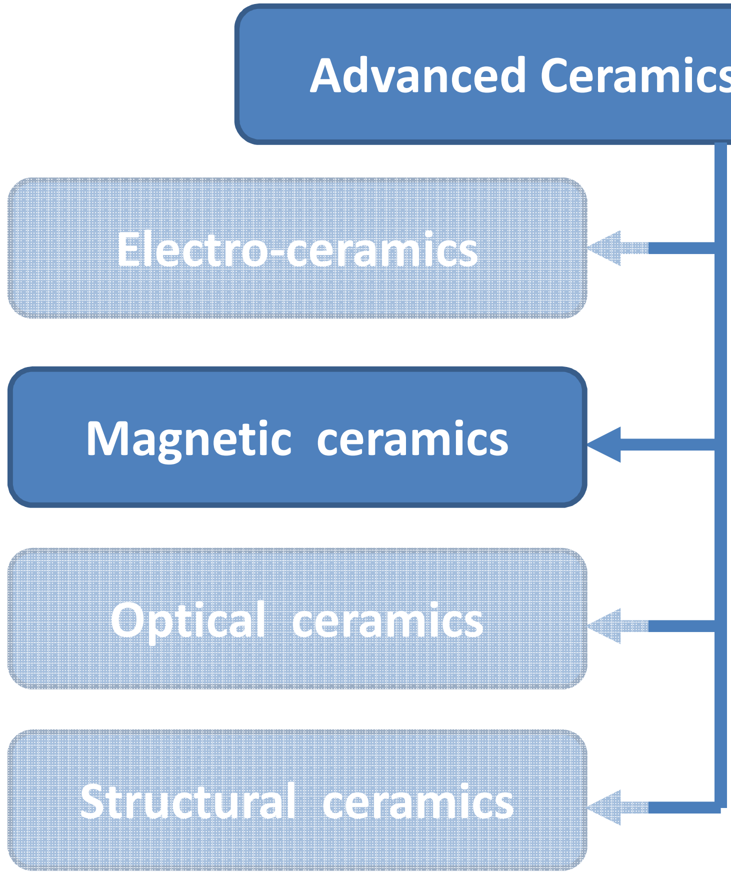
Traditional Ceramics



Ferrite with Fe_2O_3 as major constituent ($MnO.Fe_2O_3$, $SrO.6Fe_2O_3$, etc.)

→ Miniature transformers
→ Microwave absorbing paints (defence)
→ Isolators and band pass filters
→ NMR and drug delivery
→ Magnetic sensors
→ Robotics, data storage, energy storage, etc.

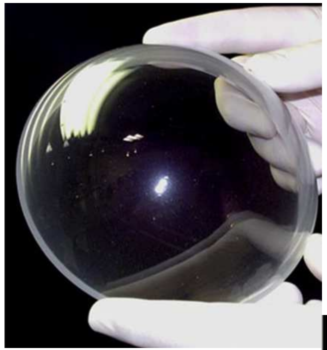
Introduction

Classification?

- Variety of materials, variety of properties… → how to classify them?

Traditional Ceramics

Spinel, YAG, etc.



Advanced Ceramics

- Electro-ceramics
- Magnetic ceramics
- **Optical ceramics**
- Structural ceramics

Introduction

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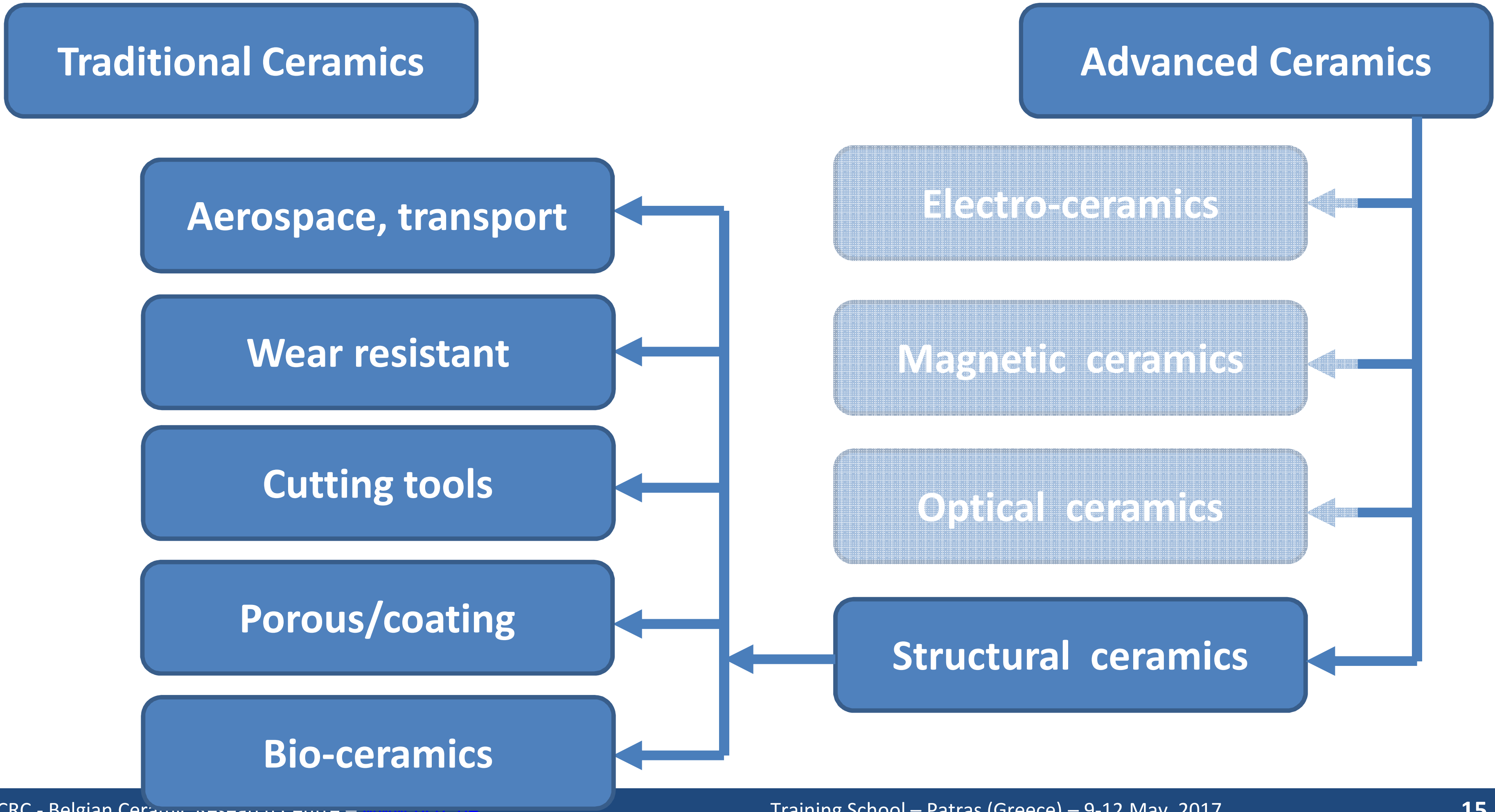

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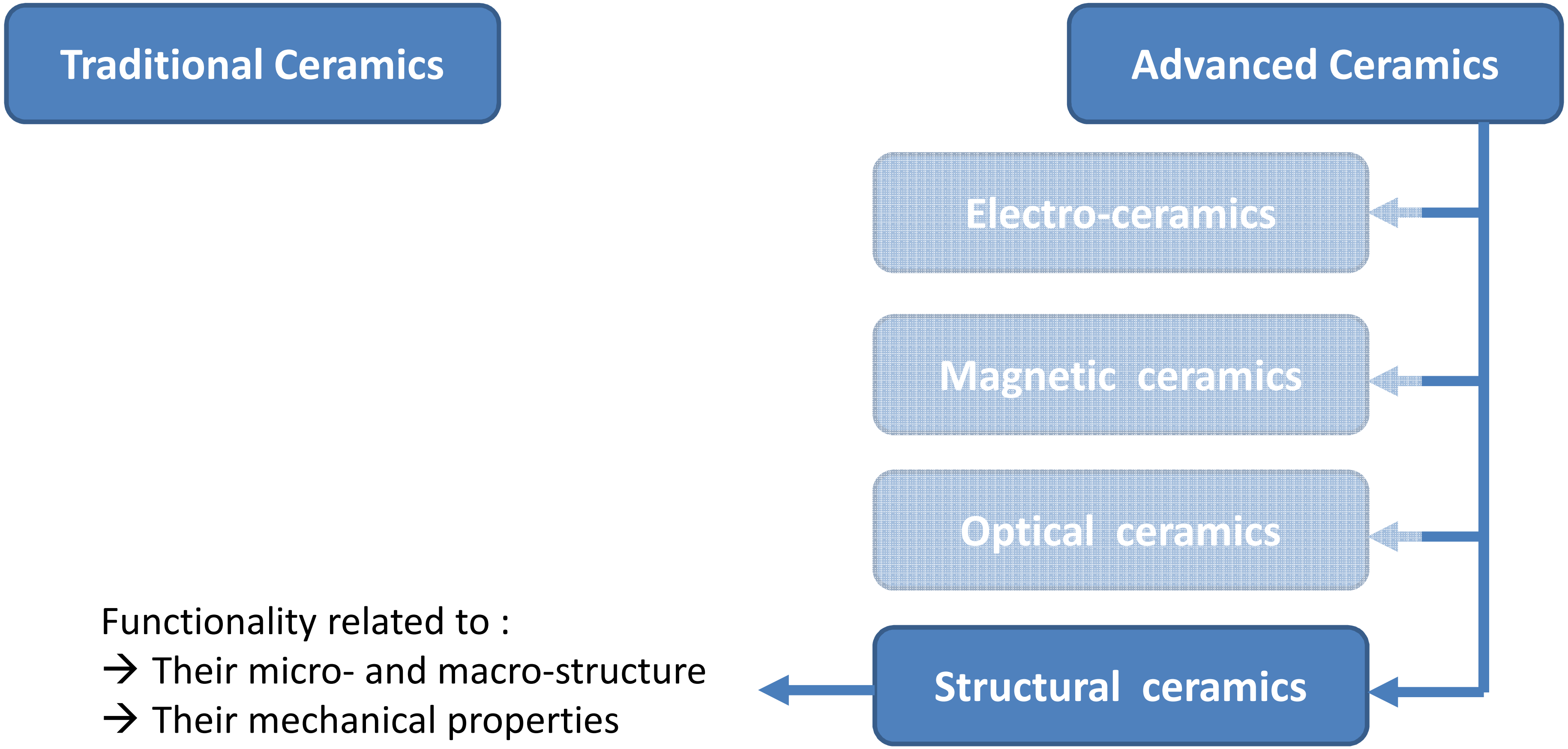


Introduction

Classification?

➢ Variety of materials, variety of properties… → how to classify them?

Traditional Ceramics

Advanced Ceramics

- **Raw materials :** synthetic powders
- **Ideally :** no physical transformation
- **Grain size:** < µm

Electro-ceramics

Magnetic ceramics

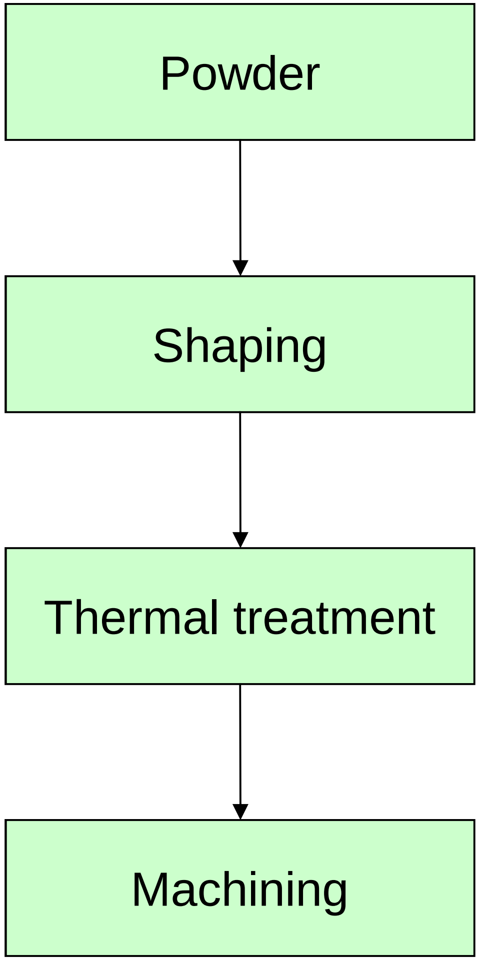
Optical ceramics

Structural ceramics

MANUFACTURING

Manufacturing

- ➢ Ceramic manufacturing = sequential process :



→ Importance of each step!

→ Need to control raw material preparation

→ The powder synthesis will impact the final material properties

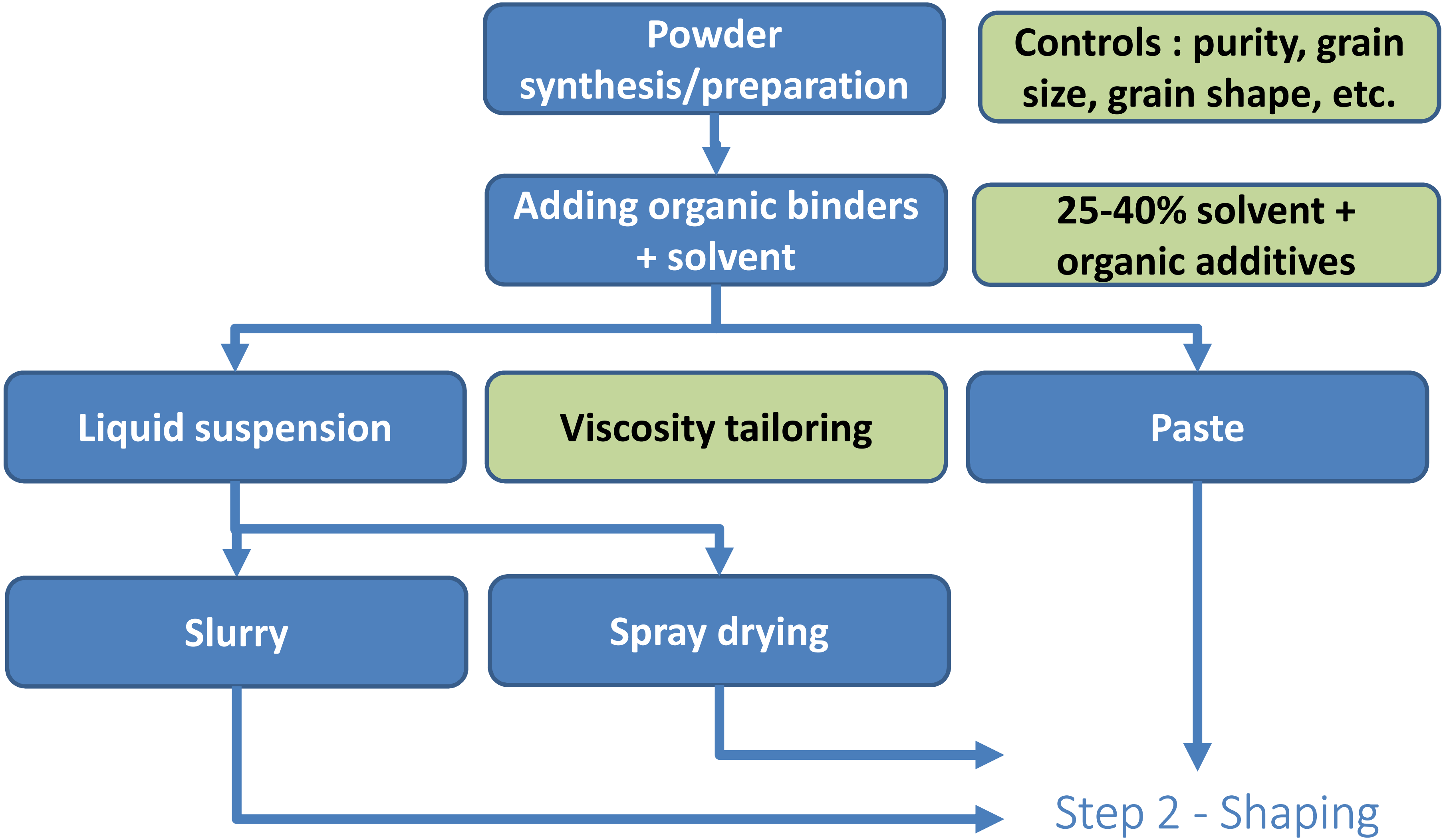
- ➢ Grain size (<µm)
- ➢ Grain size distribution
- ➢ Grain shapes
- ➢ Non agglomerate state
- ➢ Chemical purity
- ➢ Crystal phase

→ Synthesis methods are classified according to state of the reaction material

- solid-solid
- including a liquid (aquous or organic)
- including a gas

Manufacturing

Step 1 - Batch preparation of powdery raw materials



Manufacturing

Step 1 - Batch preparation of powdery raw materials

Liquid suspension

Slurry

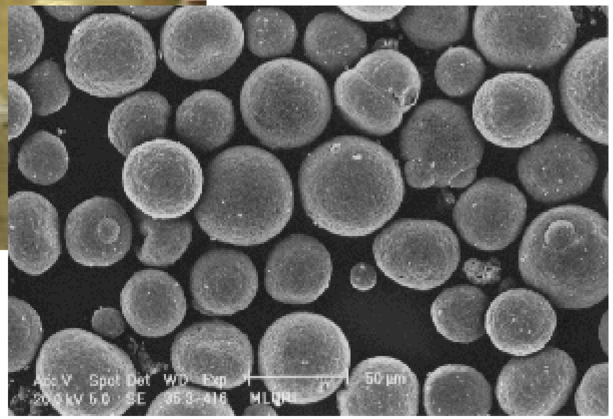
Step 2 - Shaping

Manufacturing

Step 1 - Batch preparation of powdery raw materials

Liquid suspension

Spray drying



Spray dried kaolinite

Step 2 - Shaping

Manufacturing

Step 1 - Batch preparation of powdery raw materials

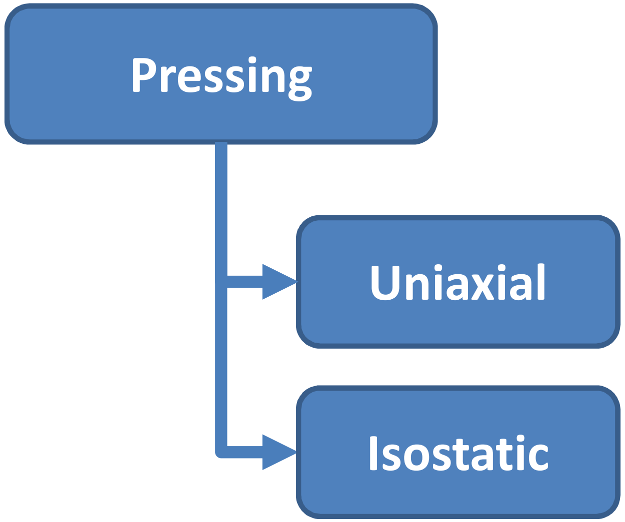
Powder synthesis/preparation

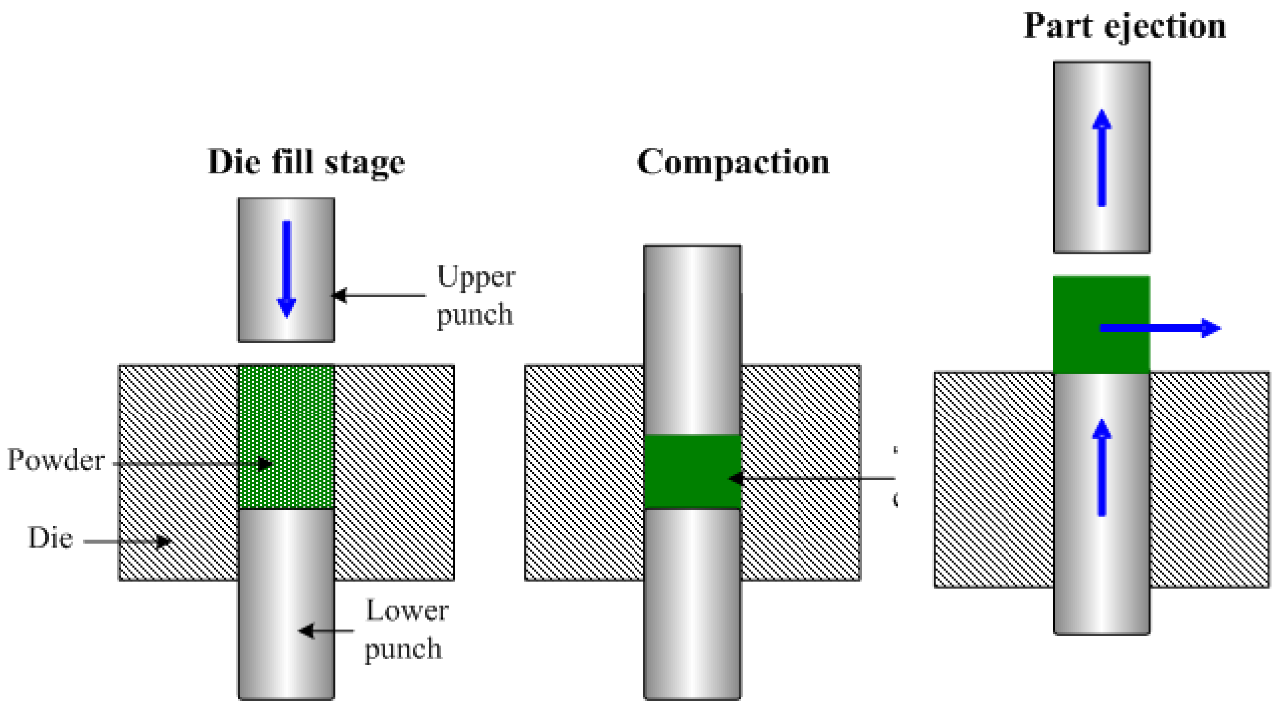
Paste

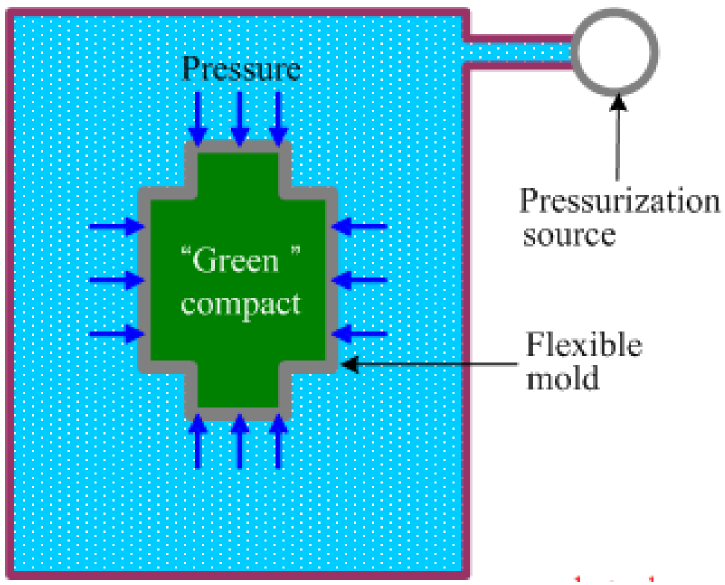
Step 2 - Shaping

Manufacturing

Step 2 - Shaping

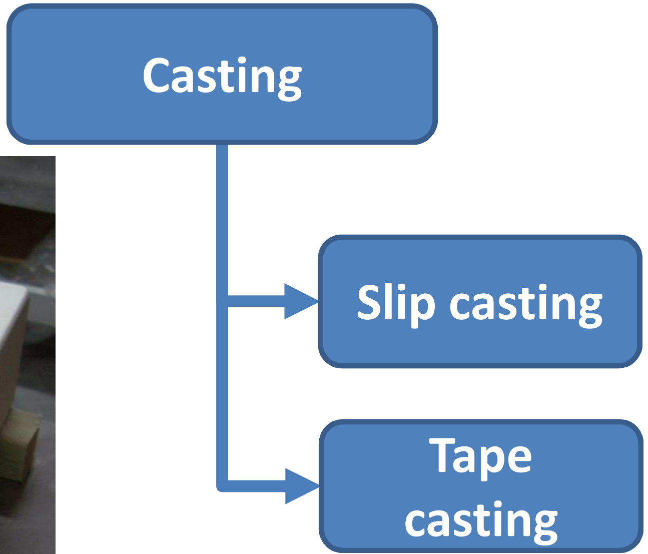


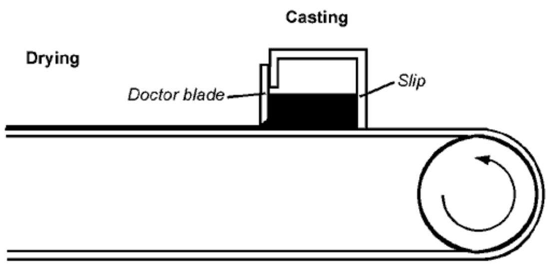




Manufacturing

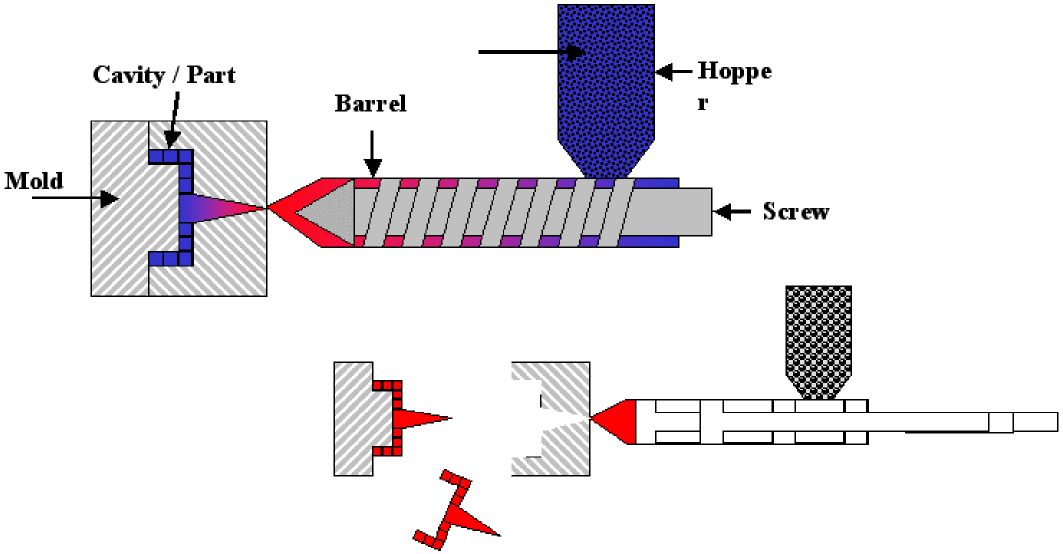
Step 2 - Shaping

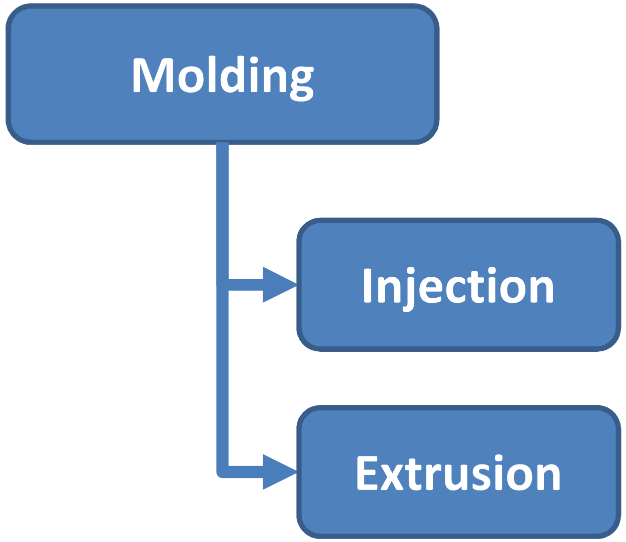


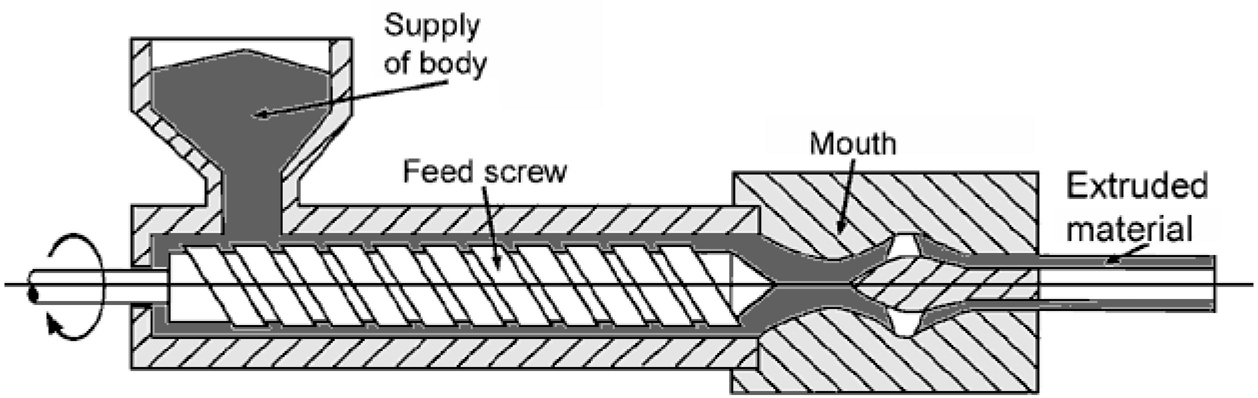


Manufacturing

Step 2 - Shaping







Manufacturing

Step 2 - Shaping

µ-machining

Robocasting
3D printing
SLA

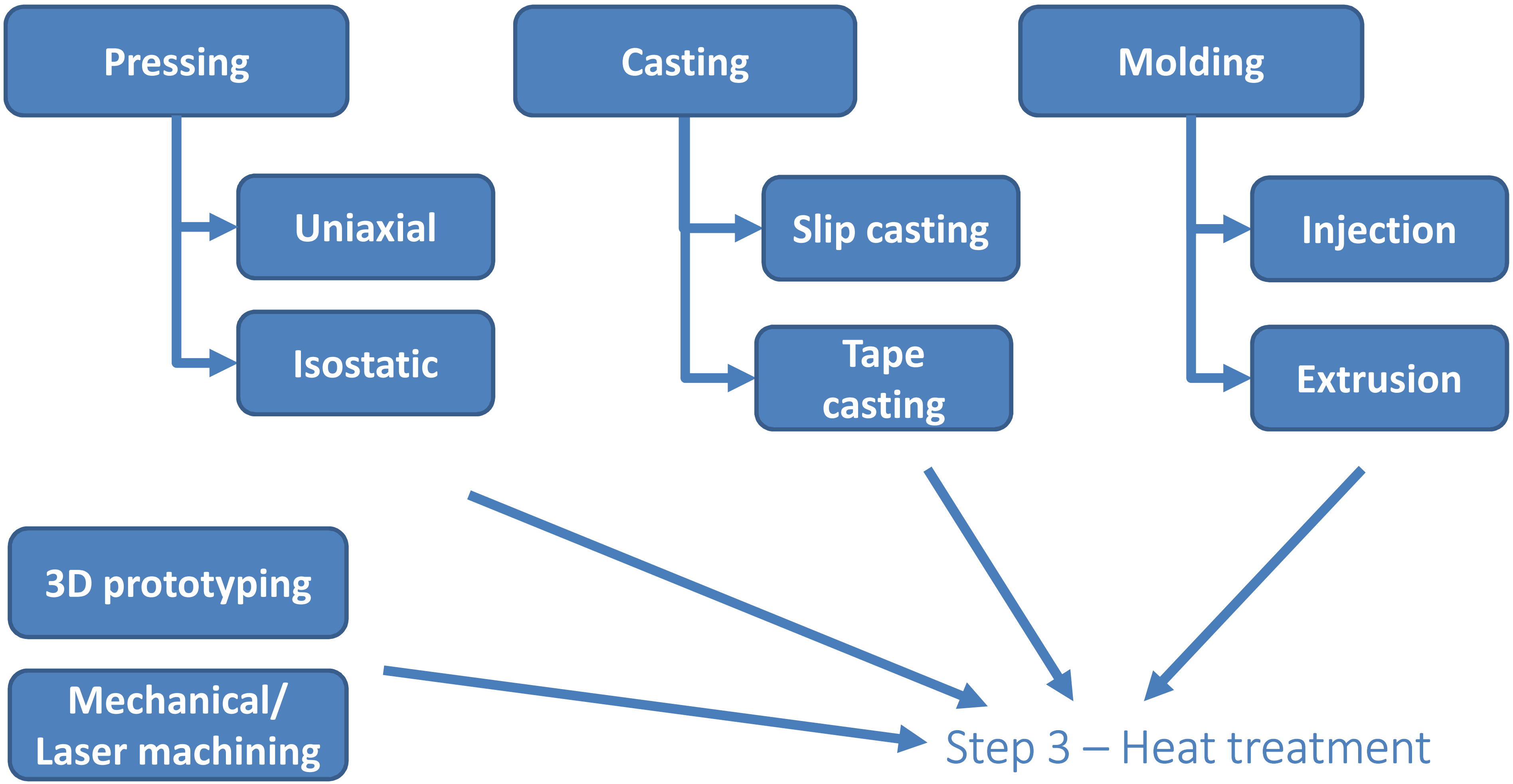
3D prototyping

Mechanical/
Laser machining

Laser milling
CRIBC Patent
WO/2012/164025 -
PCT/EP2012/060261

Manufacturing

Step 2 - Shaping



Manufacturing

Step 3 – Heat treatment

Debinding

Low temperature (300-600°C) in order to eliminate organics

↓

Sintering

= all phenomena occuring during heating, leading to the densification of a powder compact

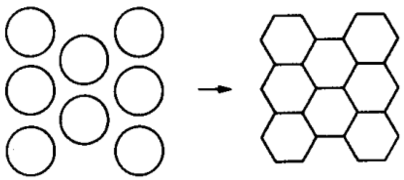
Manufacturing

Step 3 – Heat treatment

Debinding → **Low temperature (300-600°C) in order to eliminate organics**

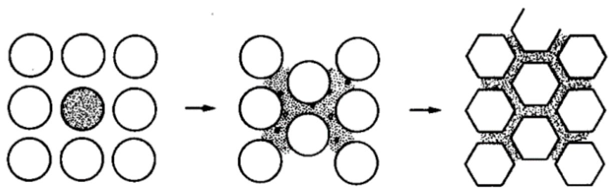
Sintering → **= all phenomena occuring during heating, leading to the densification of a powder compact**

3 main categories :



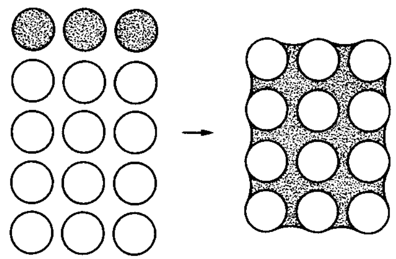
Solid-State Sintering

No liquid phase



Liquid-Phase Sintering

$V_{liquid} < V_{pores}$



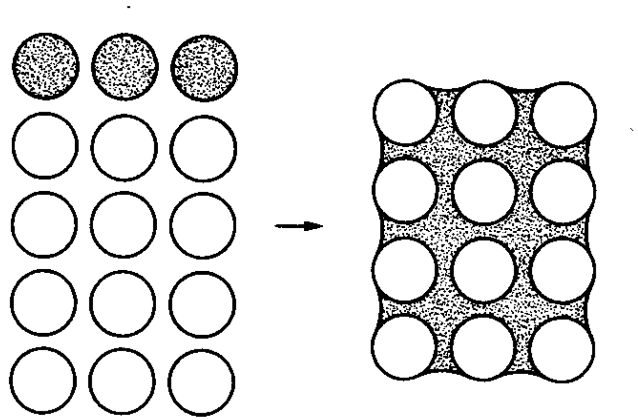
Viscous-Flow Sintering

$V_{liquide} >>> V_{pores}$

Manufacturing

Step 3 – Heat treatment

Viscous flow sintering



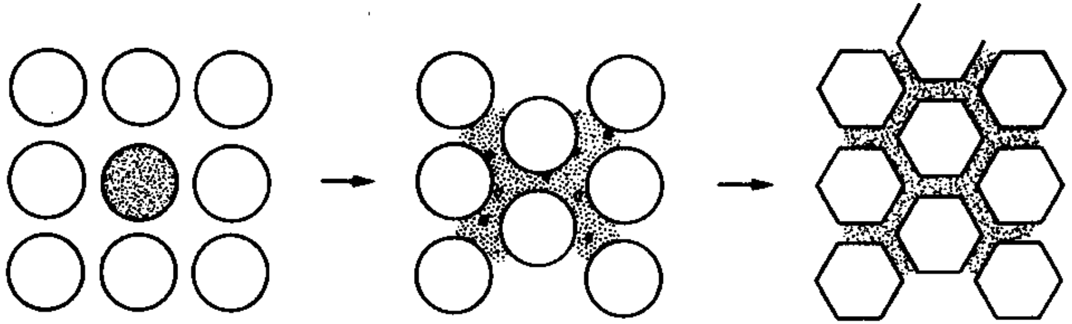
20% of initial solid particles are converted into liquid. Consolidation of materials through a liquid flux, under the action of capillary forces, and formation of a crystalline or vitrous phase during cooling.

Traditional ceramics obtained from natural raw materials

Manufacturing

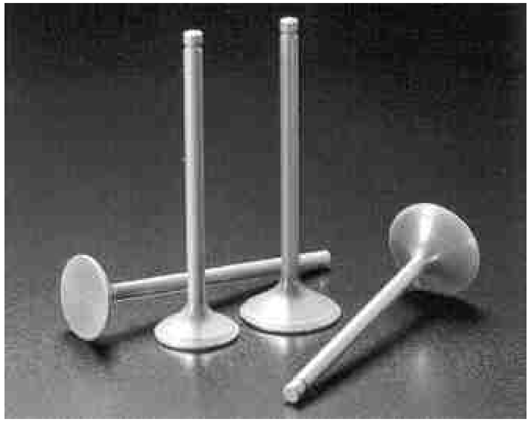
Step 3 – Heat treatment

Liquid phase sintering



Selection of constituents and sintering temperature such as a small quantity of liquid is formed, allowing an easier diffusion of matter (soluble in the liquid phase) within this liquid phase

Refractories, alumina isolators, silicon nitride parts, etc.

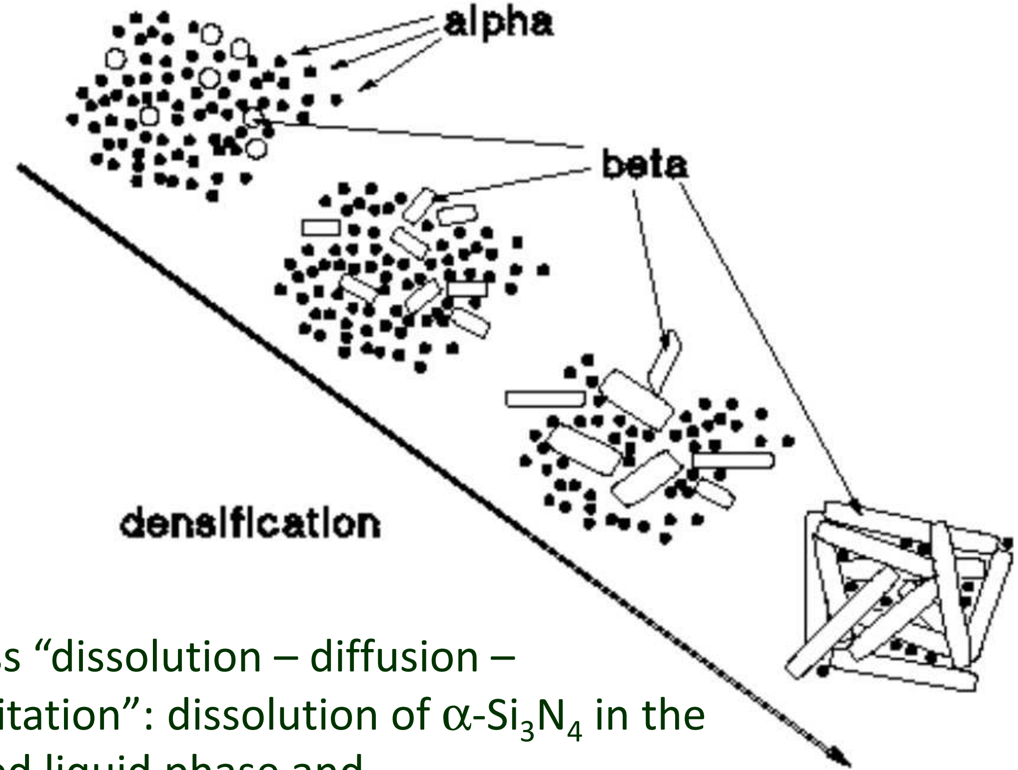


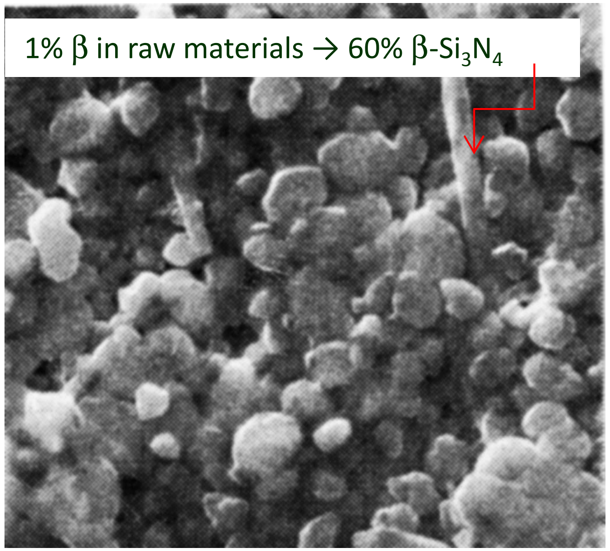
Manufacturing

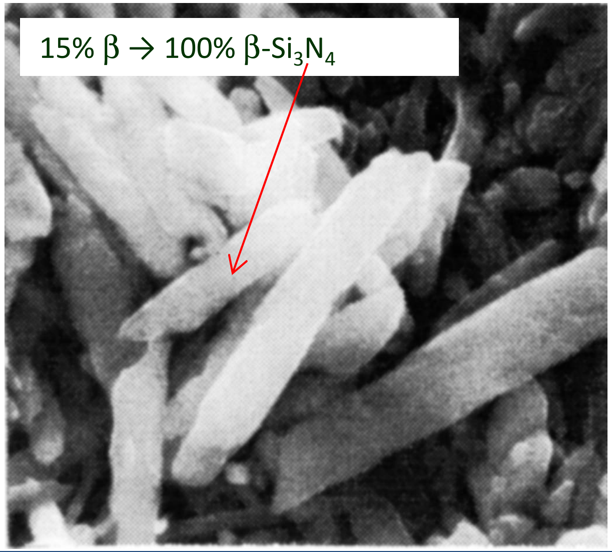
Step 3 – Heat treatment

Liquid phase sintering

Liquid phase : surface SiO_2 + MgO, Y_2O_3, CaO…







Process "dissolution – diffusion – precipitation": dissolution of α-Si_3N_4 in the silicated liquid phase and precipitation/crystallisation on the nuclei of β- Si_3N_4

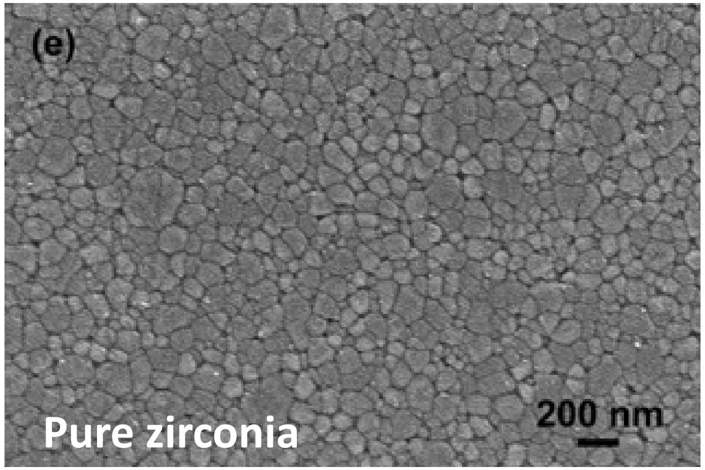
Manufacturing

Step 3 – Heat treatment

Solid-state sintering

Typical/ideal microstructure :

Equiaxial grains, with few residual porosities and no glassy phase at grain boundaries



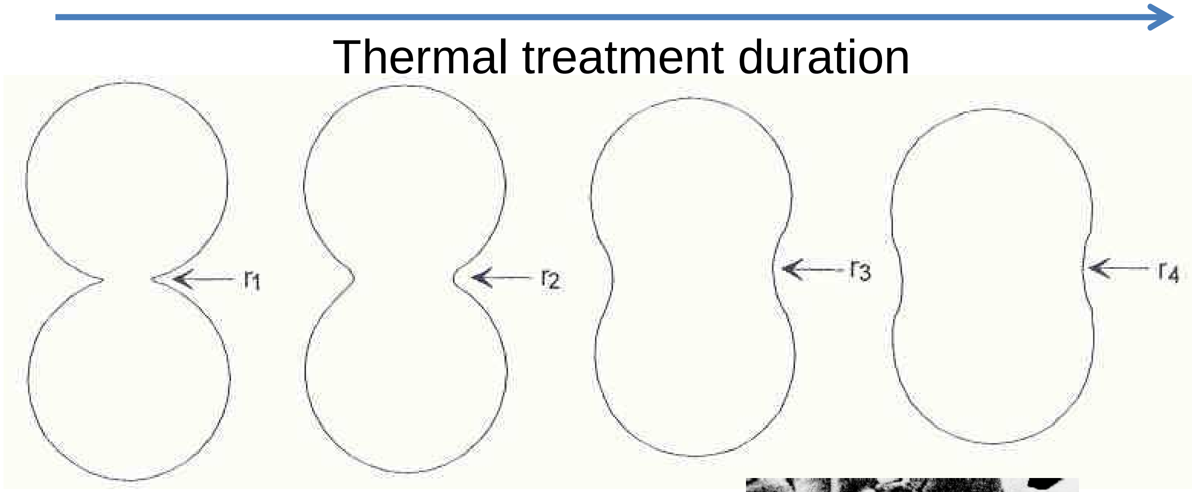
For the manufacturing of high-tech ceramics

Need for high temperature and fine grains

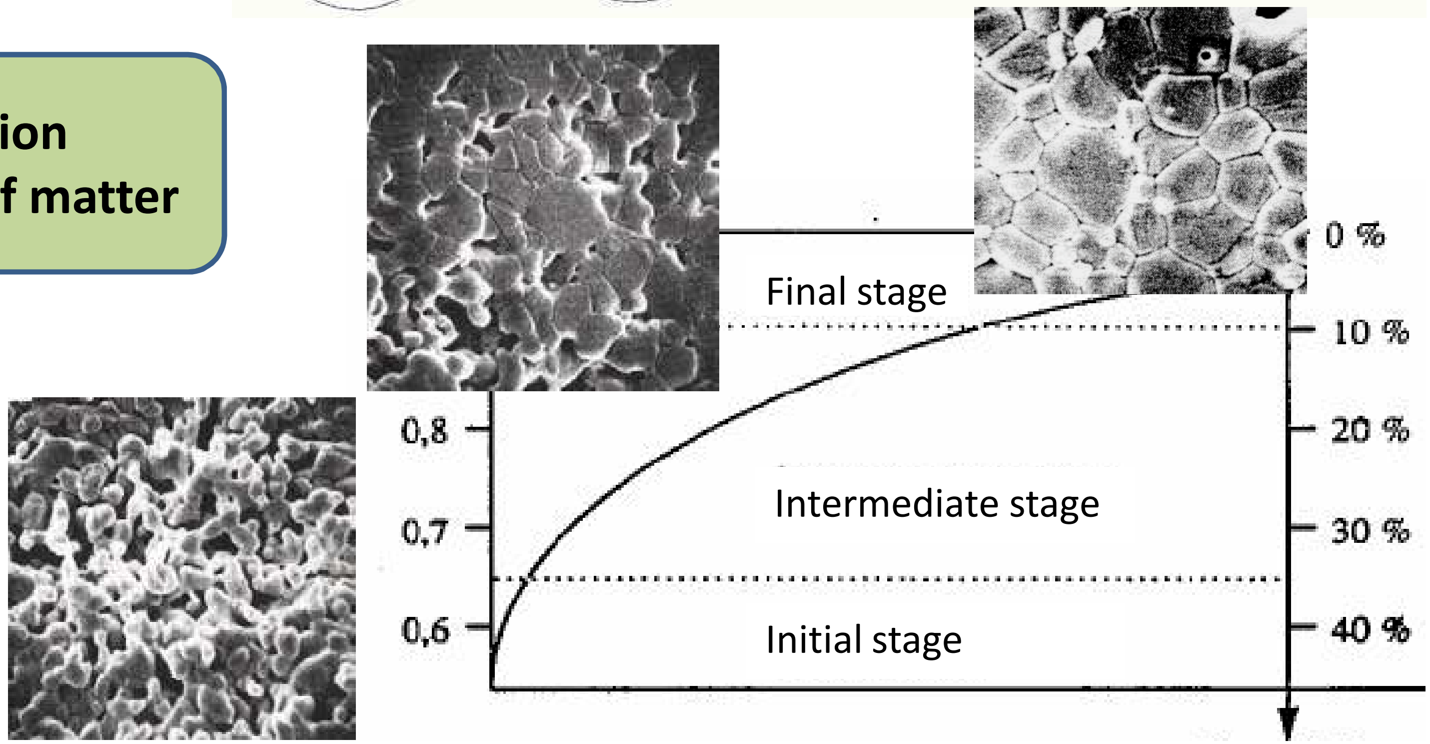
Manufacturing

Step 3 – Heat treatment

Solid-state sintering

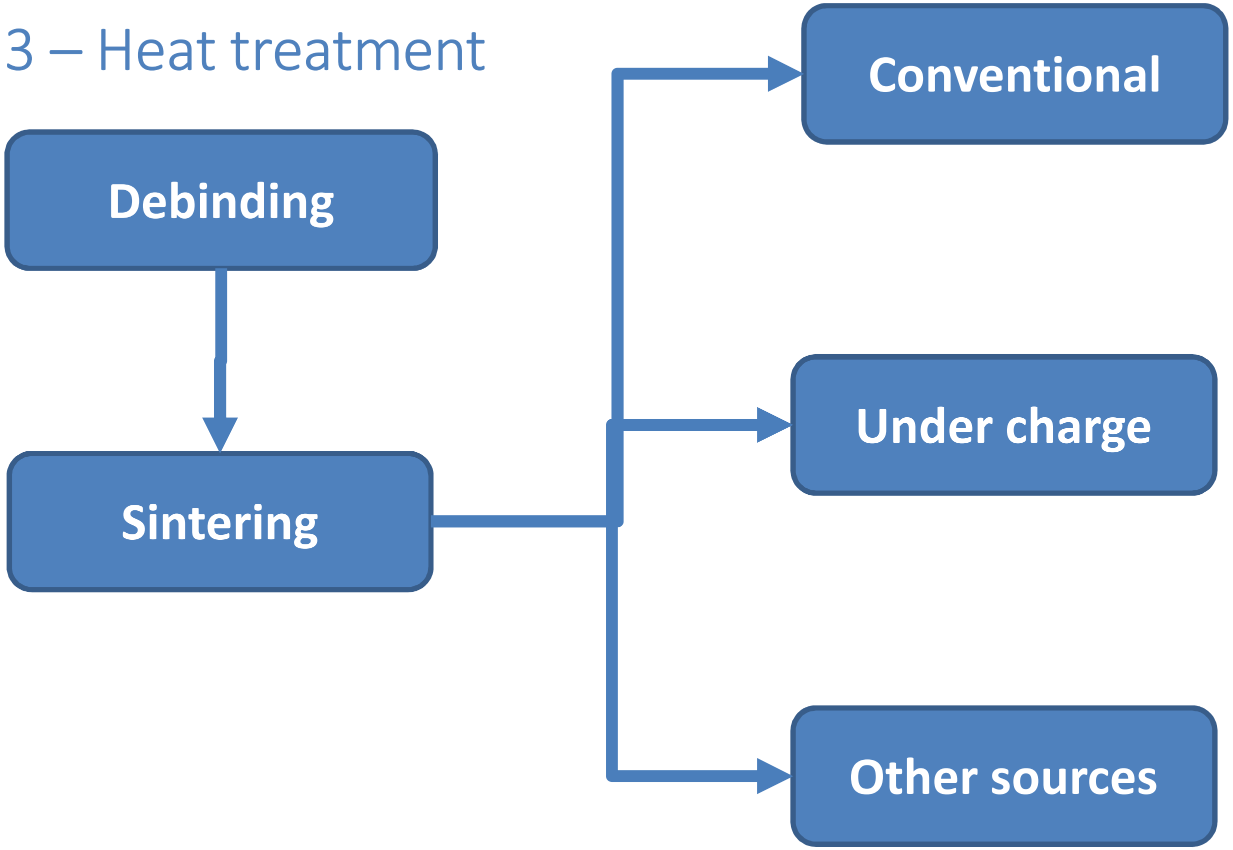


Atoms diffusion
« Necks » = sink of matter



Manufacturing

Step 3 – Heat treatment



Manufacturing

Step 3 – Heat treatment

Debinding

↓

Sintering → **Conventional**

Under air

Under vacuum
Ar, N_2, H_2, etc.

Sintering of SiC under vacuum at 2080°C (Boostec, Tarbes)

Manufacturing

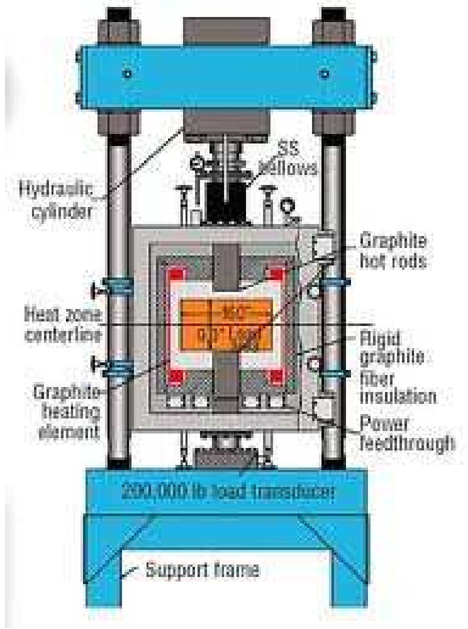
Step 3 – Heat treatment

Debinding

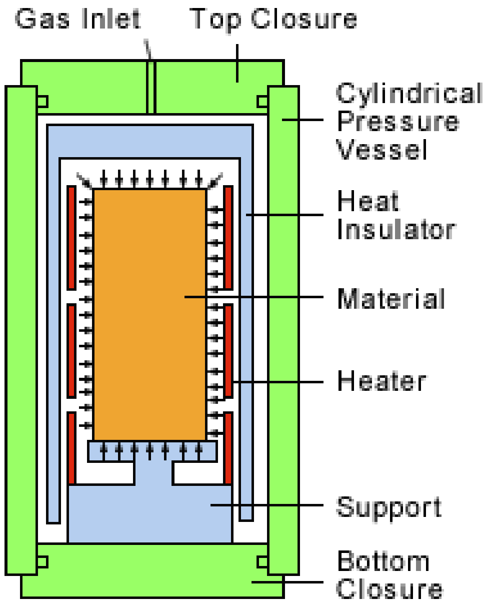
↓

Sintering → **Under charge**

HP

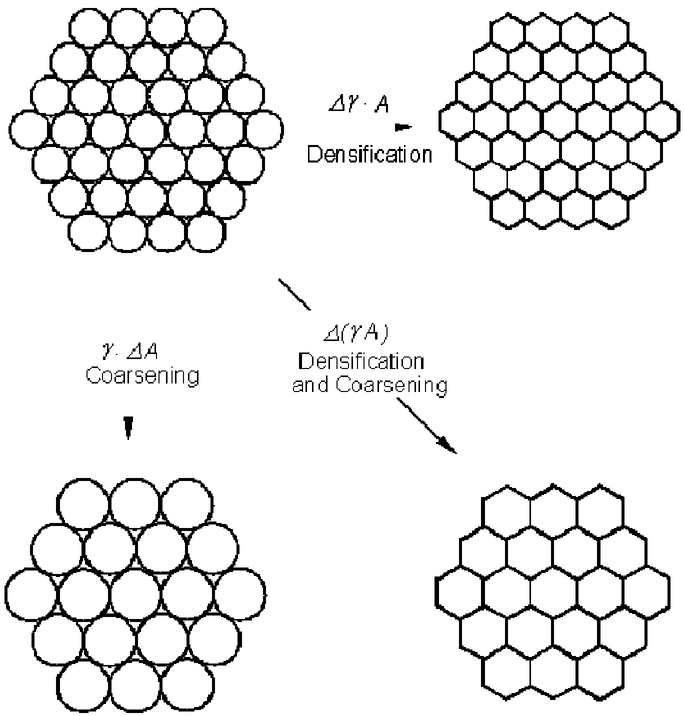


HIP

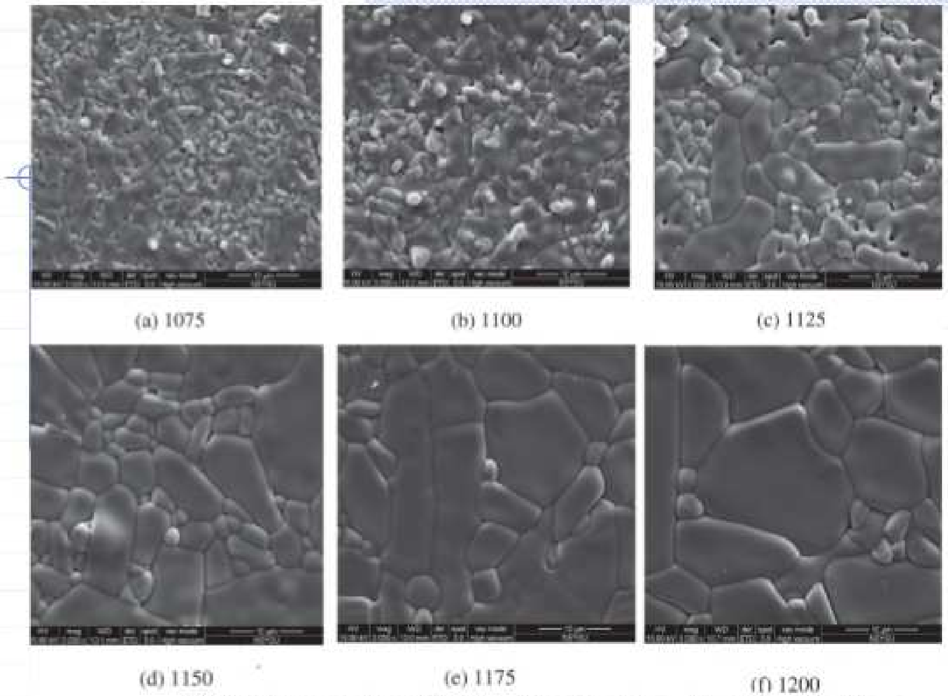


Manufacturing

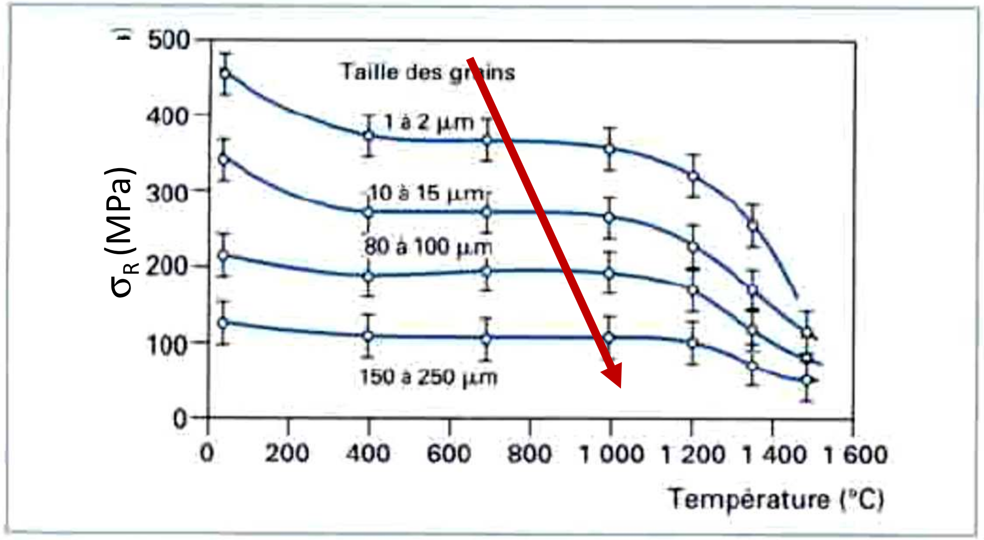
Step 3 – Heat treatment



Larger grain grow at the expense of the smaller one (Ostwald process)



SEM photographs of $[(Mg_{0.7}Zn_{0.3})]_{0.95}Co_{0.05}]_{1+\delta}(Ti_{1-x}Sn_x)O_{3+\delta}$ ($\delta = 0.02$) ($x = 0.05$) ceramics (a) 1175, (b) 1200, (c) 1225, (d) 1250, (e) 1275°C sintered at various temperatures for 4 h.

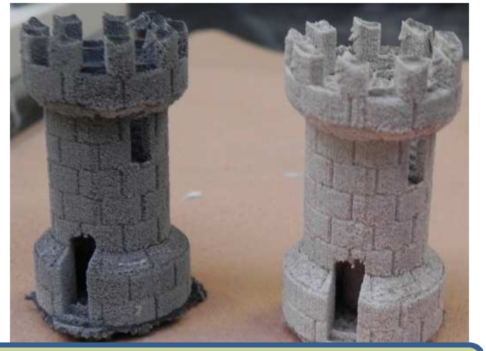


Manufacturing

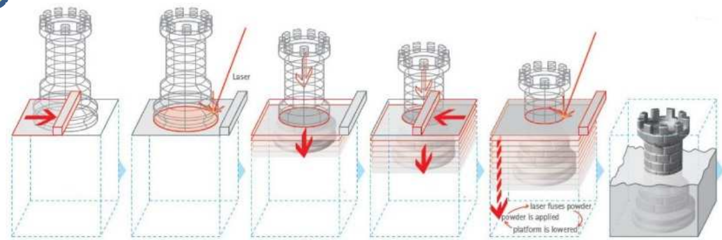
Step 3 – Heat treatment

Debinding

Microwave sintering

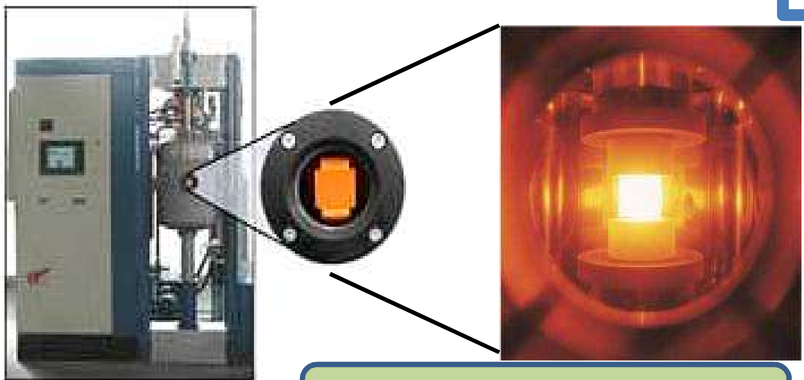


Selective laser sintering

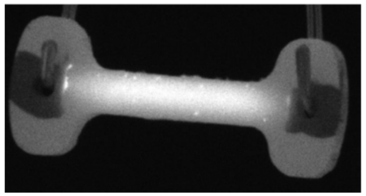


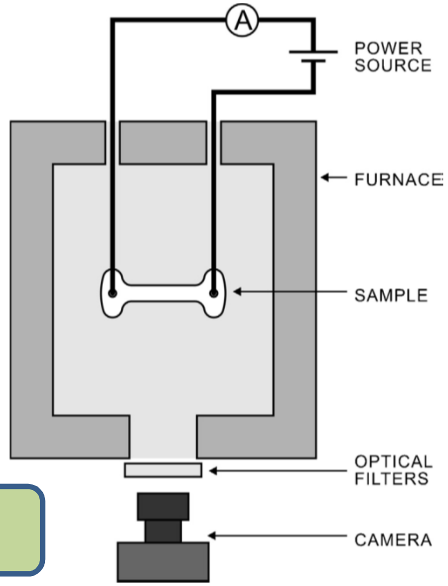
Sintering

Other sources



SPS





Flash sintering

STRUCTURAL CERAMICS

Structural ceramics

Categories of structural ceramics

Oxide

Alumina, zirconia, and their derivatives

- **Oxidation resistant**
- **Thermally stable**
- **Chemically inert**
- **Electrically insulating**
- **Low thermal conductivity**

Non-oxide

Carbides, borides, nitrides, silicides, etc.

- **Low oxidation resistance**
- **Extreme hardness**
- **Chemically inert**
- **High thermal and electrical conductivities**
- **Expensive manufacturing process**

Composites

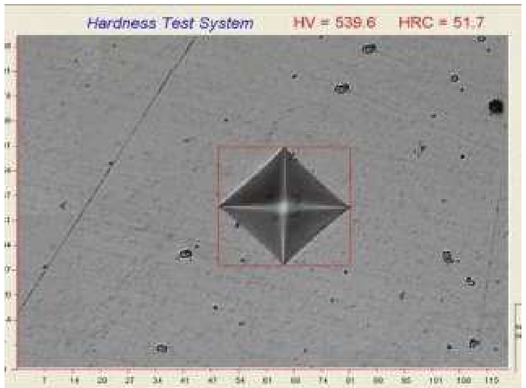
Particulate and fibre reinforced, combinations of oxides and non-oxides

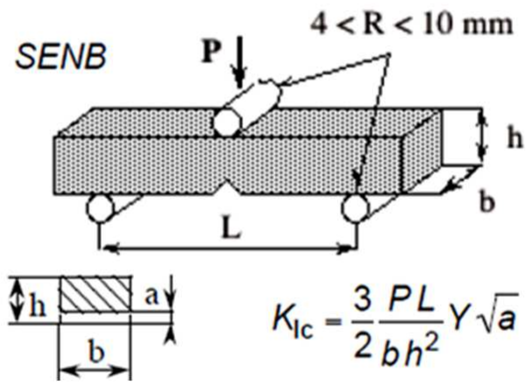
- **High toughness**
- **Variable thermal and electrical conductivities**
- **Variable oxidation resistance**
- **High cost due to complex process**

Structural ceramics

Mechanical properties

Strength	Elastic modulus	Fracture toughness
• Flexural and compressive strength • Hardness	• E, ν • Better contact damage resistance requires higher E-modulus	• Resistance to crack growth





Structural ceramics

Important aera of applications

Application aera	Required properties	Materials used
Wear parts • Pump seals • Bearings • Nozzles	High harndess Low frictional resistance Moderate strength	Alumina Silicon carbide
Cutting tools	High strength High hardness Thermal conductivity	Alumina Silicon nitride SiAlON ZTA Alumina-TiC
Engine components • Turbine rotor • Valves • Cylinder lining	High temperature strength High temperature toughness Thermal insulation	Zirconia Silicon nitride Silicon carbide
Bioceramics	High strength High toughness Inert/Bioactive/biodegradable Controlled porosity	Alumina Zirconia CaP ceramics

Structural ceramics

Properties of typical structural ceramics

Properties	Alumina	Y-TZP	SiC	Si_3N_4	Other
Compressive strength	3000 MPa	2500 MPa	2500 MPa	2800 MPa	Steel 300 MPa
Flexural strength	<600 MPa	<1200 MPa	350 MPa	1000 MPa	
K_{1C}	<5MPa.$m^{1/2}$	<12MPa.$m^{1/2}$	4-5MPa.$m^{1/2}$	6MPa.$m^{1/2}$	Steel 200MPa.$m^{1/2}$
Elastic modulus	390 GPa	250 GPa	400 GPa	300 GPa	Steel 200 GPa
Hardness	18 GPa	12 GPa	35 GPa	25 Gpa	Diamond 90 GPa

Structural ceramics

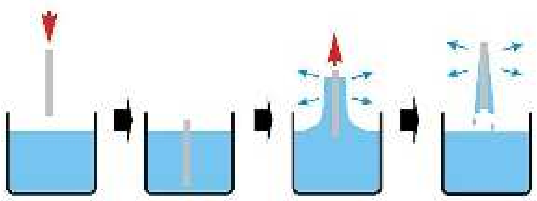
Coatings

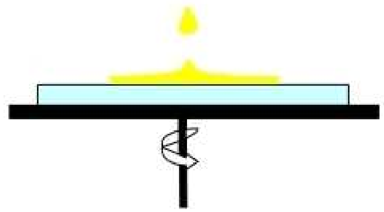
- Ceramic materials are often used as surface coating on metallic components, in order to take advantage of
  - High hardness
  - Abrasion resistance
  - Thermal insulation
  - …
- Coating of TiC, TiN, alumina on WC and high speed steel cutting tools improves their life by a factor of 2 – 5
- Zirconia coating are used as thermal barrier for engine components and for improvement of resistance to corrosion (aeronautics, aerospace, etc.)
- Hydroxyapatite coatings are also used to enhance the biocompatibility of surgical tools and medical devices

Structural ceramics

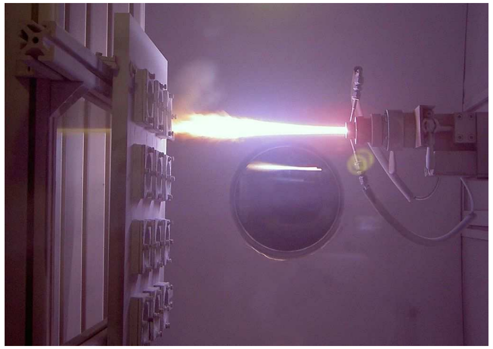
Coatings – processes used for ceramic coatings

- Sol-gel method
  - dip-coating, spin coating
  - ~10-50µm





- RF Plasma spraying
  - ~10-50µm



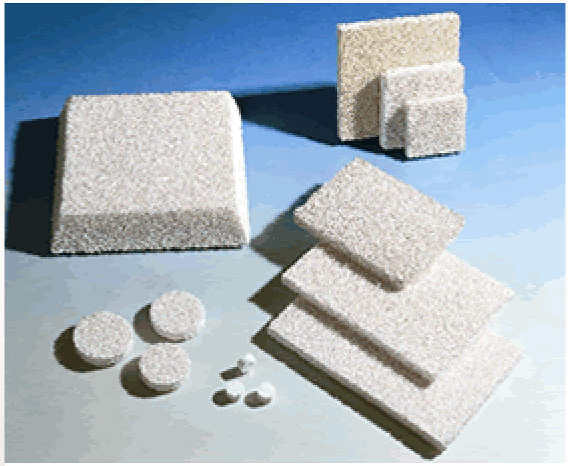
- CVD
  - ~ 10µm
- Spray pyrolysis
- Electro-phoretic deposition
  - 1 – 1000µm
- Laser Cladding
  - 0,2 – 1 mm

Structural ceramics

Porous ceramics

- Broad range of characteristics → wide variety of applications
  - Insulation

  - Membrane, filtration, catalysis



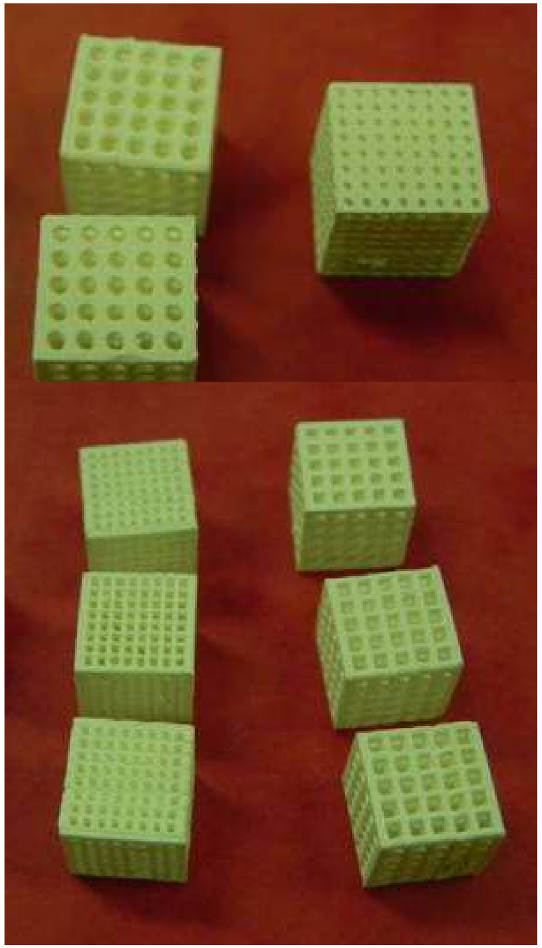
  - Biomedical applications

Structural ceramics

Porous ceramics – processing methods

- Sacrificial template – pore-forming agents
- Extrusion
- Partial sintering process
- Casting of scaffolds
- 3D prototyping
- …

→ Fine tuning of pore size distribution and pore shape

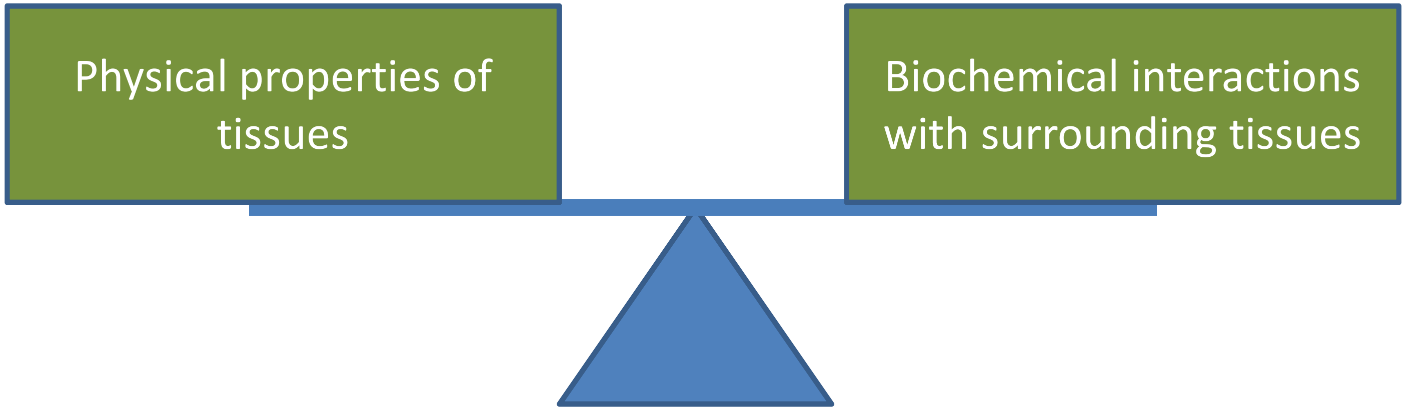


BIOCERAMICS

Bioceramics

Introduction

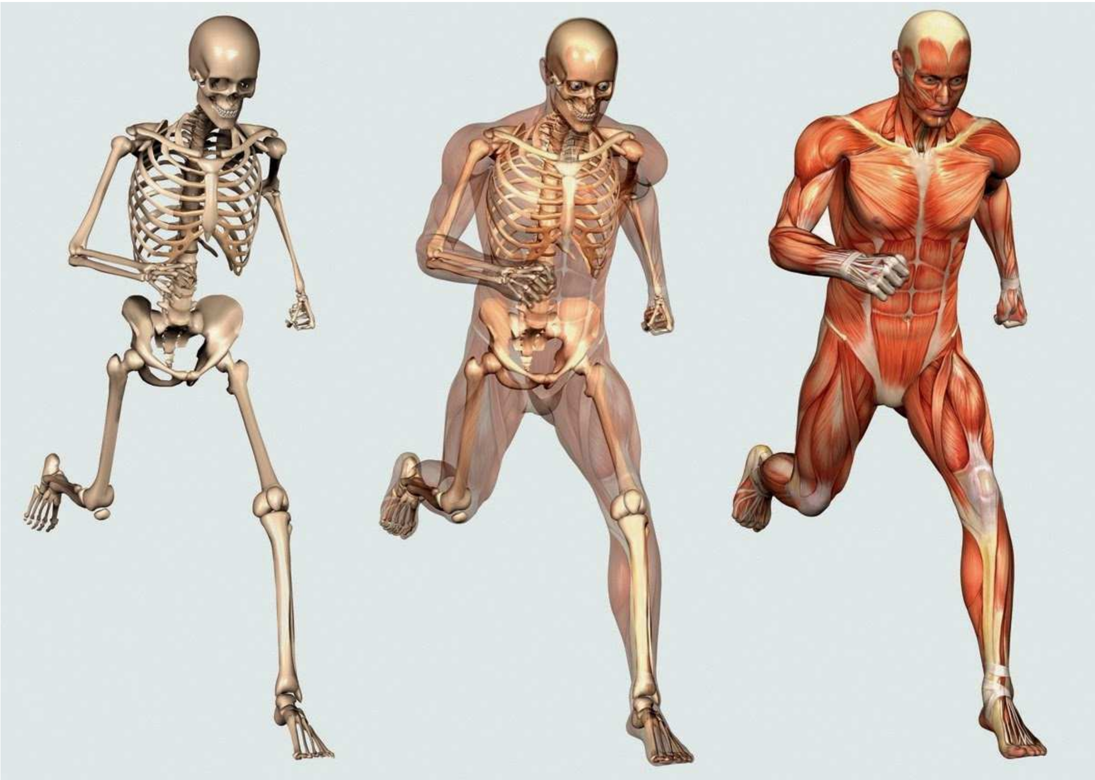
- Biomaterials : Natural or synthetic materials compatible with their introduction into contact with living tissues, within the framework of a medical device, without damaging themselves or the environment
- Biomaterials : One of the most active areas of research of Materials Science in recent years
- Human body contains several types of tissues, which are possible to be replaced by man-made synthetic materials, either ceramics, metals, polymers or their composites



Bioceramics

Introduction – human hard tissue

- Bioceramics → dedicated to replace hard tissue (bones, teeth)



See M. Alini (16:00-17:30)

206 bones (adult)

= frame of human body

- Protection of organs
  - Brain
  - Thoracic organs
- Supported by muscles, tendons, ligaments, fascias, cartilage
- Involved in blood cells formation
- Sink of minerals (Ca, Mg, …)
- 4-6 kg for men

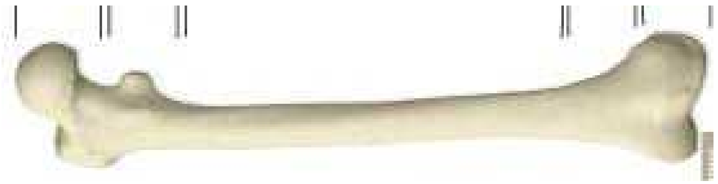
  3-4 kg for women

Bioceramics

Introduction – human hard tissue

➢ Several types of bones :

Long (i.e. femur)



Short (i.e. rotule)

Plane (i.e. clavicule)

Bioceramics

Introduction – human hard tissue

- Composed with :
  - Water (10-20%)
  - Inorganic phase – calcium phosphate (60%)
  - Organic phase – collagene, bone cells (20-30%)

Depends on the location in the body!

Bioceramics

Introduction – human hard tissue

- Composed with :
  - Water (10-20%)
  - Inorganic phase – calcium phosphate (60%)
  - Organic phase – collagene, bone cells (20-30%)

Gives the bone its hardness

Bioceramics

Introduction – human hard tissue

- Composed with :
  - Water (10-20%)
  - Inorganic phase – calcium phosphate (60%)
  - Organic phase – collagene, bone cells (20-30%)

Gives the bone its flexibility and flexural/tensile strength

Bioceramics

Introduction – human hard tissue

- Composed with :
  - Water (10-20%)
  - Inorganic phase – calcium phosphate (60%)
  - Organic phase – collagene, bone cells (20-30%)

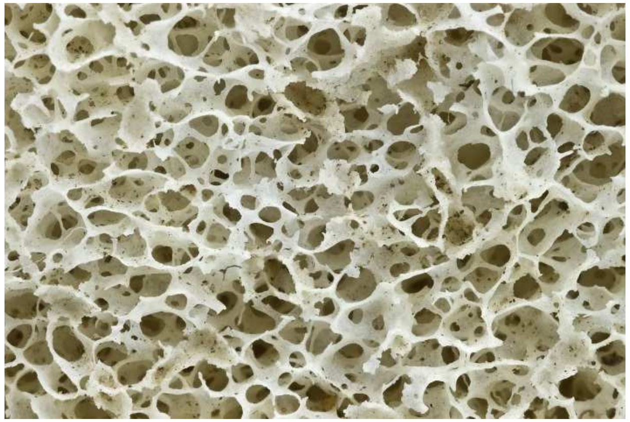
Bones = natural nano-composites in which collagens act as a bundle of fibers with dispersion on nano-particles of calcium phosphate, and proteins, polysaccharides, etc. acting as « cements »

Bioceramics

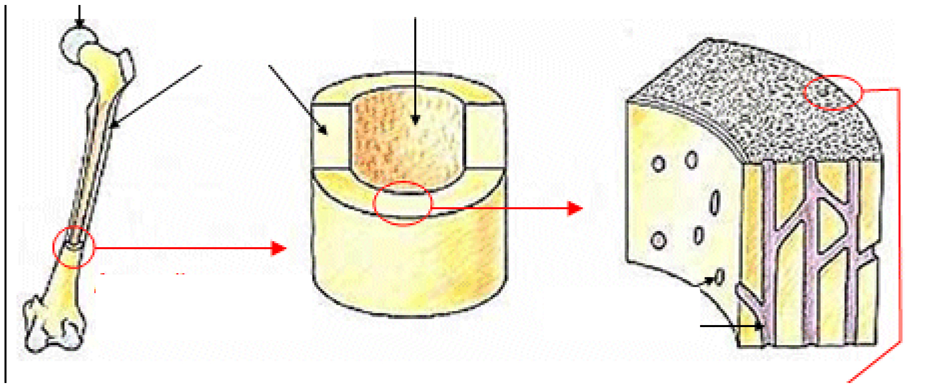
Depends on the location in the body!

Introduction – human hard tissue – 3D structure

- Cancellous or trabecular or spongy bones → characterized by porous structure (tendons, ligaments attachment, vascularization, etc.)

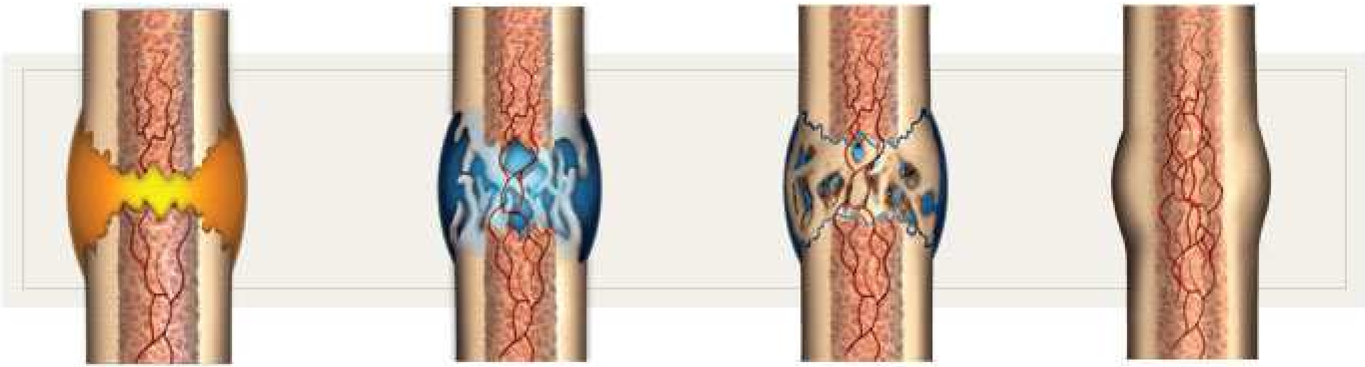


- Cortical bones → characterized by a dense structure, with much higher strength in the loading direction (best combination of strength and modulus)



Bioceramics

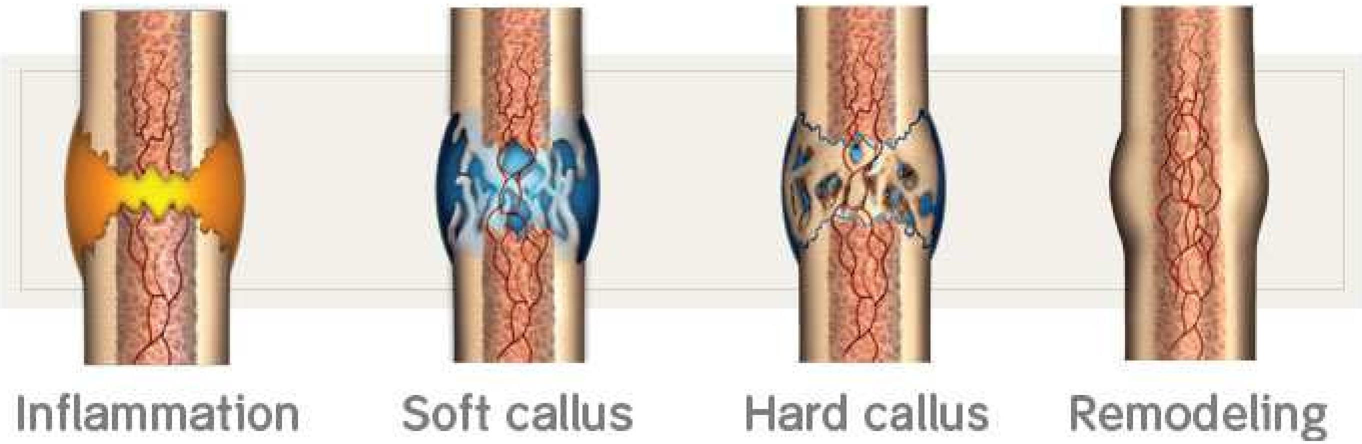
Introduction – Natural healing of hard tissues



1 2 3 4

1 - Hematoma and inflammation around the broken bone ends

Introduction – Natural healing of hard tissues

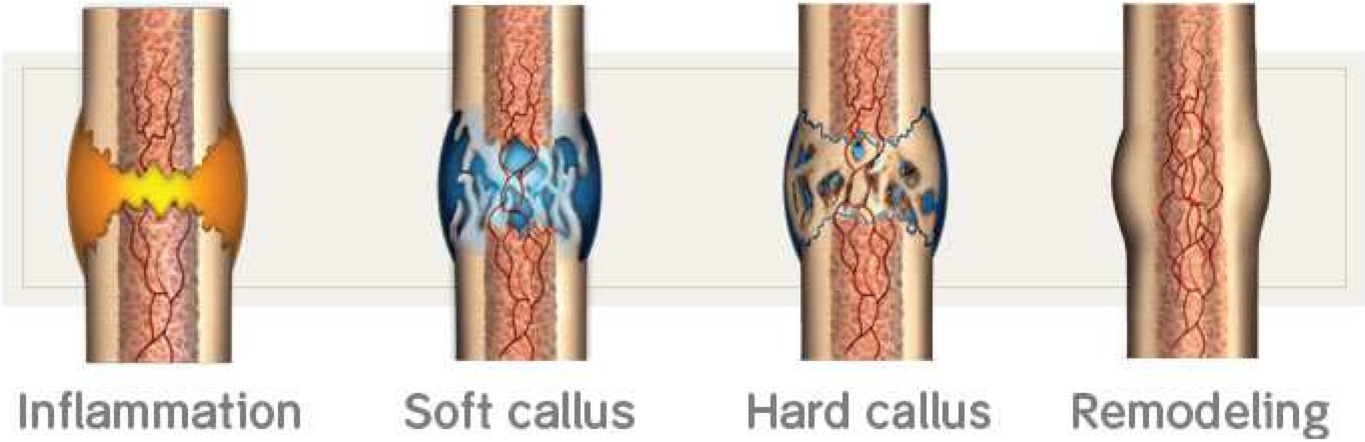


1 2 3 4

2 – Action of fibroblasts (type-III collagen) and chodroblasts (hyaline cartilage) to form the « soft callus »

Bioceramics

Introduction – Natural healing of hard tissues

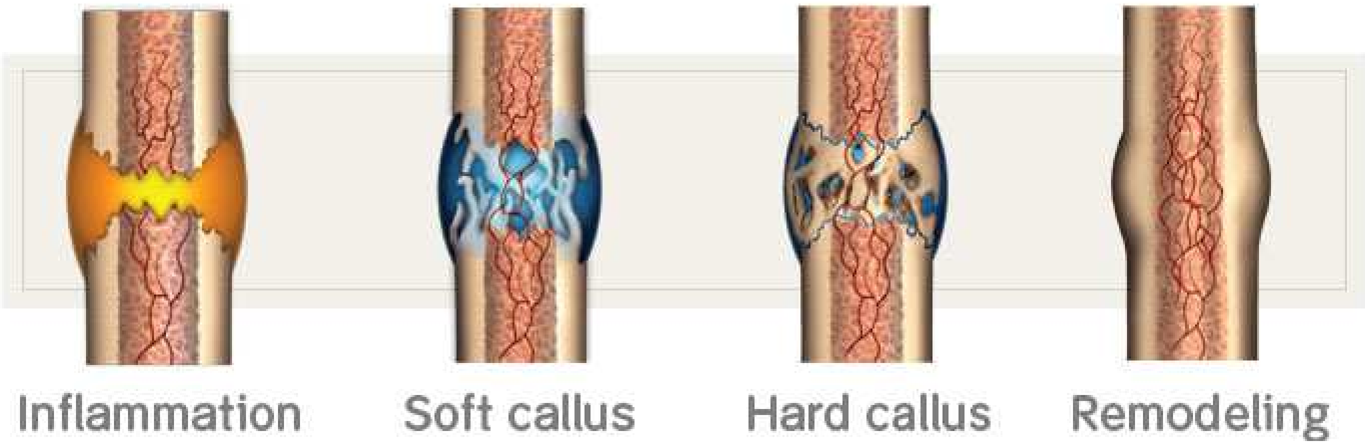


1 2 3 4

3 – Action of osteoblasts to form woven bone (with type-I collagen) and osteoclasts to produce pits and channels

Bioceramics

Introduction – Natural healing of hard tissues

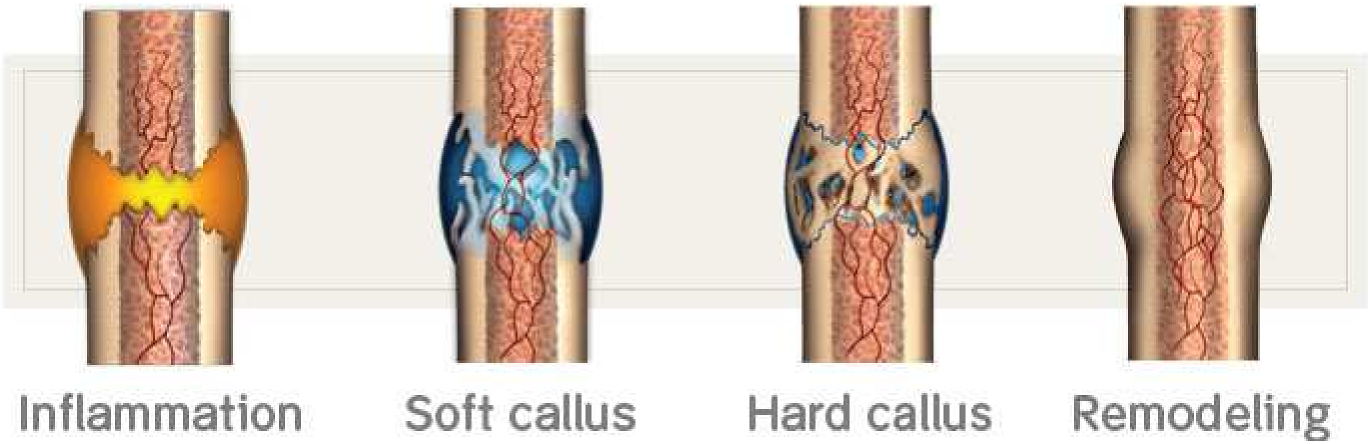


1 2 3 4

4 – Final remodelling of bone is completed by deposition of compact bone by osteoblasts in resorption pits prepared by osteoclasts

Bioceramics

Introduction – Natural healing of hard tissues



1 2 3 4

- **<u>Limits</u>** : Direct healing occurs when the gap between bone ends is < 2mm
- For larger areas of bone loss, surgeons need to intervene to bridge the skeletal defects

Bioceramics

Introduction – Biocompatiblity

- See : R. Luginbuehl, May 12, 14:15
- Ability of a material to function satisfactory without any detrimental effect on the tissues surrounding it or any deterioration of the material itself
- Three important aspects :
  - Biochemically compatible, non-toxic, non-irratitive, non-allergenic and non-carcinogenic
  - Mechanically compatible with surrounding tissues
  - There must be bio-adhesiveness between the material and the surrounding tissues

Bioceramics

Type of biomaterials

	BIOINERT	BIOACTIVE
Natural		Autograft, allograft, xenograft
Ceramic	Alumina, Zirconia	Calcium phosphates ceramics, bioglasses
Polymer(*)	PE, PEEK	Polycaprolactone, Polylactide, Polyglycolide
Metal(**)	Au, Ti, 316L	Mg alloys

(*) See E. De Barra – 14:45

(**) See M. Attalah – 11:30

Bioceramics

Type of biomaterials

	Advantages	Disadvantages
Natural	Biocompatible, osteoinductive, osteoconductive, non-toxic, no immunological problems	Additional surgical operation, time consuming, risk of disease transmission, availability
Ceramic	Biocompatible, osteoconductive, bond to bone (HA and TCP)	Poor mechanical properties
Polymer	Biodegradable, adjustable degradation rate, easy to process	Degradation products → inflammatory reactions, higher mechanical strength needed
Metal	Bioinert, high mechanical strength	Poorer biological properties

Bioceramics

Type of bioceramics

- Since 1965-1970, ceramics are intensively used as bone substitutes, orthopaedic prosthesis (knee, hip) and dental tissues replacement (implants and prosthesis).
- No ceramic is able to associate both adapted mechanical properties and biological interface with bone
  - Alumina and zirconia lead to the formation of fibrous tissue at the interface with bone
  - Calcium phosphate ceramics have poor mechanical properties

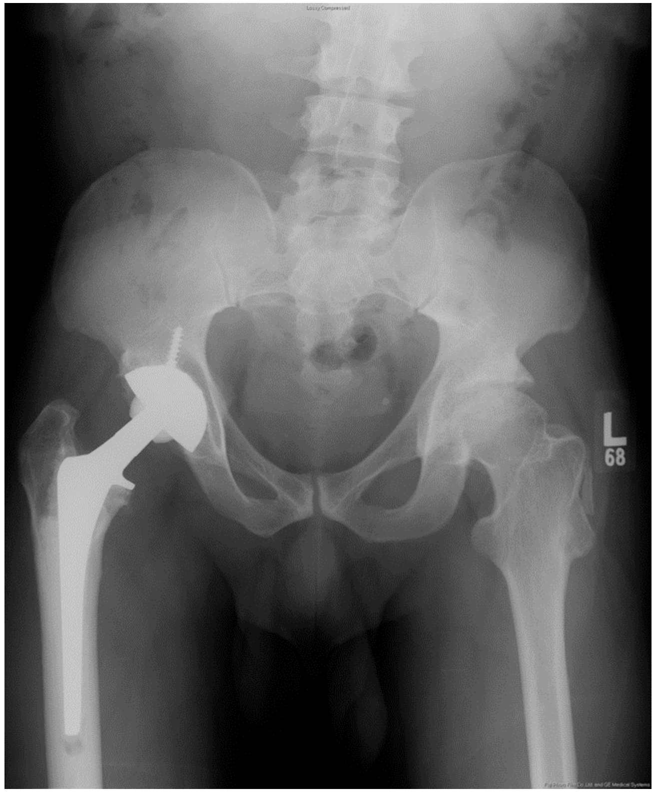
- <u>Two categories of BIOCERAMICS</u>

  - Bio-inert (alumina, zirconia) → for dense parts (cortical bones, teeth, etc.)
  - Bio-active (calcium phosphate) → bone filling, porous parts (trabecular bone)

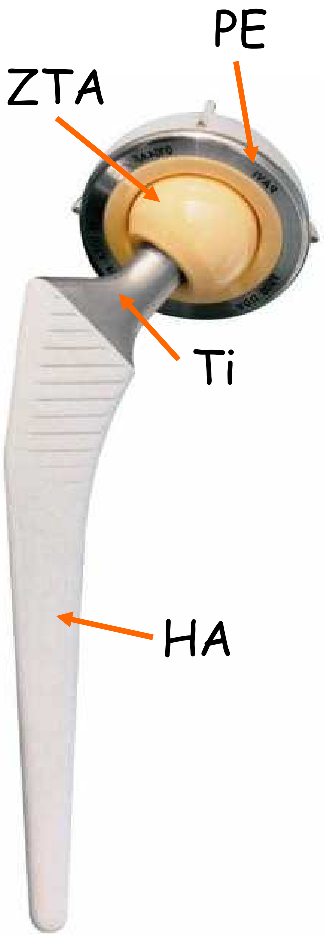
Bioceramics

Bio-inert ceramics

- Mainly : alumina, zirconia + composites ZTA
- Applications : hip, knee, prosthesis, dental crown, etc.



~ 1.500.000/year

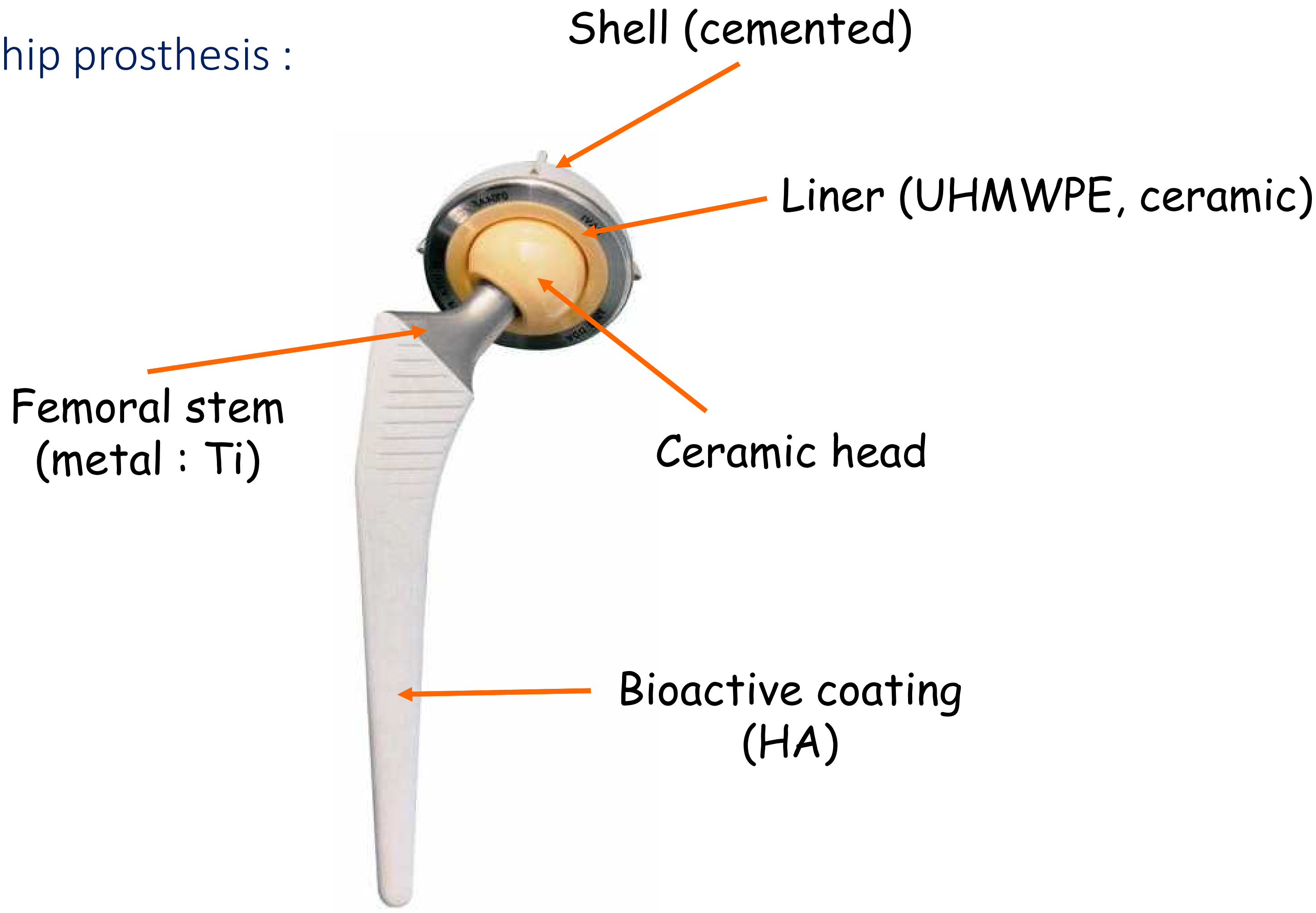


Actual prosthesis

Bioceramics

Bio-inert ceramics

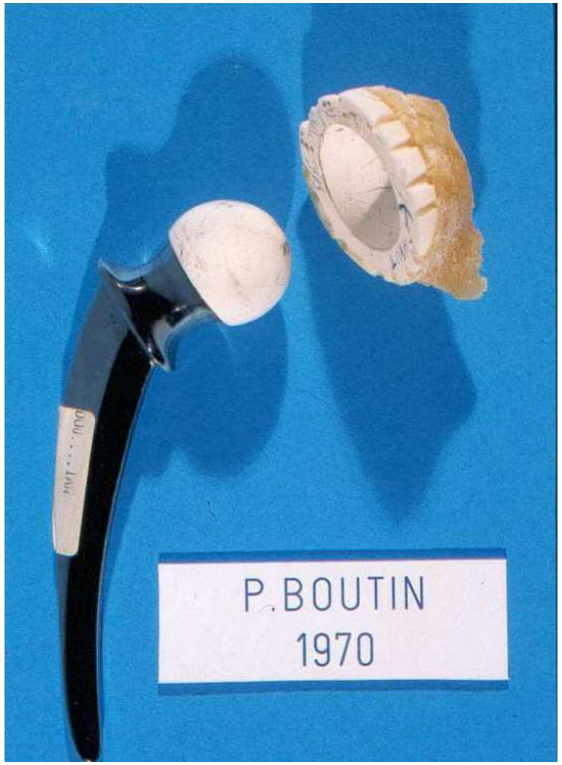
- Modern hip prosthesis :



Bioceramics

Bio-inert ceramics

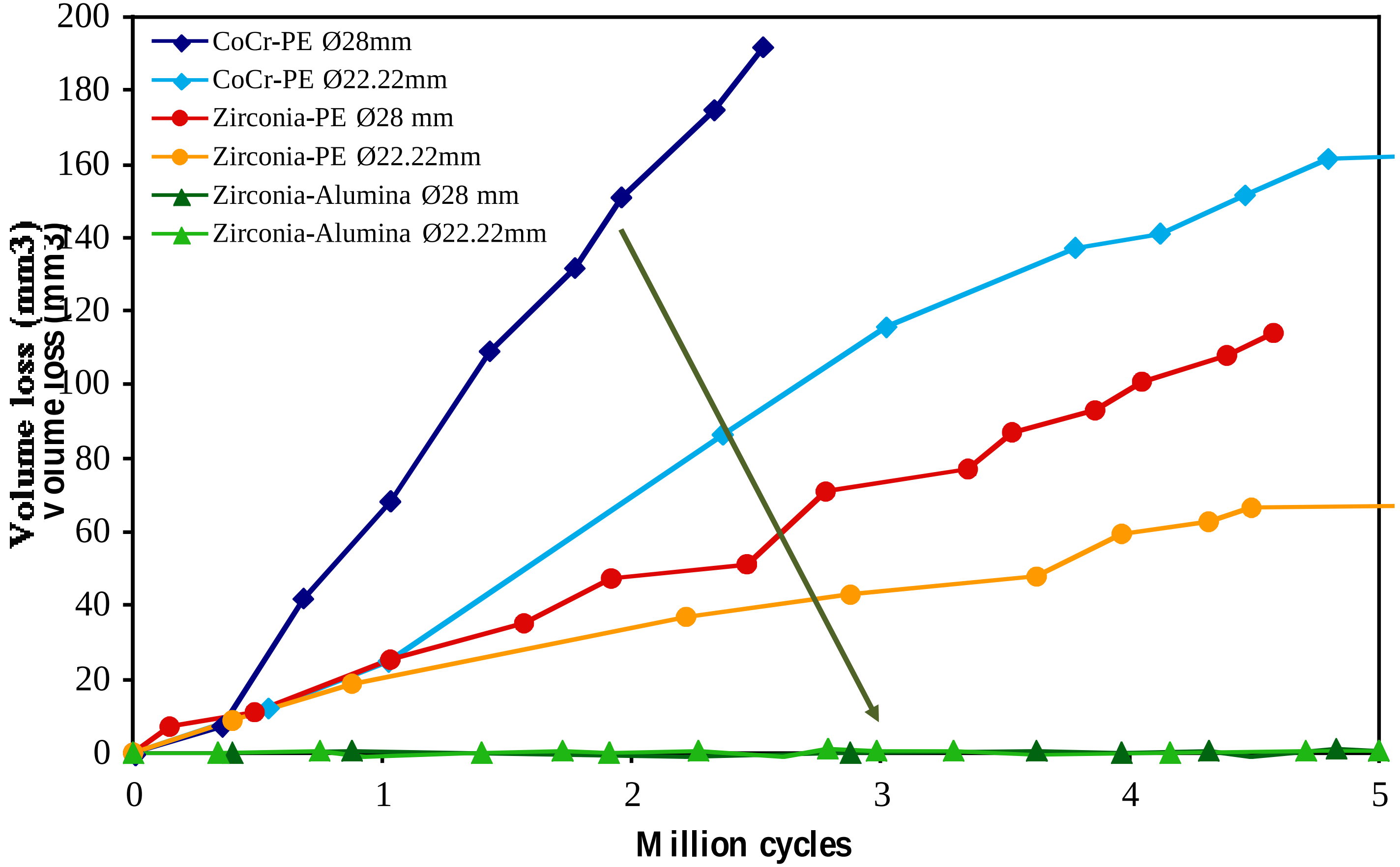
- Alumina was first introduced for orthopedic applications in 1970's (Boutin, FR/Daniel Blancquaet, FR), with mixed success (rate of rupture >10%...)



Bioceramics

Bio-inert ceramics

- One of the most important advantage with ceramics → high hardness → roughness ~ nm → limitation of the PE wear debris → no inflammation → no disassembly



Bioceramics

Bio-inert ceramics

- How to increase the strength of ceramics ?

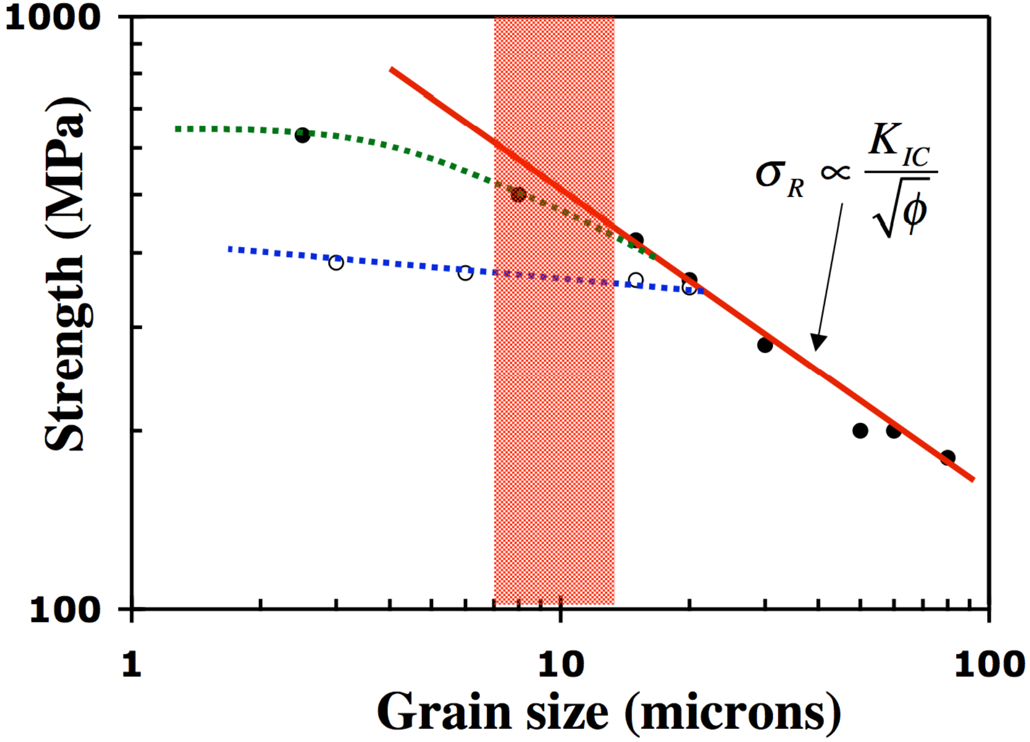
$$\sigma_R = \frac{K_{IC}}{\sqrt{\pi \times a}}$$

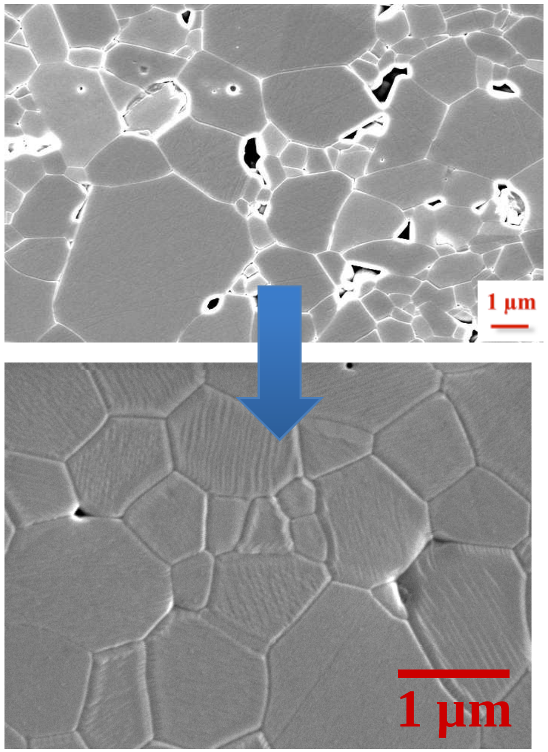
1. Reduce the size of defects
2. Increase the fracture toughness

Bioceramics

Bio-inert ceramics

- The reduction of the rate of rupture (0,1%) was related to an improve of the process of elaboration, with a control of the grain size and density .
- Since 1977, alumina parts are post-hipped and even with a mean fracture toughness of around 4 MPa.m$^{1/2}$, the flexural strength was increased up to 600MPa

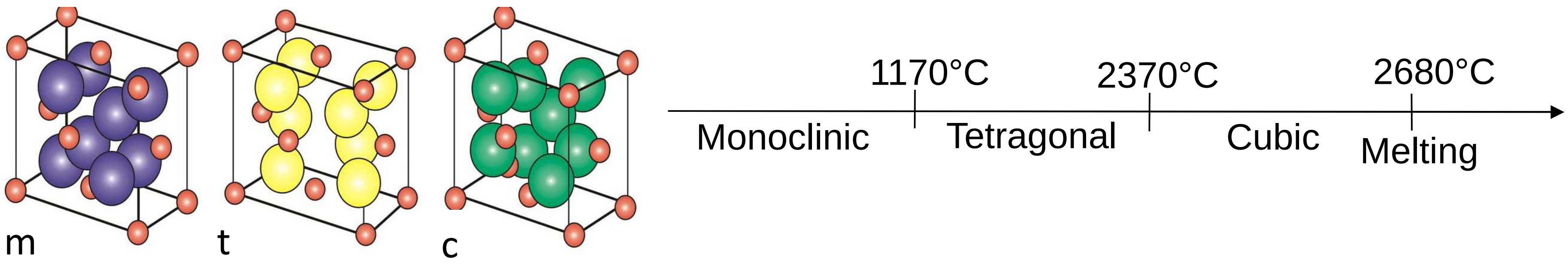




Bioceramics

Bio-inert ceramics

- But due to the poor fracture toughness of alumina (K_{1C} = 4MPa.$m^{1/2}$), it is limited to femoral head of at least 28mm diameter, and certainly not for knee prosthesis.
- Yttrium Stabilized Zirconia was then considered, for its interesting mechanical properties (K_{1C} > 6-12 MPa.$m^{1/2}$) and flexural strength > 1000MPa!



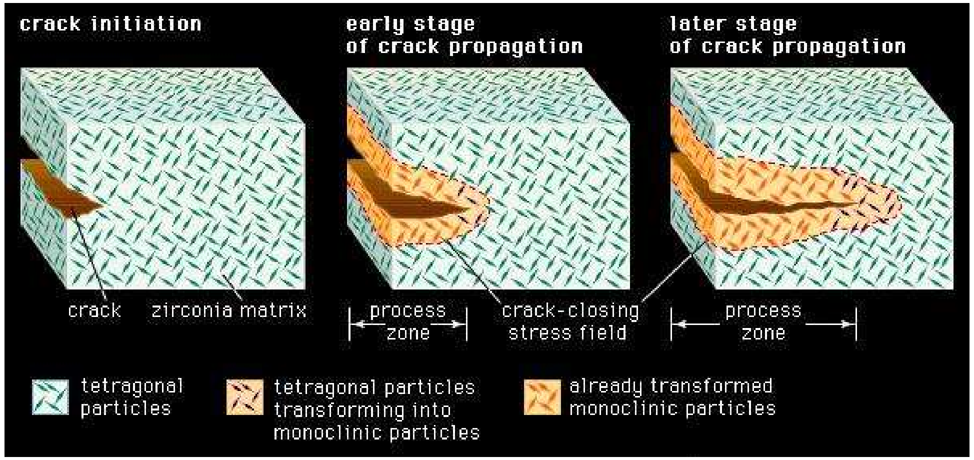
- Zirconia : mechanism of reinforcement : transformation toughening (t → m) (Garvie, 1975)

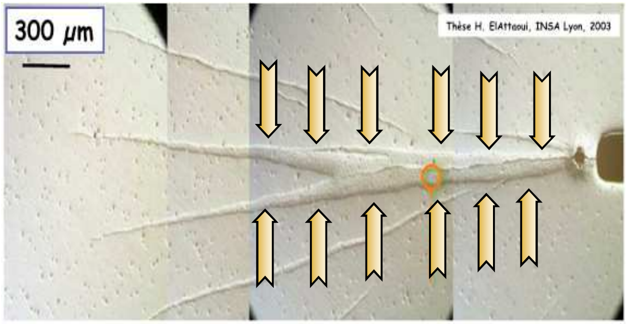
Bioceramics

Bio-inert ceramics

- Zirconia : mechanism of reinforcement : transformation toughening (t → m) (Garvie, 1975)

t → m : volume change (3-5%)





- Before 2001 : rate of rupture < 0,1%, manufacturing of femoral head with a small diameter

Bioceramics

Bio-inert ceramics

- But : controversial success after more than 20 years of clinical test!

- **Steam Re-Sterilization Causes Deterioration of Zirconia Ceramic Heads of Total Hip Prostheses, May 21, 1997,** FDA (USA)
- **'Urgent information on spontaneous disintegration of zirconia femoral heads: Hazard alert', 23 August 2001,** Therapeutic Goods Administration (Australia)
- **Ruptures de têtes des prothèses de hanche en céramique de zircone lots TH, Septembre 2001**, AFSSAPS (France)

Change of sintering process (tube furnace)

Modification of the microstructure

Aging (very fast, unwaited) also in vivo!

Subcritical crack growth → Ruptures **(up to 37%)**

Bioceramics

Bio-i

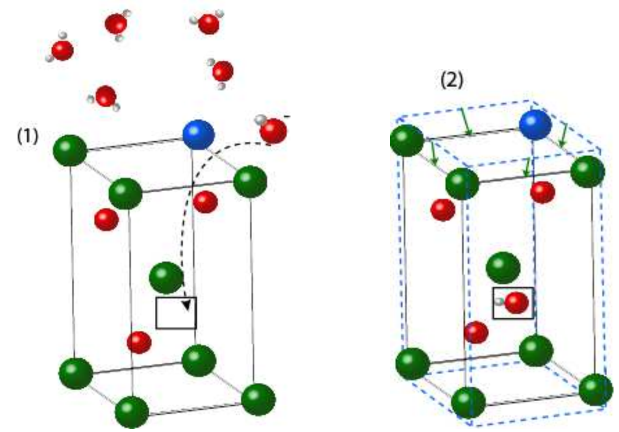
➢ Bu

- Ste … tal Hip
  Pros
- 'Urg … lazard
  aler
- Rupt
  Sep

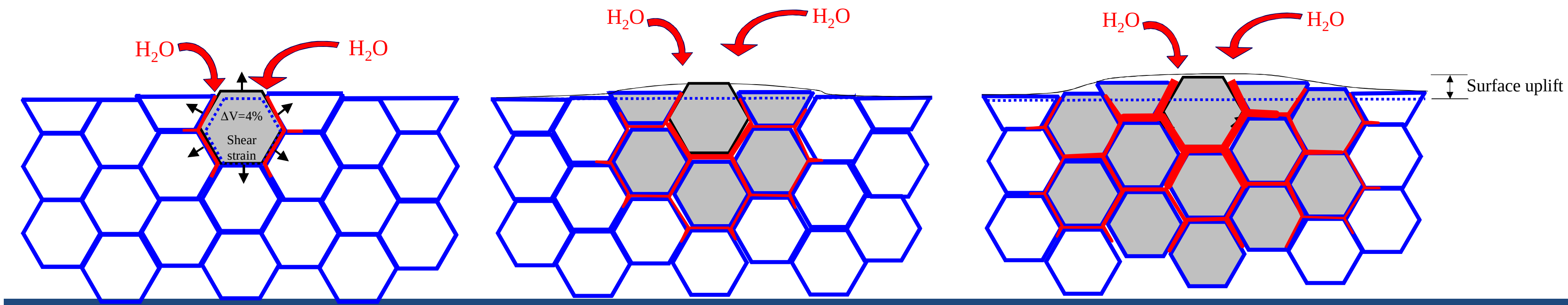
Bioceramics

Bio-inert ceramics

- Diffusion of OH^- ions in the tetragonal network, accelerated with Y-TZP due to lack of oxygen (Y^{3+})



- Destabilization of grains in surface to monoclinic phase → increase of volume → increase of roughness → microcracks → rupture!



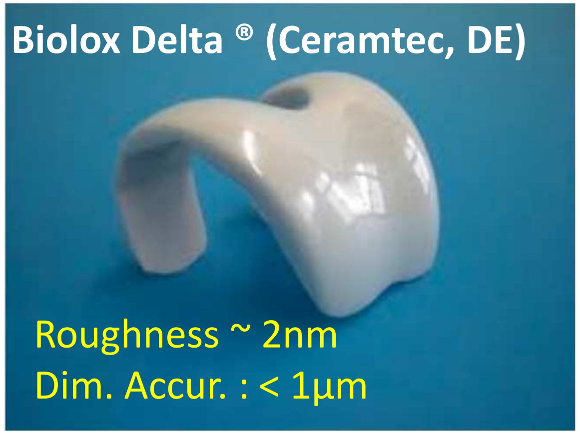
Bioceramics

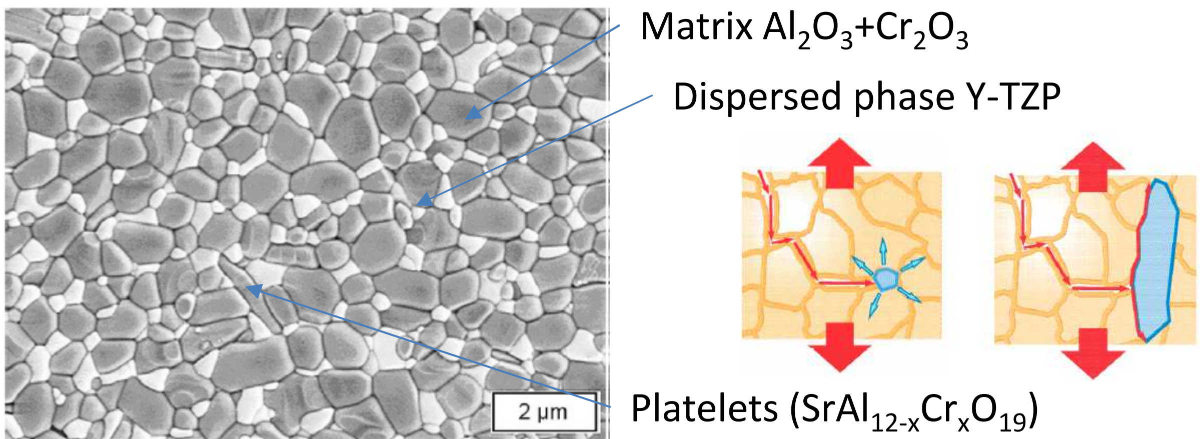
Bio-inert ceramics

- Ce-TZP or Mg-TZP can solve the problem, with an increase of K_{1C}
- But although this degradation has been demonstrated and indirectly associated with a number of flaws in femoral head ceramic prostheses, nowadays, zirconia was completely abandoned for orthopedic applications

Development of composites composed with zirconia toughened alumina

Material	K_{1C} (MPa.m$^{1/2}$)	Strength (MPa)	Hardness (Vickers, MPa)
Alumina	4-5	400-600	1800-2000
3Y-TZP	6-12	800-1200	1200-1300
Biolox Delta ®	8,5	1150	2000



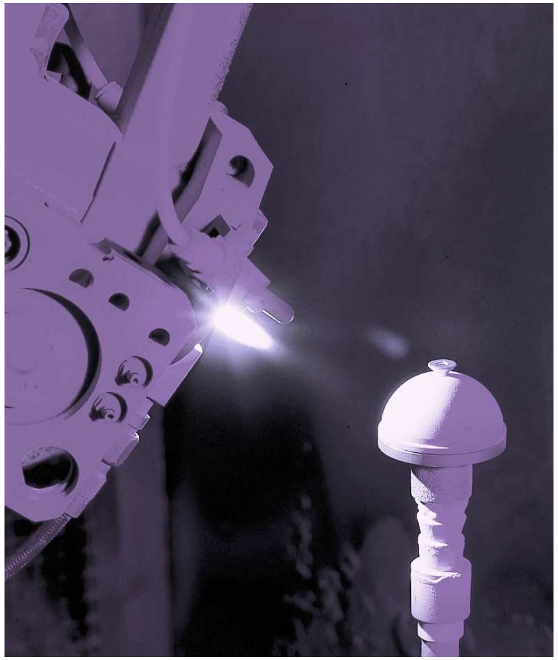


Bioceramics

Bio-inert ceramics

- HIP prosthesis : cemented (PMMA, for instance) in order to anchor the metal part with the bone
- Since 1986 : coating of HA ($Ca_{10}(PO_4)_6(OH)_2$ (main constituent of bone)

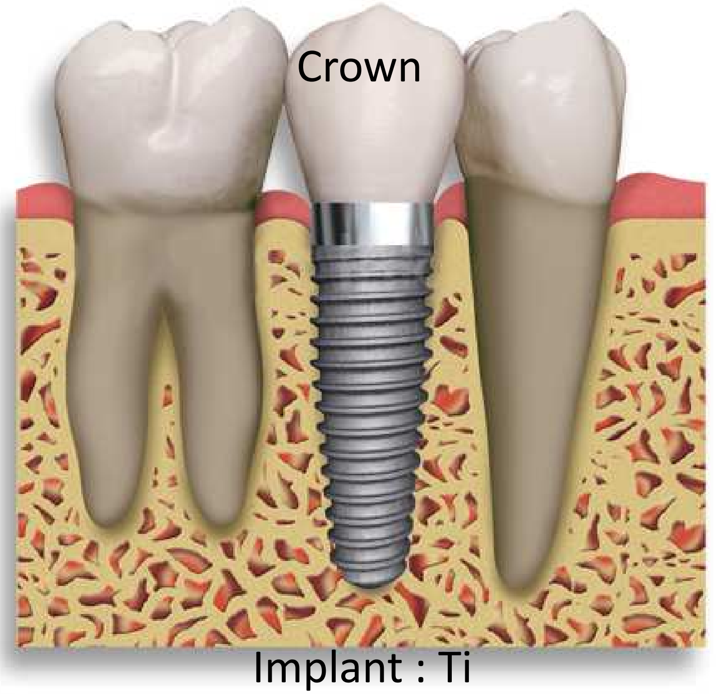
- Plasma sputtering



Bioceramics

Bio-inert ceramics

- For dental prosthesis and crowns : strength of material > 600MPa.
- More than only mechanical considerations, the esthetic aspect is critical
- White to Ivory color of bio-inert ceramics (alumina, zirconia) have encouraged their selection to replace metallic implants and prosthesis.



Micromilling

Laser machining

Bioceramics

Bio-active ceramics

- Due to ageing of population, bone filling and bone regeneration are a major and daily clinical aspect (more than 700.000 surgical operations / year in Europe!)
- The use of synthetic bone substitutes has greatly developed since 1980 as alternative to autograft
- Most of the commercial products on the market are bi-phasic calcium phosphate porous part, composed with :
  - Hydroxyapatite (HA) (Ca/P ratio = 1,67) – $Ca_{10}(PO_4)_6(OH)_2$
  - β-tricalcium phosphate (β-TCP) (Ca/P ratio = 1,5) – $Ca_3(PO_4)_2$

Bioceramics

Bio-active ceramics

- For load-bearing applications, surgeons will obviously select inert materials (Ti, Stainless Steel, Co-Cr alloys, alumina, ZTA, composites with polymers…)
- Calcium phosphate ceramics have poor mechanical properties :

Materials	Compressive strength (MPa)	Flexural strength (MPa)	Young modulus (GPa)	Fracture toughness ($MPa.m^{1/2}$)
HA	600	150-200	140	< 1
β-TCP	600	150-200	100	< 1
Alumina	3000	400-600	400	4-5
Cortical bone (*)	80-200	150-200	15	2-12

(*) with 5 to 10% of porosity!

- But HA/TCP have good biological properties!

Bioceramics

Bio-active ceramics

- HA/TCP integrate perfectly with bone tissue (BIO-INTEGRATION) without fibrous tissue formation! Indeed, they are chemically similar to the mineral phase of hard tissues in human body!

	Enamel	Dentine	compact bone	TCP	HAP
Ca	36,1	35	35,5	38,8	45,2
P	17,3	17,1	17,1	20,0	21,0
CO_2	3	4	4,4	-	-
Ca/P (molaire)	**1,61**	**1,58**	**1,60**	**1,50**	**1,667**

Bioceramics

Bio-active ceramics

- HA/TCP integrate perfectly with bone tissue (BIO-INTEGRATION) without fibrous tissue formation! Indeed, they are chemically similar to the mineral phase of bones!
- HA/TCP are osteoinductive and osteoconductive : they guide bone cells and promote bone tissue development
- HA/TCP can be used as permanent substitutes either as bioresorbable material
- HA/TCP regulate the operation of bone cells (osteoblasts, osteoclasts)

Bioceramics

Bio-active ceramics : manufacturing

- Powder synthesis : mixture of aqueous solution of calcium and phosphate salts, precipitation, calcination

$$\mathbf{Ca(NO_3)_2 + (NH_4)_2HPO_4 \rightarrow Ca_{10-x}(PO_4)_{6-x}(HPO_4)_x(OH)_{2-x}}$$

1000°C	CaO	HA	TCP	Pyrophosphates
Ca/P ratio		1,667	1,5	1

UVHC UNIVERSITE DE VALENCIENNES ET DU HAINAUT - CAMBRESIS

- Sintering
  - HA ~ 1230-1260°C
  - β-TCP ~ up to 1125°C (to avoid α-TCP formation)
  - To get dense bi-phasic parts → need for non-conventional sintering process (microwave, post-HIP, SPS)

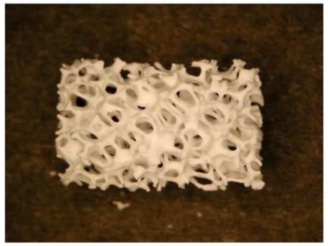
Bioceramics

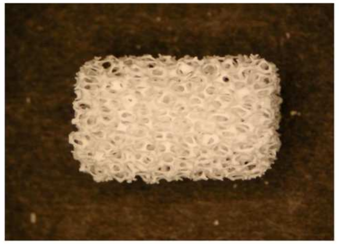
Bio-active ceramics : actual "shapes"

Granules

Biomatlante MBCP^{TM}

Porous part





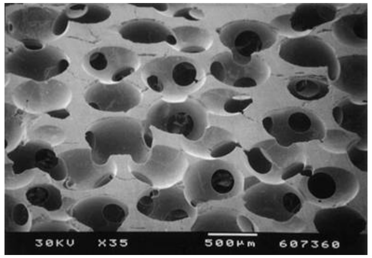
Coating

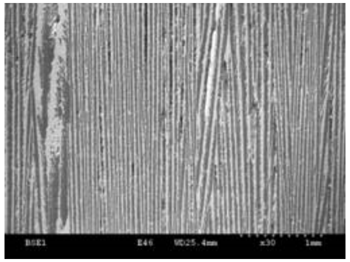
Cement

Bioceramics

Bio-active ceramics : new trends/ fields of R&D *(see Prof. A. Leriche, May 12th, 9:00)*

- Recent technologies to design porous scaffolds, with complex/customized shape and controlled porosities (size, shape, interconnection of pores)
  - Replica
  - Ice-templating
  - 3D technologies



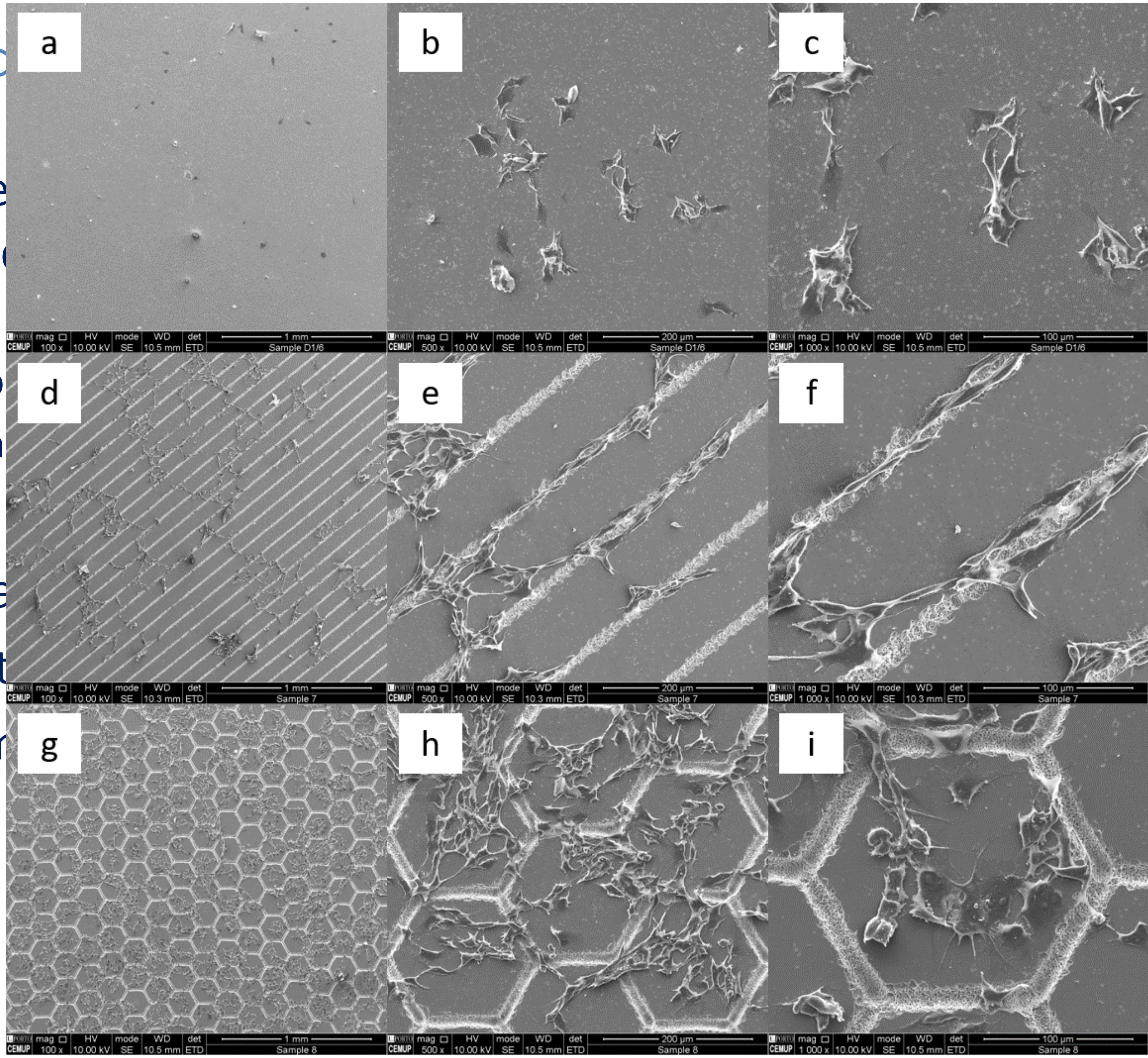


- Incorporation of stem cells, growth factors, antibacterial agents
- Composites polymer (PCL, PLA-PGA, PEKK)/ Bioceramics
- Surface modifications to enhance cells adhesion and proliferation

Bioceramics

Bio-active c … *, May 12th, 9:00)*

- Recent te … stomized shape an … pores)
  - Replica
  - Ice-temp
  - 3D techn
- Incorpora
- Composit
- Surface m … n



GLASS & BIOGLASS

BCRC member of EMRA

What means « glass »?

Definition

Either a material or an object (to drink, a part of spectacles, …)

- Internet: non-crystalline amorphous solid
- Dictionary: a hard, brittle, non crystalline, more or less transparent substance produced by fusion

In general: obtained by supercooling of a liquid: the solid material keeps some properties of the liquid

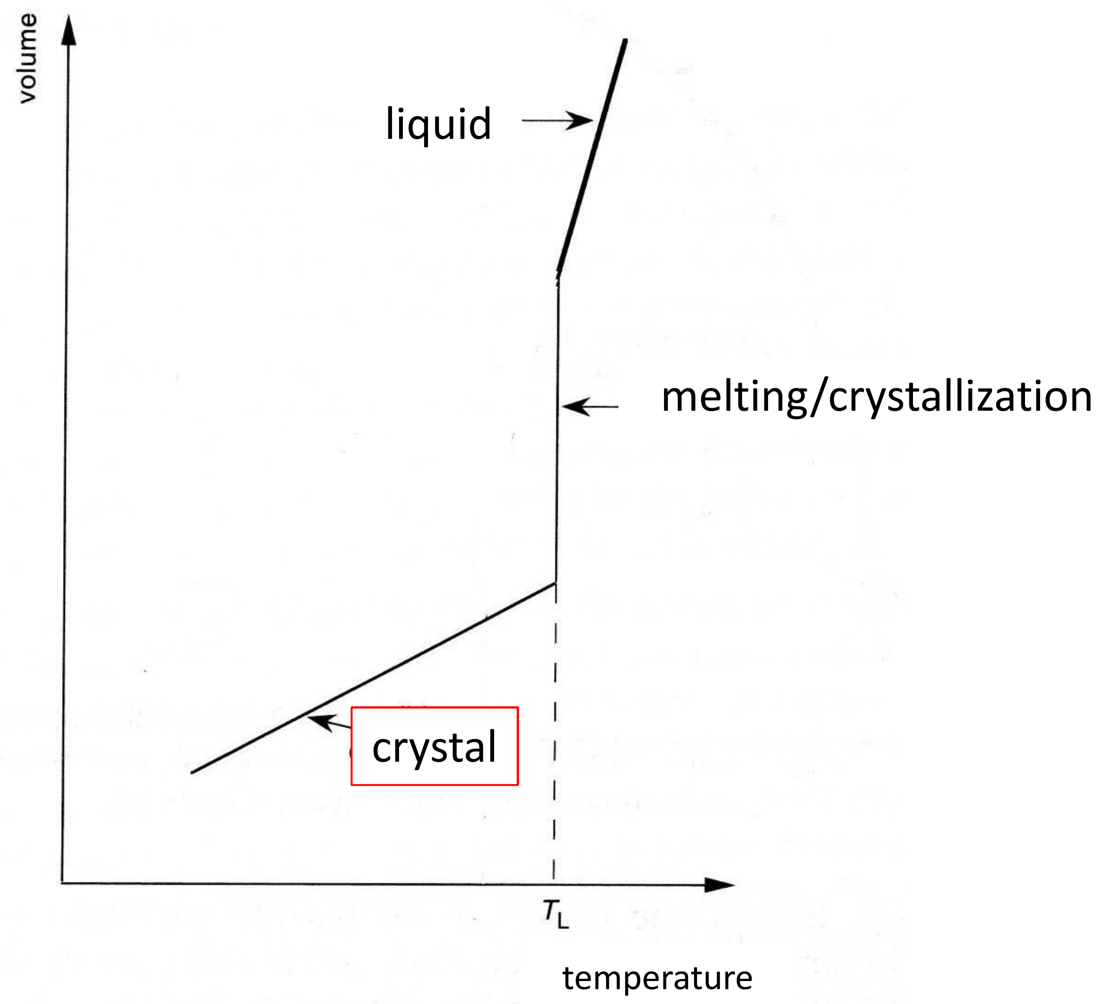
non crystalline mineral = amorphous

processing:

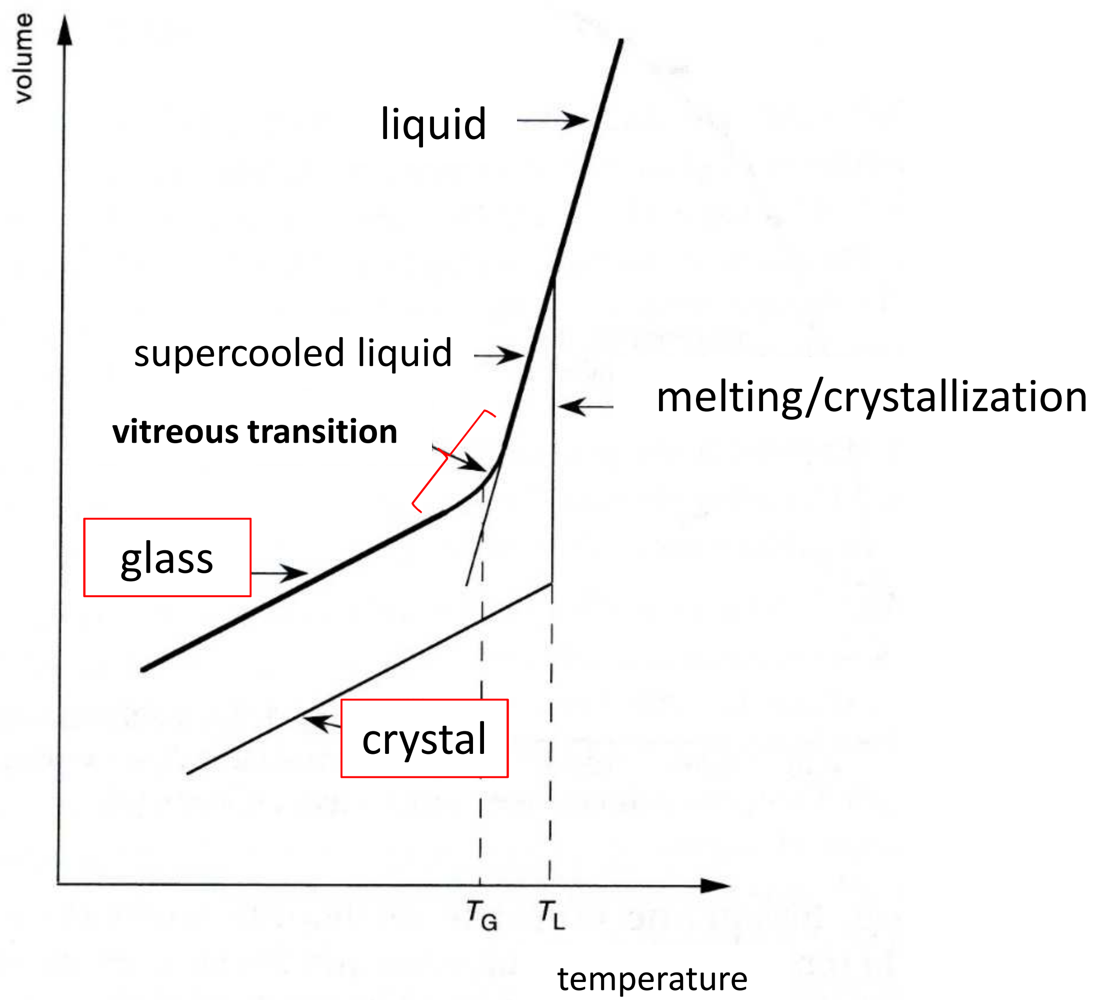
powder mixture → high temperature → liquid → shaping → cooling

Homogeneity and Isotropy

What means « glass »?



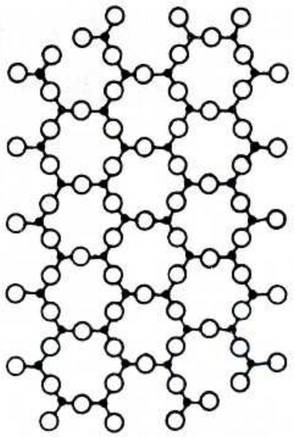
What means « glass »?

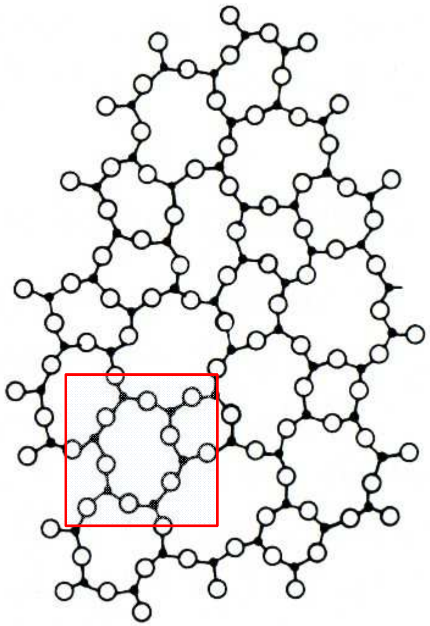


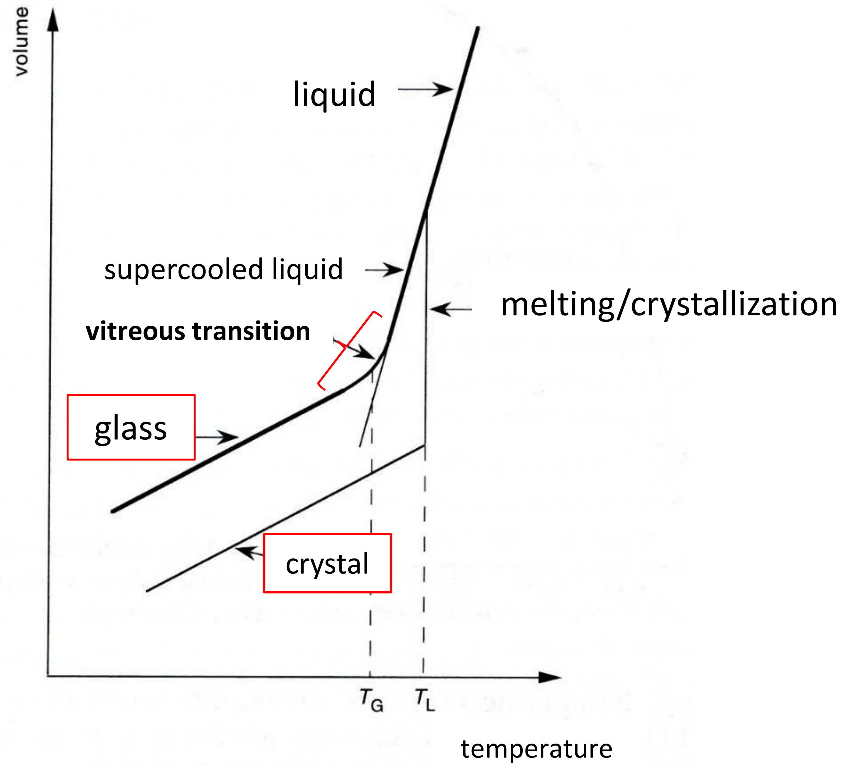
glass is a metastable material

More scientific definition:

Glass: a non crystalline solid characterized by a glass transition phenomenon


(a)

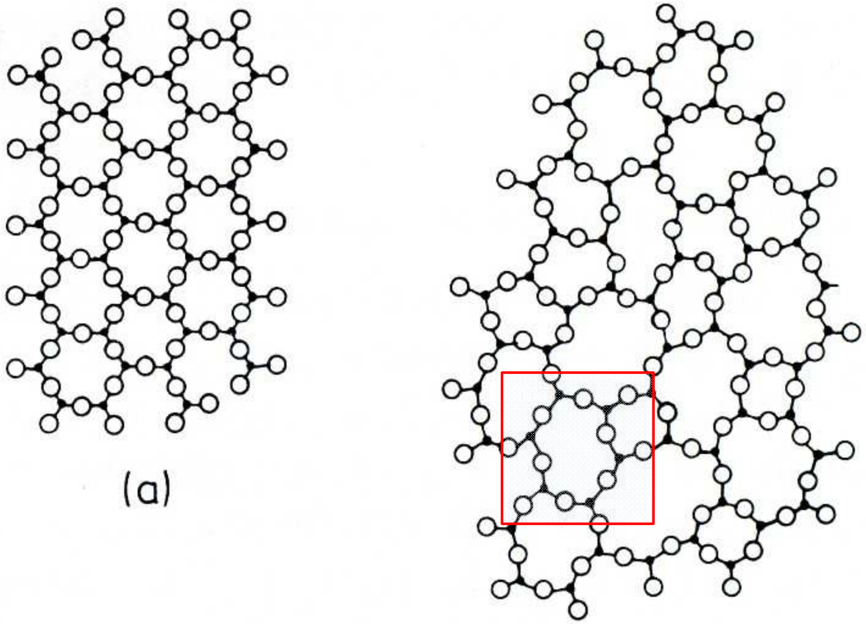

(b)



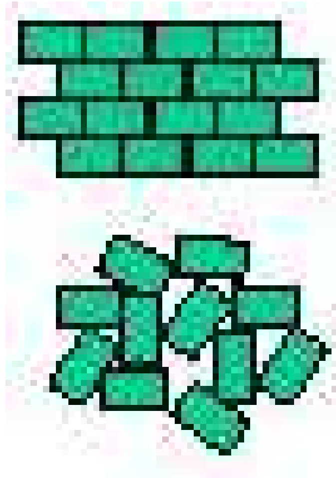
no long distance organization

More scientific definition:

<u>Glass</u>: a non crystalline solid characterized by a glass transition phenomenon

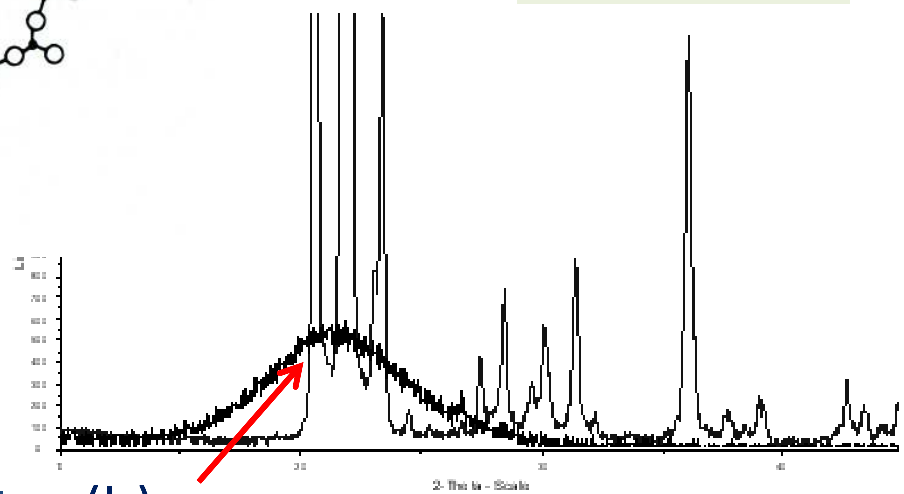


(a) (b)



(a)

example: SiO_2



(b)

no long distance organization

Glass forming (a)

From liquid

- Idea: keep the structure disorder of a liquid phase
- Most of the melted substances rapidly crystallize at the melting point, even if the cooling rate is very high

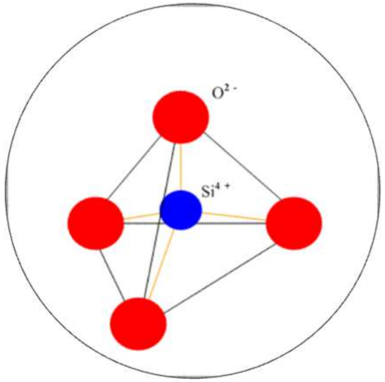
- Some substances form when melting very viscous liquids that will crystallize slowly under the melting point
- In such a case, if the cooling rate is enough high, the liquid will freeze without crystallization and form a glass

→ which liquids have a high viscosity? why?

→ "organization" within liquids

Glass forming

Liquid freezing



The glass making substances are:

a) elements : P, S and Se

b) oxides : **SiO_2, GeO_2, B_2O_3 and P_2O_5** are called « **network former ions** »: they can form tridimensional networks

III	IV	V	VI
B	C	N	O
Al	**Si**	**P**	S
Ga	**Ge**	As	Se
In	Sn	Sb	Te
Tl	Pb	Bi	Po

As_2O_3 and Sb_2O_3 , (As^{3+} et Sb^{3+}) are network formers if the cooling rate is very high

- oxides of neighbor elements (Ga, Bi, Se, Te, **Al**) are called "conditional network formers", i.e. alone, they cannot form glass but if they are associated with non forming oxides (e.g. $CaO-Al_2O_3$) → they are also called **"intermediate"**
- Electro-positive cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, etc.) do not take place in the structure, they are called **"modifier"** → their role:
  - ✓ melting (↓ $T_{melting}$ of silica ~ 1700°C) : Na_2O, K_2O, Li_2O, CaO, MgO
  - ✓ stabilizers (↓ reactivity against water): CaO, MgO, BaO, PbO

Oxygen can be substituted by other anions (example S^{2-} or N^{3-})
→ sulfide glasses or oxy nitride glasses

As_2O_3 and Sb_2O_3 , (As^{3+} et Sb^{3+}) are network formers if the cooling rate is very high

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- … …ure,
  … K_2O, Li_2O, CaO, MgO
  …tivity against water): CaO, MgO, BaO, PbO

- The energy of Si-O covalent bond is high: ~ 800 kJ/mol (**former**)
- On the contrary: Na-O ionic ~ 256 kJ/mol; Ca-O ~ 402 kJ/mol (**modifiers**)
- Al-O ~ 571 kJ/mol (**intermediate**) → either former if too less Si, or modifier

Oxygen can be substituted by other anions (example S^{2-} or N^{3-})
→ sulfide glasses or oxy nitride glasses

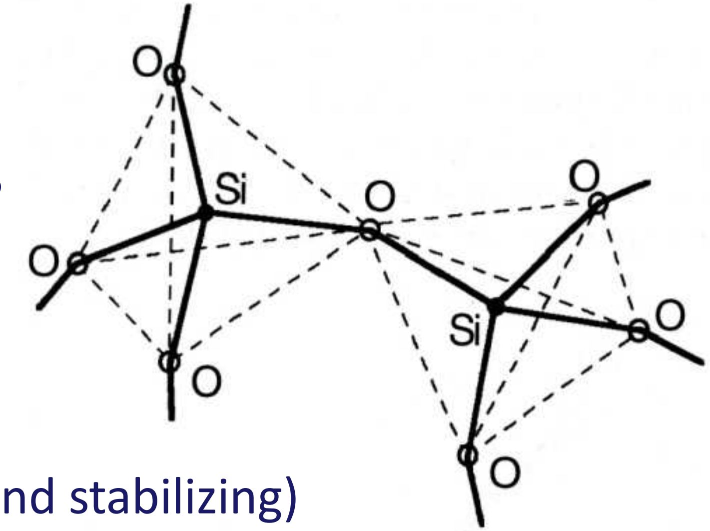
> **95 % of industrial glasses are silicates**, however other glass compounds exist:

- With S (binary As–S, As–Se, P–Se, Ge–Se, …)
- Halogenides (BF_2, $ZnCl_2$)

- Molten salts (sulfates, carbonates, phosphates, acetates, …)
- Aqueous solutions of salts, acids, bases, …
- Organic compounds (methanol, ethanol, glycerol, glucose, …)
- Organic polymers (PE, PVC, …)
- Metals (some hyper cooled alloys)

Generally, for those systems, the ranges of compositions are much more limited

Industrial glasses



Main constituents (wt %) of a classical glass are:

70 SiO_2, 15 Na_2O (melting), 15 CaO (melting and stabilizing)

Composition changed very few in centuries (except purity)

(wt %)	Modern glass	Palestine (4th century)
SiO_2	72.0	70.5
Na_2O	13,5	15.7
K_2O	0.5	0.8
CaO	10.0	8.7
MgO	2,0	0.6
Al_2O_3	2.0	2.7
Fe_2O_3	0.05	0.4

→ better **optical properties**

Multiple components oxide glasses

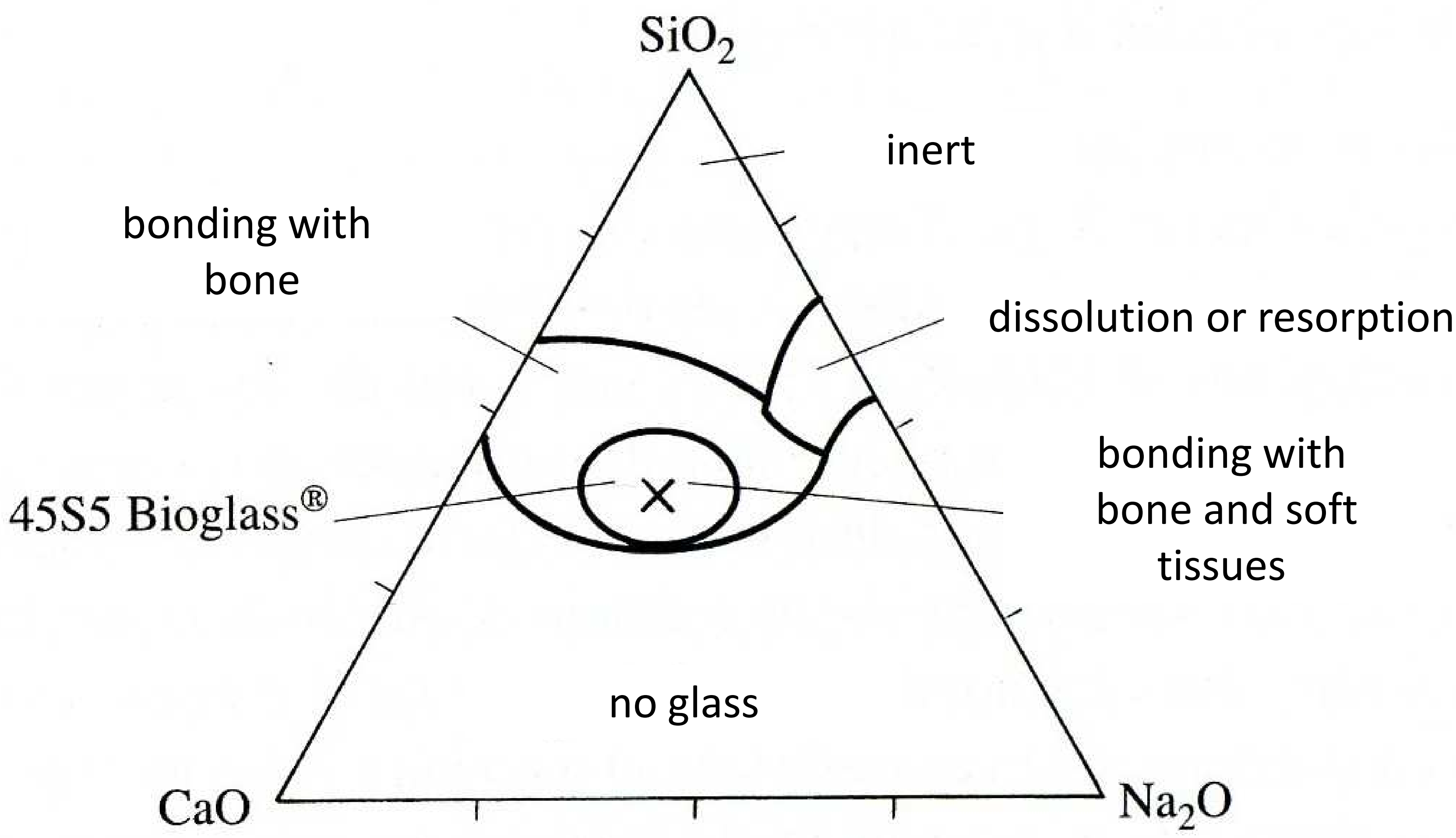
Glass	SiO_2	B_2O_3	P_2O_5	Al_2O_3	CaO	MgO	Li_2O	PbO	K_2O	Na_2O
Silica	99,5									
Vycor®	96,3	3		0,4					0,2	0,2
Soda-lime (windows)	72			1	9	4			0,2	14
Soda-lime (bottles)	72			2,0	10	2			0,5	13,5
Soda-lime (lamps)	73,6			1,0	5,2	3,6			0,6	16
Low lead content (< 24%)	63	0,2		0,6	0,3	0,2		21,0	6,0	7,6
High lead content (X rays)	35							58,0	7,2	
Borosilicate (low α)	80,5	12,9		2,2					0,4	3,8
Borosilicate (low σ)	70,0	28,0		1,1			1,2		0,5	
Alumina-silicate	57,0	4,0		20,5	5,5	12,0				1,0
Bioglass® – ex : 45S5®	**46,1**		**2,5**		**26,9**					**24,4**

not very stable because very few Si-O bonds

σ electrical conductivity
n refraction index
ρ density

Bio-reactivity domain of glasses

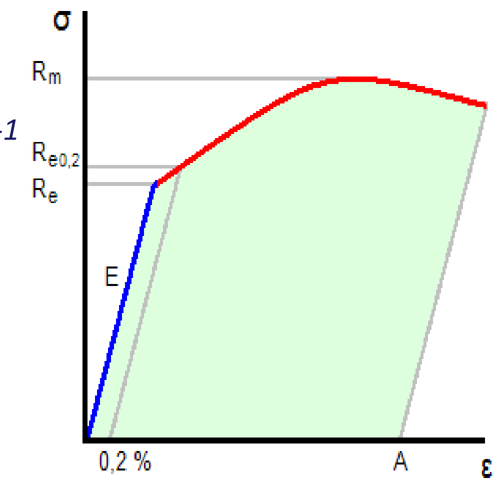
often contain P



What are the properties of glasses & which ones are of interest for bioactive glasses

1. **Viscosity (η) (*for shaping*): glass transition temperature (T_g) & annealing temperature**

- *Density: ~2.2 g.cm$^{1/3}$*
- **Mechanical resistance**: *σ_F~30 to 100 MPa; K_{Ic} ~ 0.7 to 1 MPa.m^{½};*
- *Elastic coefficients (E ~150 GPa, ν ~0.2 to 0.3) & CTE*
- *Electrical properties: insulator at room T ~10^{-9} à 10^{-8} $\Omega^{-1}m^{-1}$ ↑ ~ 10^{19} at about 1200°C*
- *Optical properties (transparency)*
- *Thermal conductivity: 0,8 à 1,4 W.m^{-1}K^{-1}*



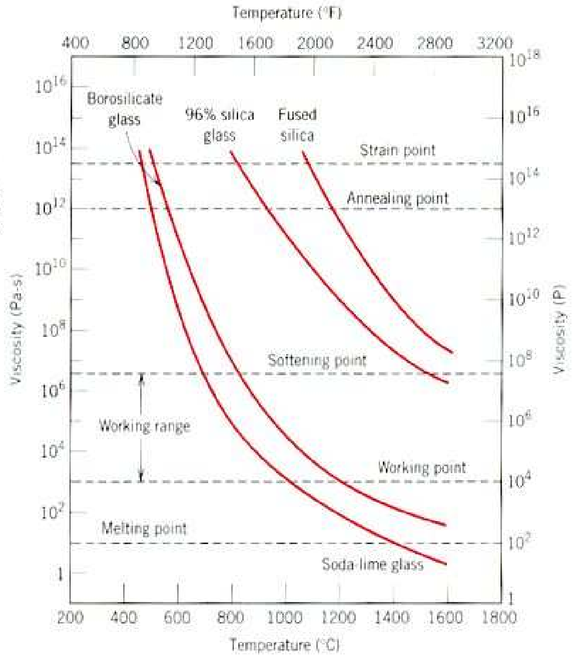
2. **Chemical properties (corrosion resistance)**

What are the properties of glasses & which ones are of interest for bioactive glasses

1. Viscosity (η) (*for shaping*): glass transition temperature (T_g) & annealing temperature

Important Temperatures

- Melting point = viscosity of 10 Pa.s
- Working point= viscosity of 1000 Pa.s
- Softening point= viscosity of $4x10^7$Pa.s
  Temperature above which glass cannot be handled without altering dimensions)
- Annealing point= viscosity of 10^{12} Pa.s.
- Strain point = viscosity of $3x10^{13}$Pa.s
  Fracture occurs before deformation



- Viscosity decreases with T
- Impurities lower T_{deform}

1 poise = 1 dPa.s

$T_g \sim 10^{13}$ to $10^{13.6}$ poises
(between strain and annealing points)

What are the properties of glasses & which ones are of interest for bioactive glasses

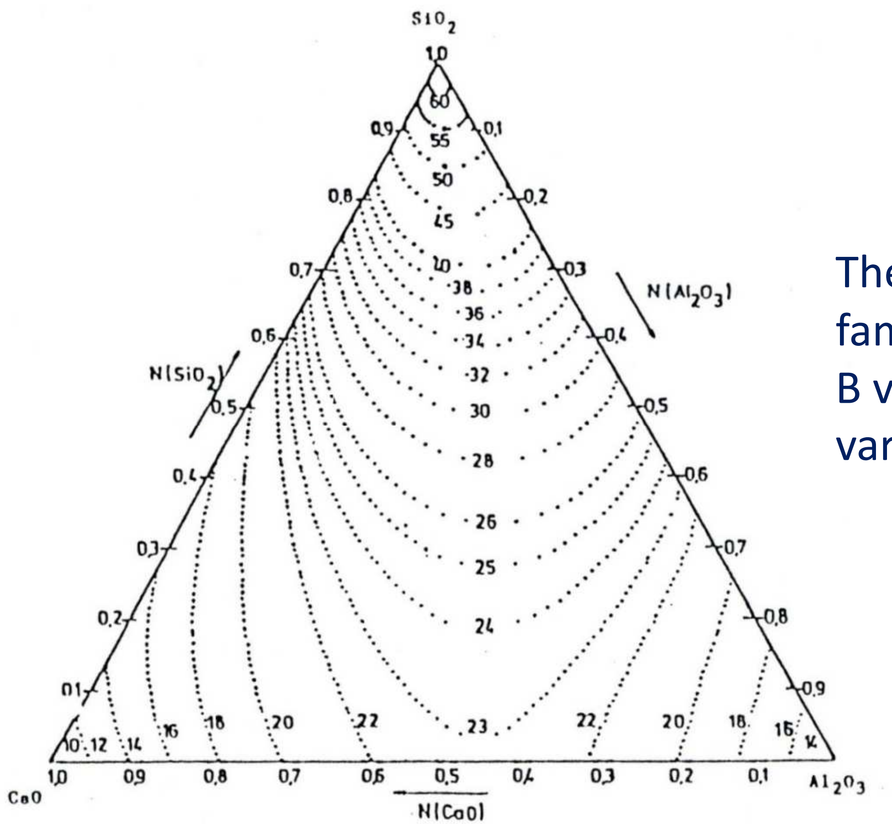
1. Viscosity (η) (*for shaping*): annealing

quenching and forming induce residual stresses → **annealing**

- heating the glass at an uniform T ~ > Tg, during enough time to relax the stresses, then the material is cooled down very slowly
- practically, cooling rate are chosen as a function of part dimensions
  - classically: v < 5°/min
  - precise optical parts: v < 0,7°/min.

What are the properties of glasses & which ones are of interest for bioactive glasses

1. Viscosity (η) : how it varies with composition at a given temperature

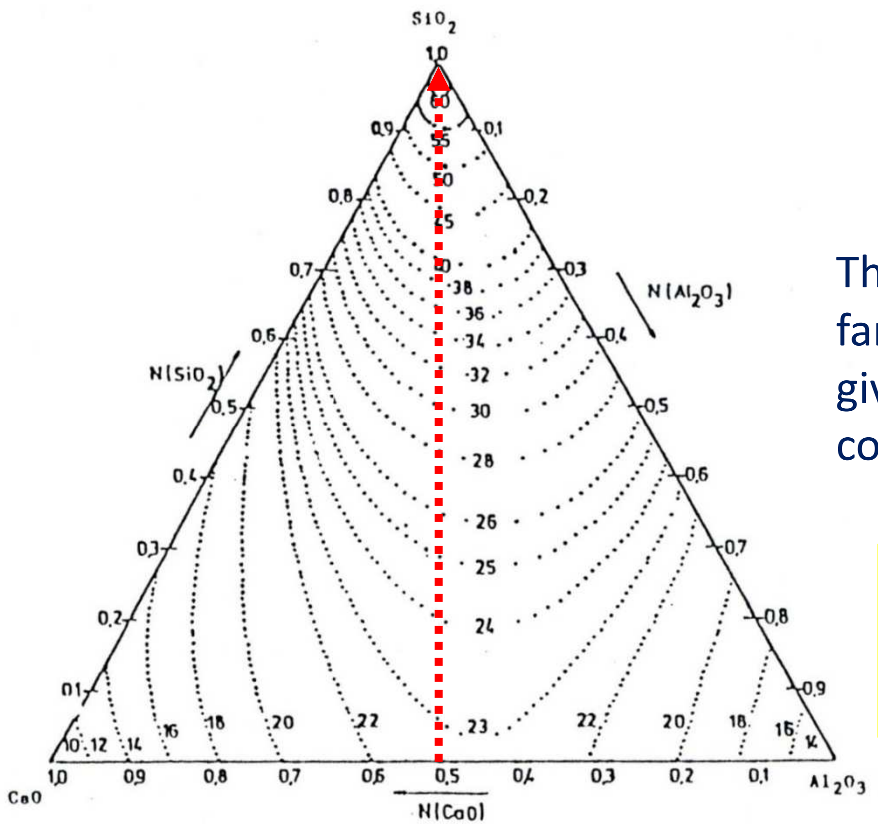


$$\eta = AT\exp\left(\frac{10^3 B}{T}\right)$$

The parameter A is known for a given family of glasses (silicates) → therefore B value give a rough idea of how η varies with composition

What are the properties of glasses & which ones are of interest for bioactive glasses

1. Viscosity (η) : how it varies with composition at a given temperature



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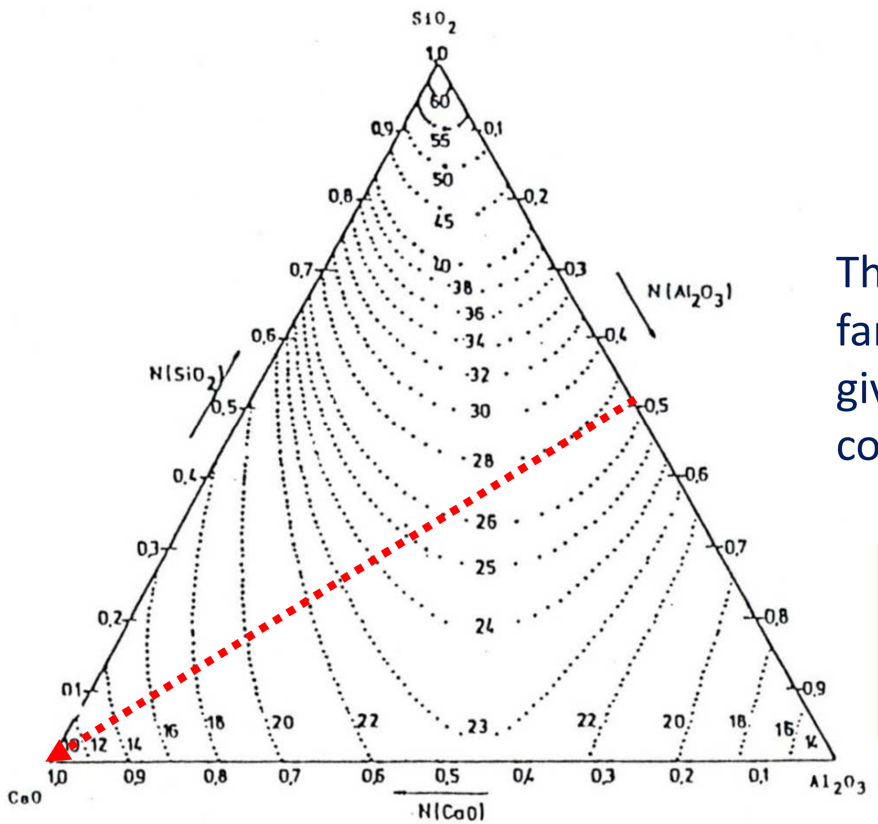
<u>1st example</u>: SiO_2 (network former) ↑ from 0 up to 100%: B (η) increases monotonically

What are the properties of glasses & which ones are of interest for bioactive glasses

1. **Viscosity (η) : how it varies with composition at a given temperature**



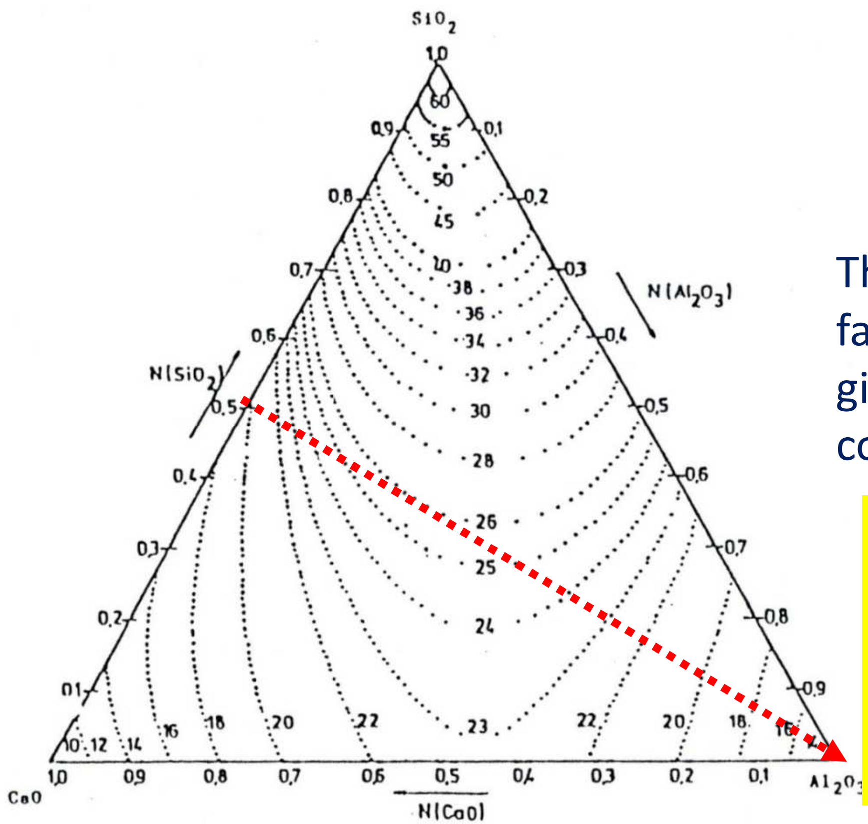
$$\eta = AT\exp\left(\frac{10^3 B}{T}\right)$$

The parameter A is known for a given family of glasses → therefore B value give a rough idea of how η varies with composition

2nd example: CaO (network modifier) ↑ from 0 up to 100%: B (η) decreases ~ monotonically

What are the properties of glasses & which ones are of interest for bioactive glasses

1. Viscosity (η) : how it varies with composition at a given temperature



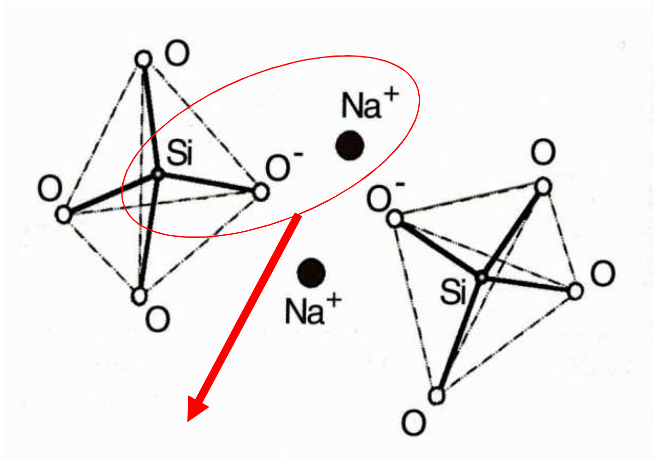
$$\eta = AT\exp\left(\frac{10^3 B}{T}\right)$$

The parameter A is known for a given family of glasses → therefore B value give a rough idea of how η varies with composition

<u>3rd example</u>: Al_2O_3 (intermediate) ↑ from 0 up to 100%:
B (η) increases, reaches a maximum, then decreases: (depending on to the location of Al^{3+} in the glass network)

What are the properties of glasses & which ones are of interest for bioactive glasses

2. Chemical properties (corrosion resistance) – ex soda-lime glass

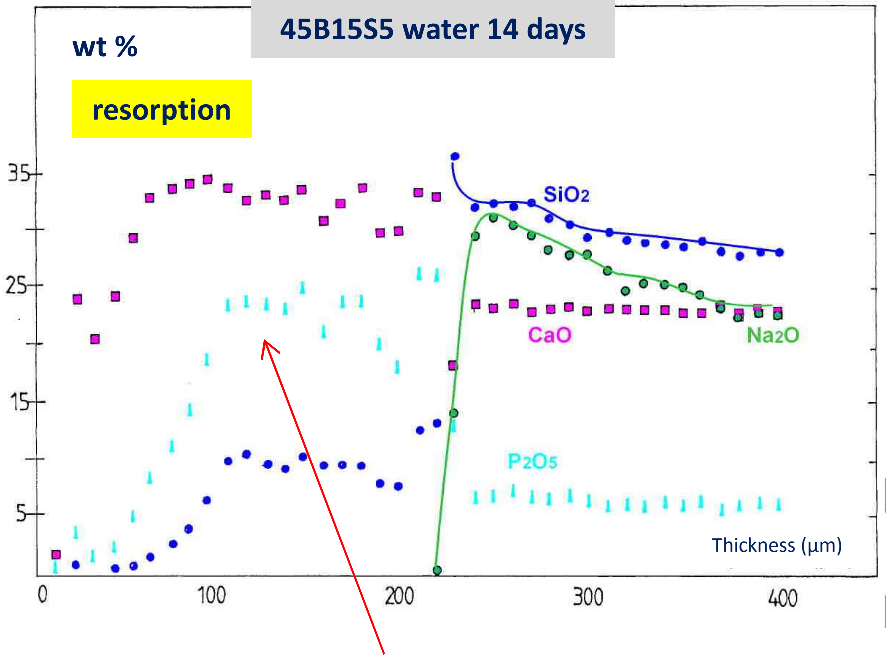


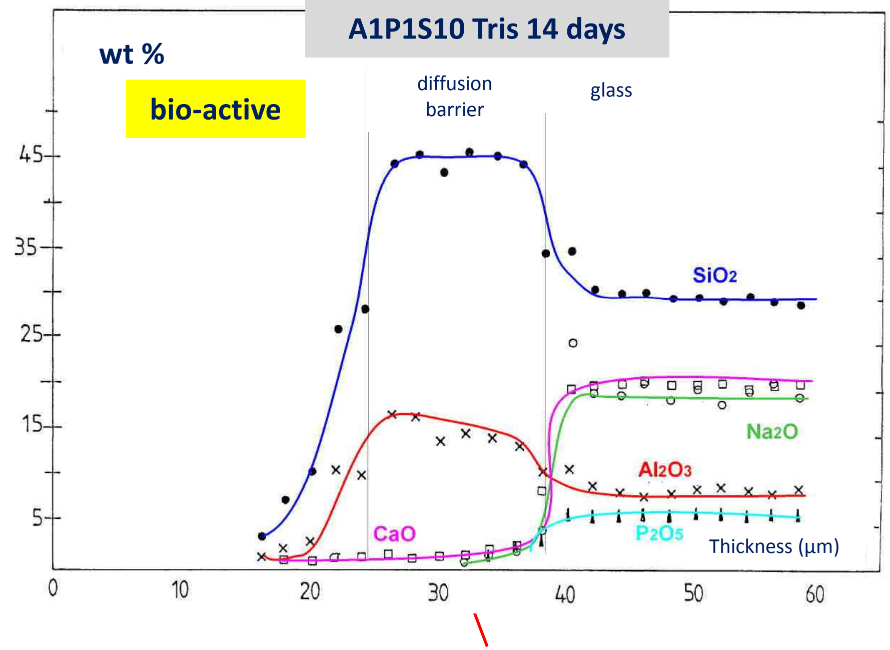
$$-Si-O^{-}Na^{+} + H_2O \rightarrow Si-O^{-}H^{+} + Na^{+}OH^{-}$$

With aqueous solutions: exchange between the modifiers ions and protons → increase of pH; then without pH control, elimination of silicate anions (which are soluble)

What are the properties of glasses & which ones are of interest for bioactive glasses

2. Chemical properties (corrosion resistance) – example of bio-glasses





Glass surface is completely disorganized (on ± 250 µm), but still contain a high amount of CaO and P_2O_5

A stable silica gel layer (± 15 µm) was formed, where bone will grow

Types of bioactive glasses

1969 : discovery of the first bioactive glass (Prof Larry Hench, Univ. Florida)

- 45S5 : known as Bioglass® 45S5

Bioactivity depends on: **Composition** (Ca or P are not necessary), **solubility** of constitutive ions, **texturing**, **structure**, etc.

Commercial name	Composition (mol %)	Process
45S5 *(Bioglass®, PerloGlas®, Novabone®, Biogran®, Novamin®)*	46.1 SiO_2-24.4 Na_2O-26.9 CaO-2.6 P_2O_5	Melting
S53P4 *(BonAlive®)*	53.8 SiO_2-22.7 Na_2O-21.9 CaO-1.7 P_2O_5	
13-93	54.6 SiO_2-6 Na_2O-22.1 CaO-1.7 P_2O_5-7.9 K2O-7.7 MgO	
58S	60 SiO_2-36 CaO-4 P_2O_5	Sol-gel
S7030C	70 SiO_2-30 CaO	
MBG95	85 SiO_2-10 CaO-5 P_2O_5	
B75-Sr5	75.5 SiO_2-21.6 CaO-2.9 SrO	

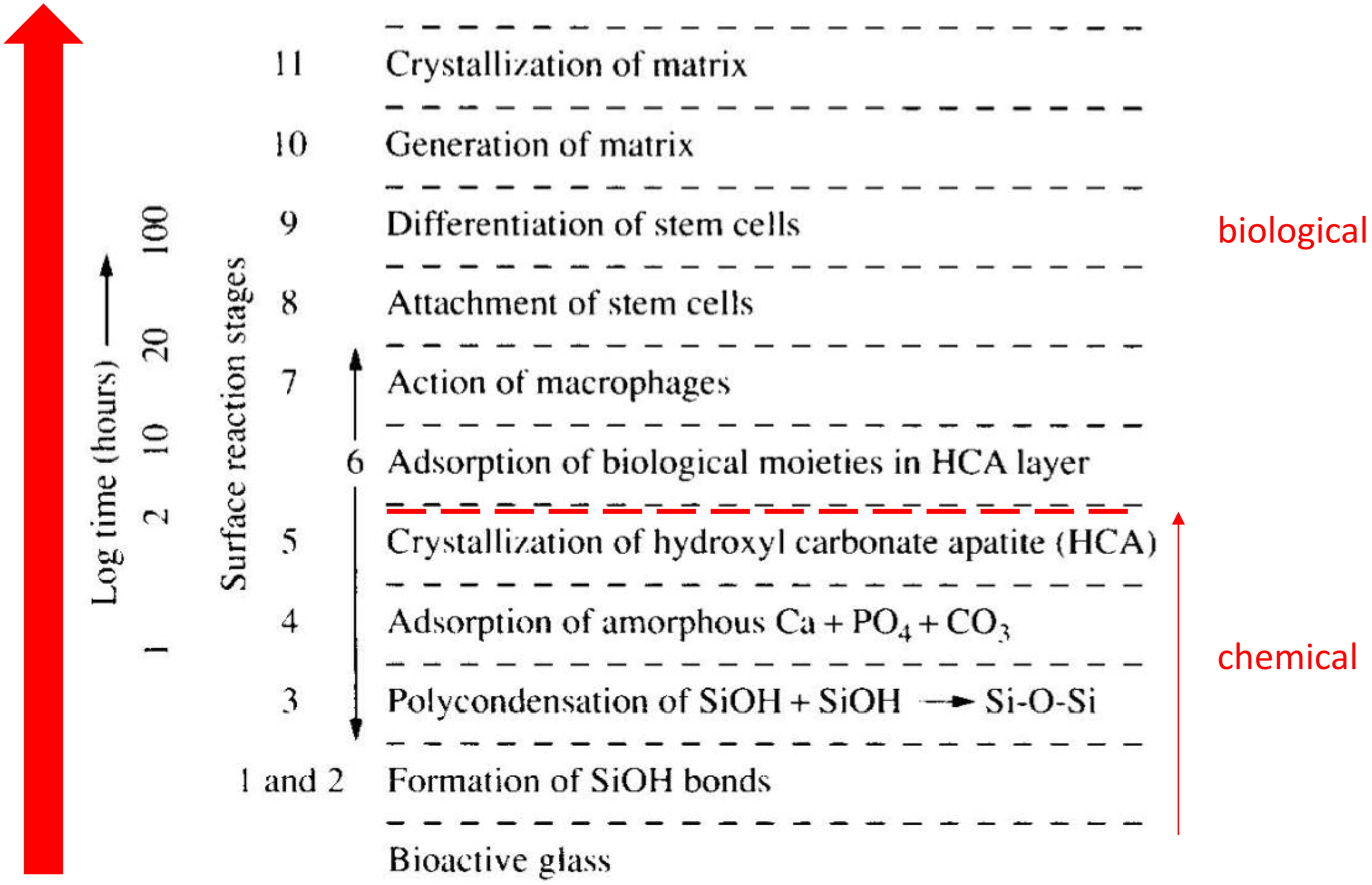
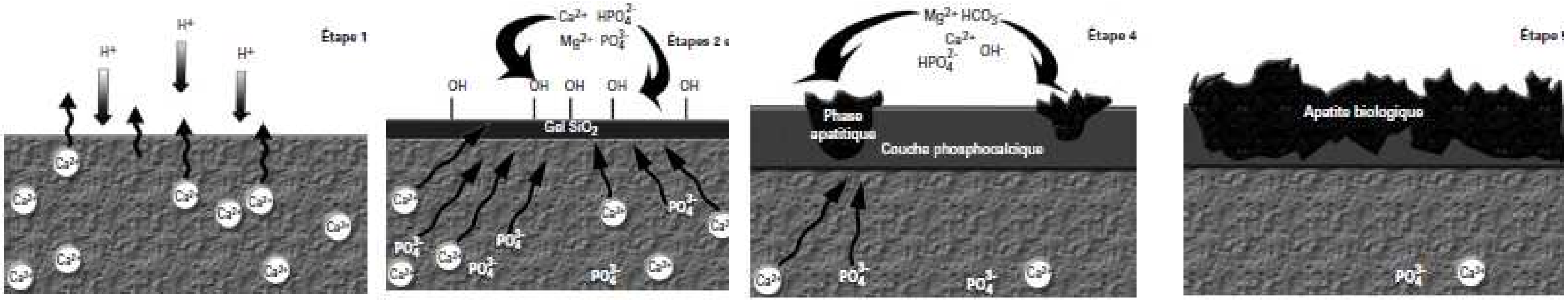


Fig. 3. Sequence of interfacial reactions involved in forming a bond between tissue and bioactive glasses.

Mechanism of interaction



First step: exchange of H^+ from biological medium with modifier ions at the glass surface → silanol formation, medium pH increases
If P is present, could also leave the glass surface

Step 2 : Increase of pH → rupture of Si-O-Si bonds of the glass network by hydrolysis, giving soluble $(SiO_4)^{4-}$ and formation of more Si-OH at the surface

Step 3: Polymerization of a silica gel layer by silanol condensation at the surface → the bioactive surface is poor in terms of alkaline and/or alkaline-earth ions

Step 4 : Migration of Ca^{2+} et PO_4^{3-} (both coming from the biological medium and/or the glass) through the SiO_2 layer to the glass surface → the surface becomes rich in calcium and phosphorus

Step 5 : Nucleation of calcium phosphates – incorporation of OH^- and CO_3^{2-} from the biological medium – partial crystallization of a HAC layer

Processing & applications

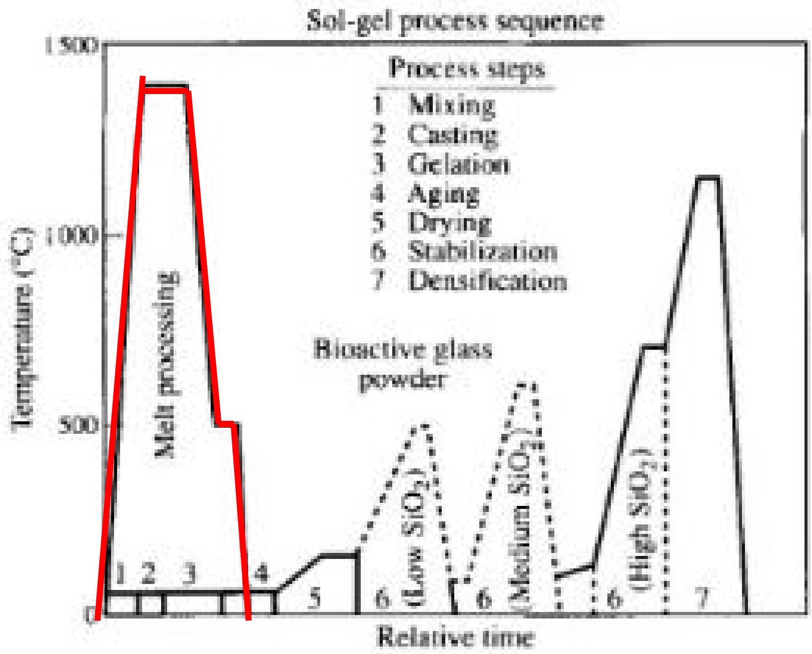


Fig. 5. Processing steps in making bioactive gel-glasses by the sol–gel method.[74]

Hench's 45S5 has been implanted to more than one million patients from its discovery

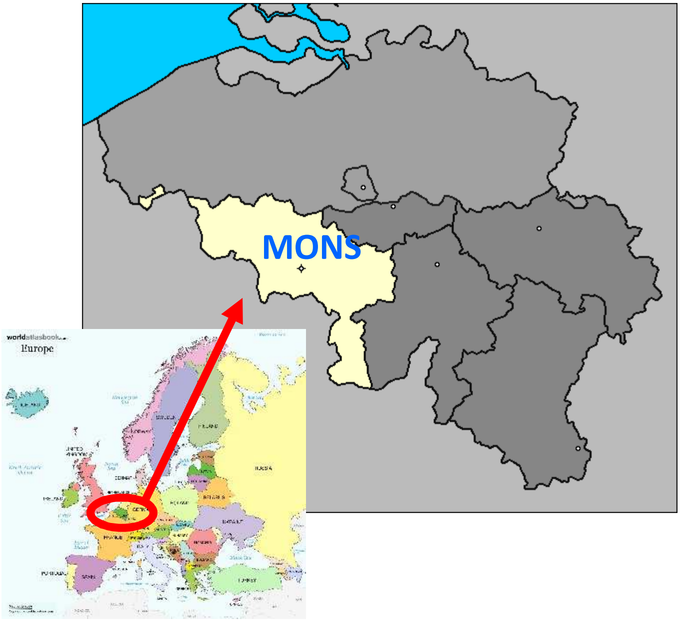
Monoliths: orbital and jaw bones restauration, intern ear bones

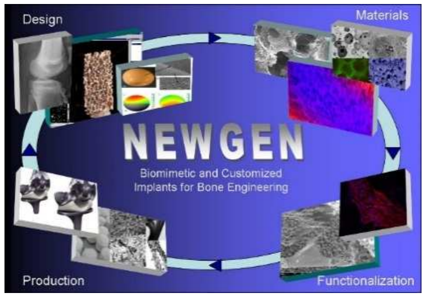
More common: as particles, i.e. Perioglass® commercialized by NovaBone (USA), as synthetic bone substitute to regenerate jaw bone, stabilize healthy teeth or allow to place a metal implant, also as bone filling in orthopedic surgery

From 2004 → 45S5 is added in toothpaste (commercialized by GSC from 2010) to reduce the dental hypersensitivity

Very few coatings tests

Thank you for your attention!





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