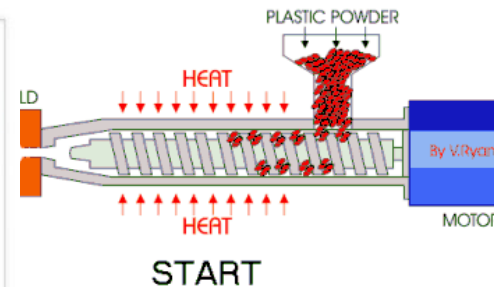


Ceramic and Colloidal Processing

Week 11

11. Ceramic forming methods, drying and binder removal (binder burnout)

A. Testino



Courtesy: HAPPS POTTERY
Western Australia

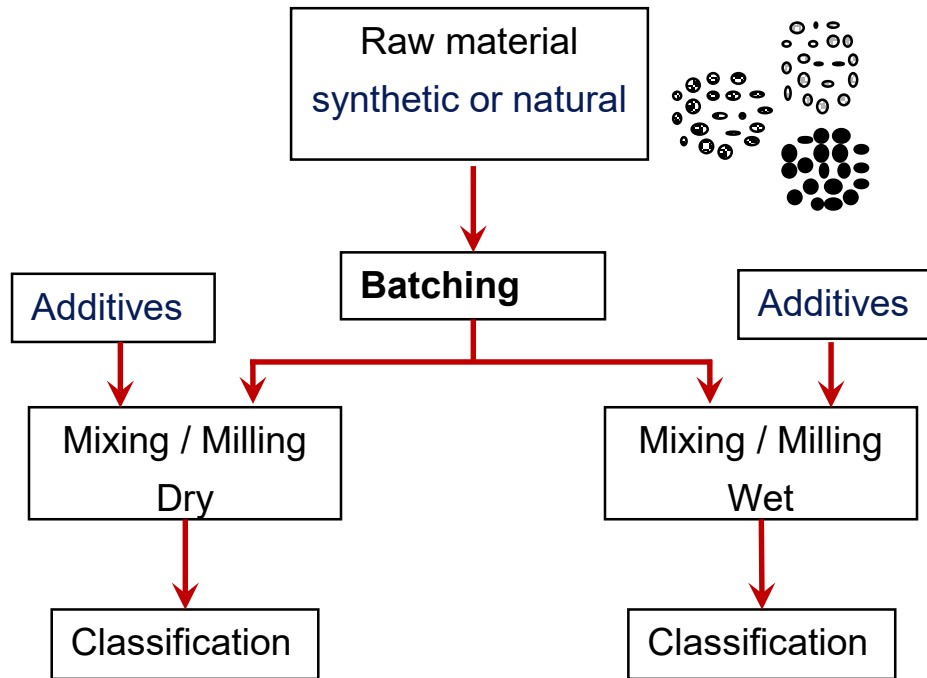
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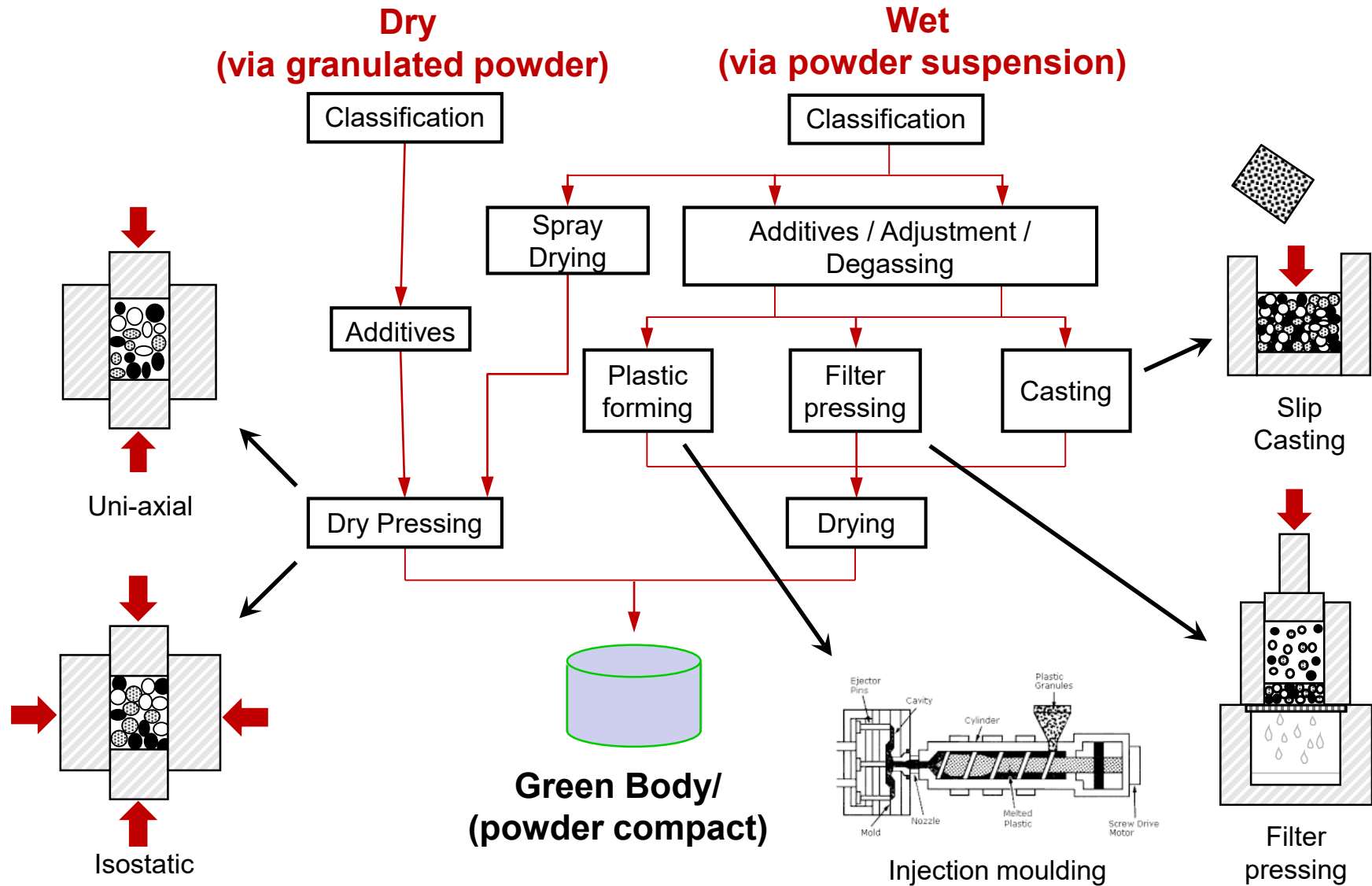
Ceramic Processing – 1 - Powders



- ❖ Commercial powders, often modified for application
- ❖ milling step in order to break up the agglomerates,
- ❖ Synthesized by solid route or by precipitation
- ❖ Different types of equipment - practical aspects and some scientific principles

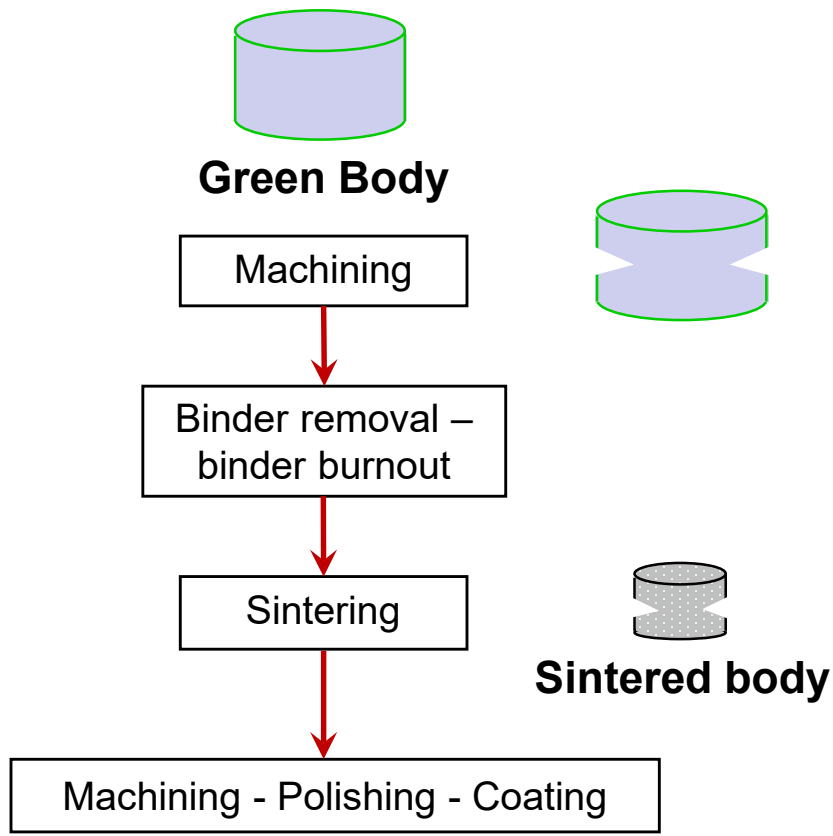
- **known** chemical purity,
 - good reactivity
 (size $\sim 1 \mu\text{m}$ and specific surface $\sim 5\text{-}15 \text{ m}^2/\text{g}$) and
 -good homogeneity - physical and chemical.

Manufacture of Ceramics - Ceramic Processing

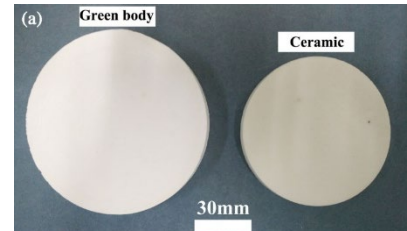


Manufacture of Ceramics - Ceramic Processing - Firing

- Sintering (firing) and Finishing



Source: ceramicartsdaily.org



Gan et al. DOI:10.1002/app.48889

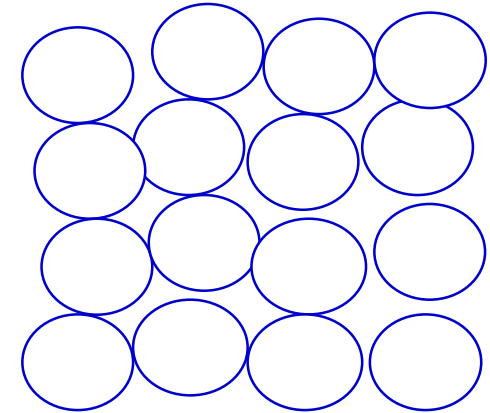


© CeramTec

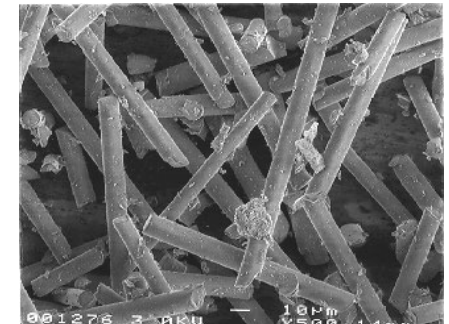
Particle Packing - Compaction

- Make sintering easier - minimize shrinkage
 - best packing – compaction desired
 - also important influence on the rheology of pastes and suspensions – that scale on maximum particle packing
- Packing of spheres - one size - monosize
 - Simple cubic 52.4%, Face centered cubic 74%
 - Randomized 64%

Monomodal 64%



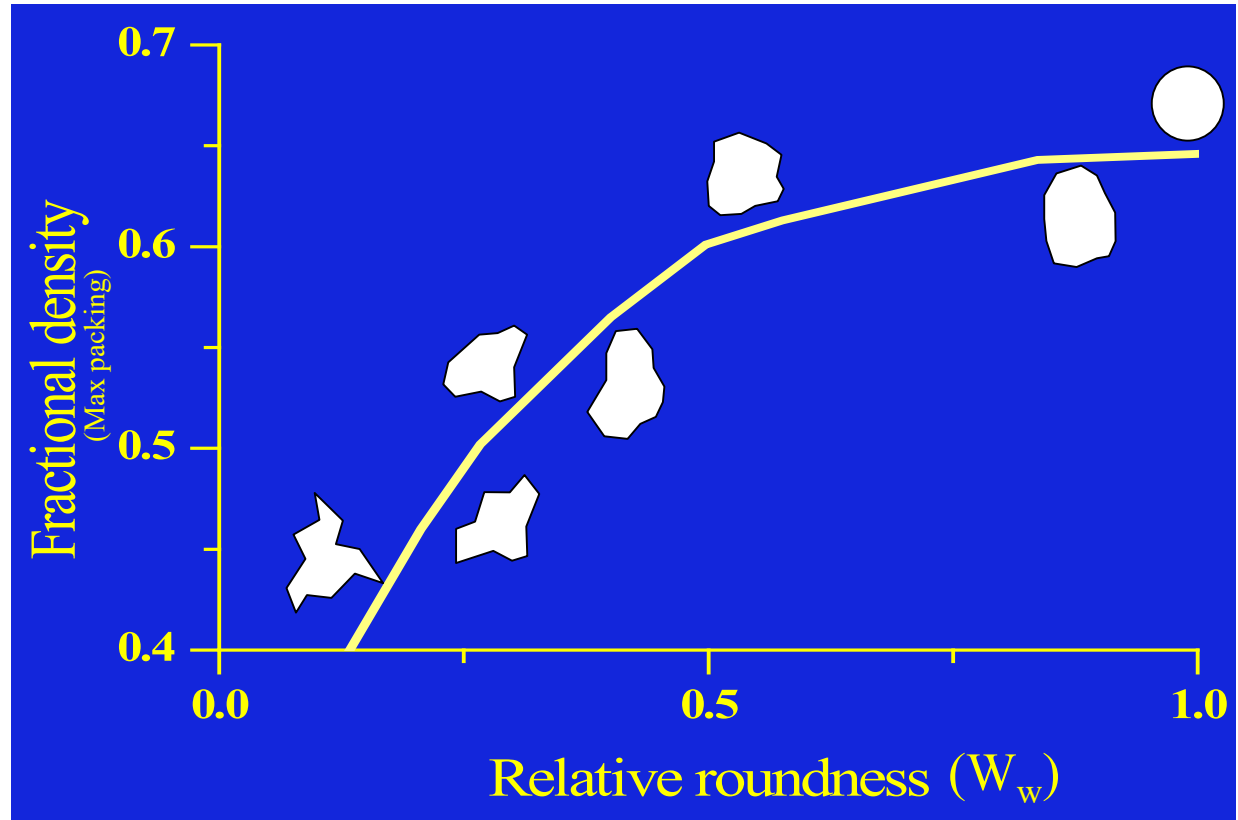
- ◆ For spheres - monosized
 - other particle shapes* such as cylinders, discs
 - maximum packing decreases with increase in length /diameter ratio for cylinder or diameter /thickness ratio for discs
 - i.e. the aspect ratio – longest dimension/smallest dimension
 - Slide 25 – Week 1 course 2.1 Powder characterization -I



* RM German "Particle Packing Characteristics", Metal Powder Industries Federation, Princeton, NJ, 1989.

Sphericity W_w : influence on packing of monosized particles

- ◆ German* - « relative roundness » - sphericity
- ◆ Slide 25 week 1
- ◆ Course 2.1 Powder characterization
- ◆ Clear Effect
- ◆ Decrease in packing fraction – i.e. the maximum packing fraction when we have particles that deviate from a sphere



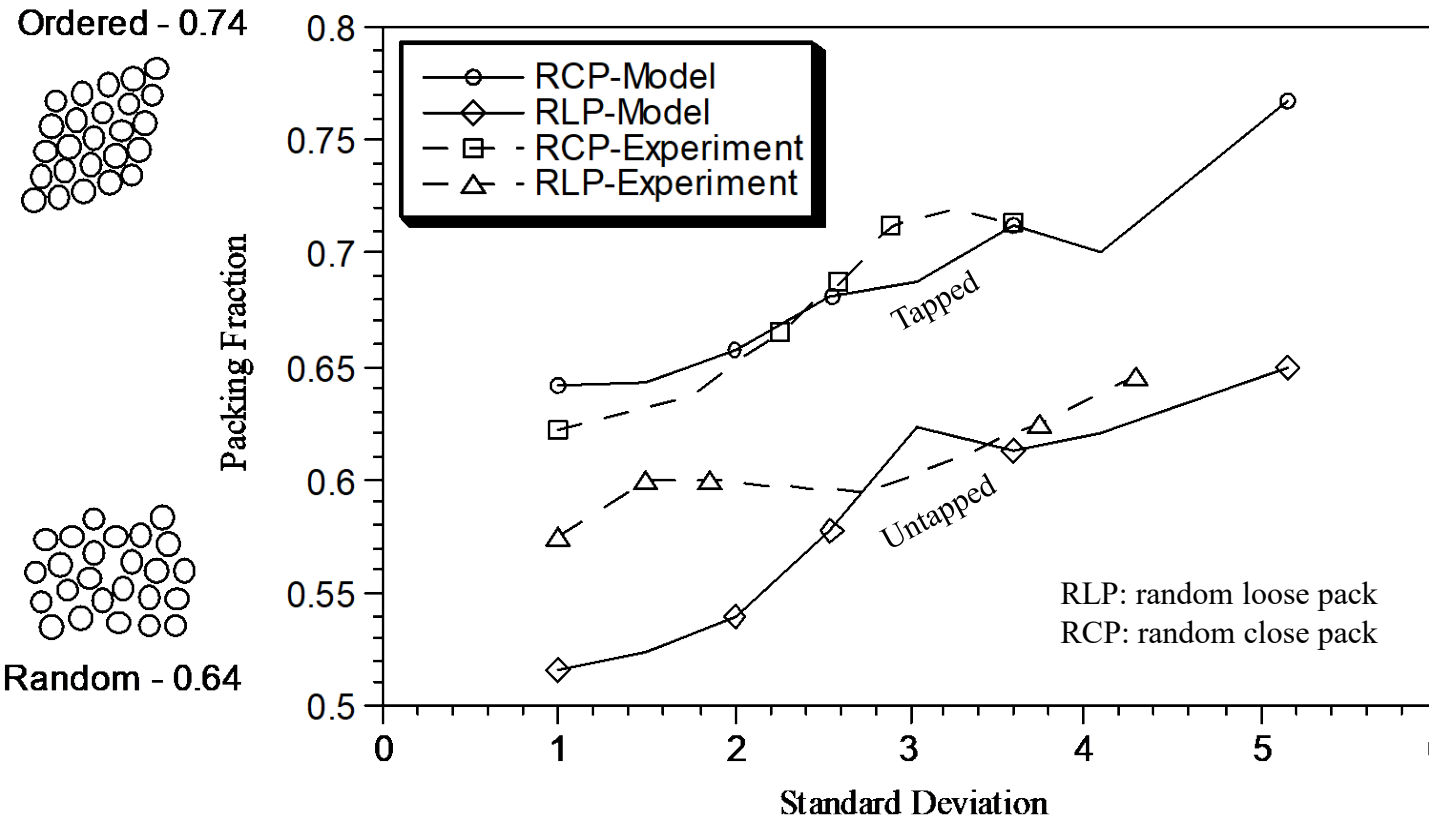
❖ Sphericity (W_w):

$$W_w = \frac{\text{Specific surface area of a sphere with same volume as particle}}{\text{Specific surface area of particle}}$$

* R.M. German "Particle Packing Characteristics", Metal Powder Industries Federation, Princeton, NJ, 1989.

Particle Packing - Models

- Size distribution - example of lognormal distribution
- Increasing the width of the distribution increases the maximum packing *

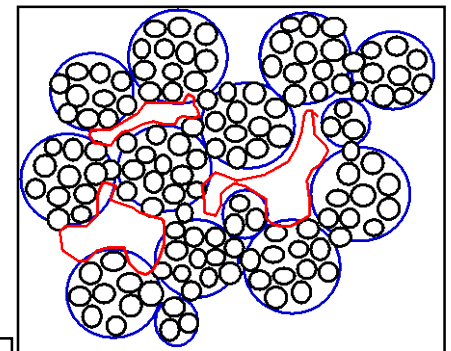
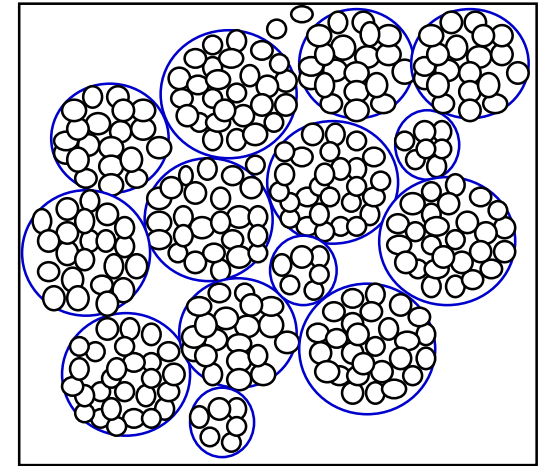
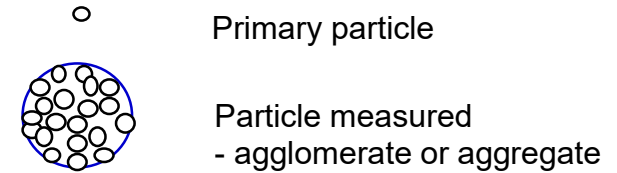


- ◆ First interpreted as pores between large particles are filled with fine particles
- ◆ BUT
- ◆ Modeling * showed there are **not enough fines**
- ◆ Rather there are many large particles **without pores**.
- ◆ N.B. - microstructure - influenced by original particle sizes
- ◆ Ceramics - desire a narrow distribution
- ◆ Concept of multimodal successfully used in cement fields

* GT Nolan and PE Kavanagh, Powder Technology, 231-238, 78 (1994).

Compaction and Agglomeration Factor

- Lower packing fraction for agglomerated powders
 - voids in particles between primary particles
 - voids between agglomerates
 - bimodal pore size distribution (inter-particle and intra-particle)
 - densification during sintering is thus inhomogeneous
intra-particle pores densify more quickly
- F_{ag} gives a comparative figure between powders and de-agglomeration treatment e.g. Milling, sonication, high shear mixing
- Slide 19 – week 2
- Course 2.2 Powder Characterization-II



$$F_{ag} = \frac{d_{v50}}{d_{BET}} \quad d_{BET} = \frac{6}{SSA \cdot \rho}$$

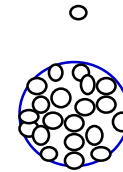
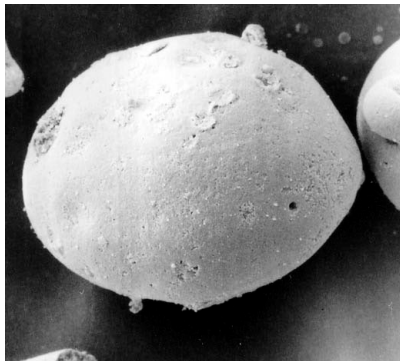
d_{v50} - median diameter (volume, μm), d_{BET} is an average diameter (μm) calculated from specific surface area, SSA (m^2/g) measured by nitrogen adsorption (model BET), ρ powder density (g/cm^3)

Dry Pressing

- ◆ Pressing - compaction of **atomized (spray dried) granules**

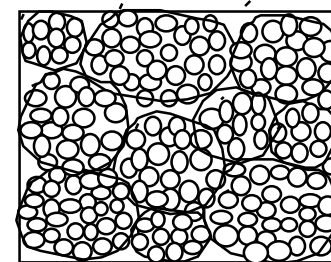
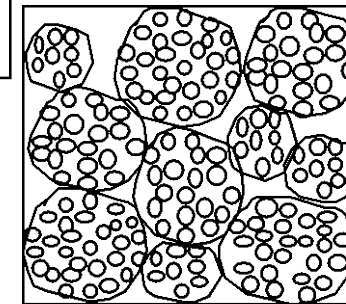
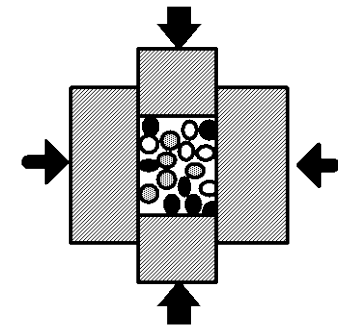
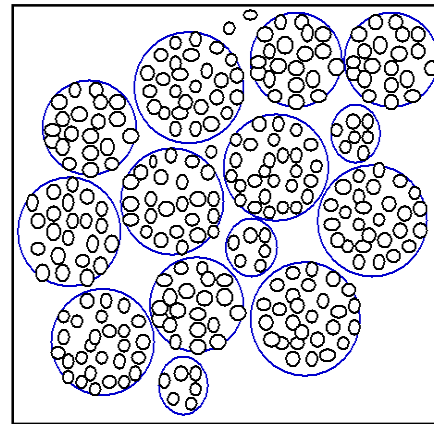
Effects of powder characteristics on compaction

- ◆ 3 stages
 - Rearrangement
 - Deformation of granules
 - Granule fracture (rarely seen in practice)



Primary particle (1 μ m)

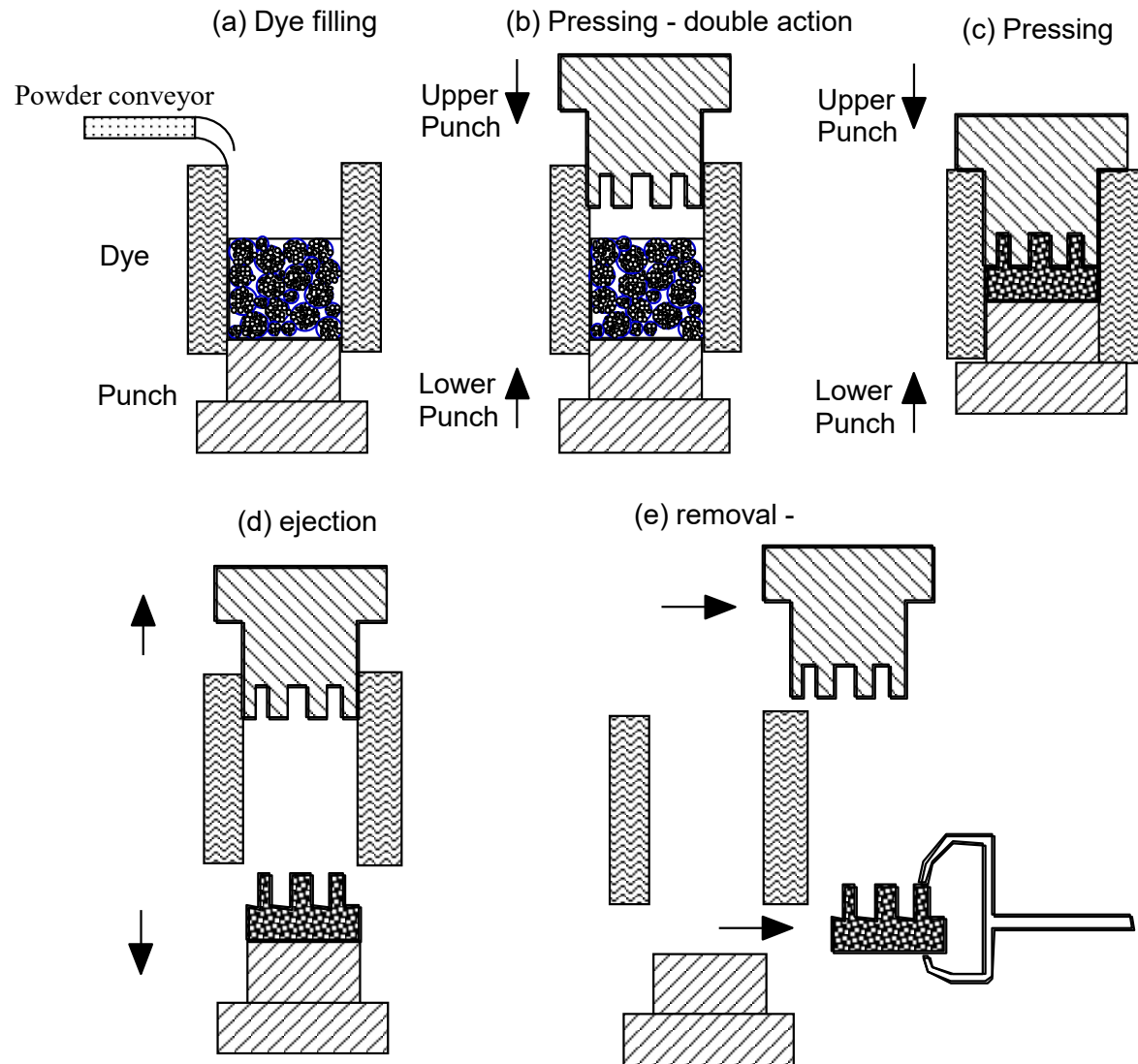
Granule for pressing (50-300 μ m)



Uniaxial Dry Pressing - Automatic

Figure 3.5.3

- ◆ Can be used for samples with relatively simple geometry at least in 2D
- ◆ Limited to mm thicknesses
- ◆ High rate up to 1000 pieces per hour!



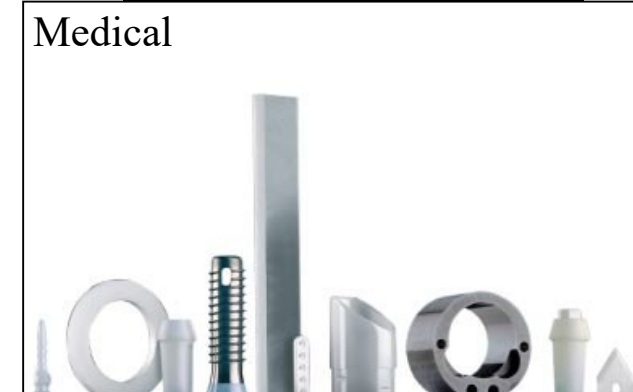
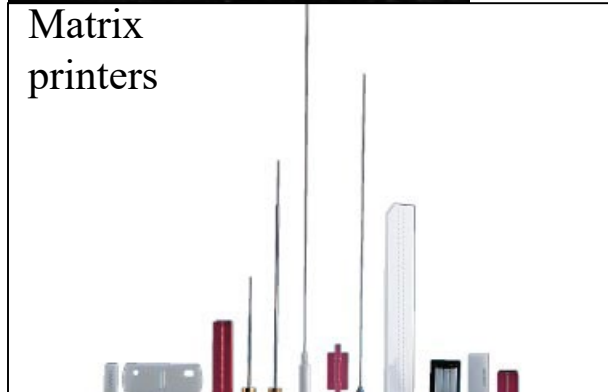
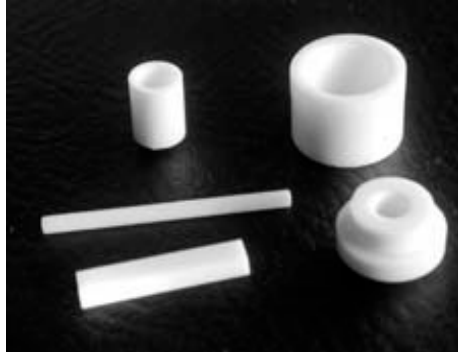
Limitations

- Elongated shapes
- Complex shapes too
- Large pieces cm.....

Uniaxial pressing - automatic - examples of Ceramaret SA Bole - CH

<http://www.ceramaret.ch/index.php>

- ◆ 1-2 micron precision as pressed without post-machining - only debinding, sintering and polishing



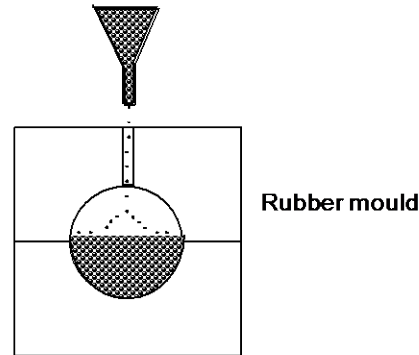
- By compacting the powders to obtain parts close to the final dimensions, Ceramaret decreases the number of expensive secondary operations.
- This approach significantly reduces production costs. The savings are all the more significant as the manufacturing is repetitive, even for a high number of parts to be produced.
- **Tungsten Carbide Forming Tools** guarantee maximum precision and longevity
- For shaping ceramic powders, Ceramaret has fully automated mechanical presses, single and double acting, cold and hot isostatic presses (CIP and HIP).

Cold Isostatic Pressing- CIP

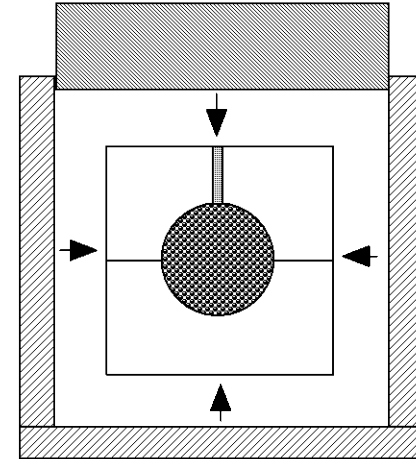
- ◆ Can be semi-automatic with gas as compression fluid
- ◆ Normally oil in lab presses....
- ◆ Can be used for parts with more complicated relief
- ◆ longer pieces i.e. too long for dry pressing ...
- ◆ And for high quality spheres
- ◆ Such as hip-joint prosthesis



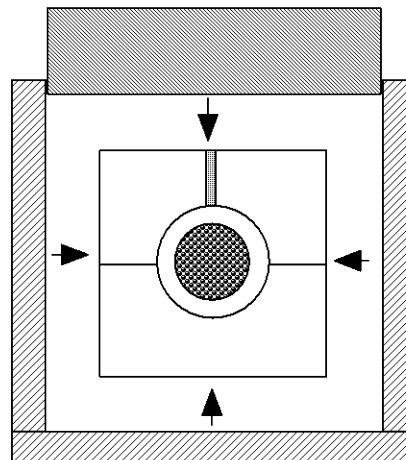
(a) Filling of mould



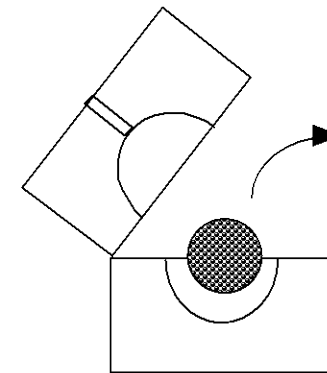
(b) Loading into pressure chamber



(c) Pressing and decompression



(d) demoulding and removal



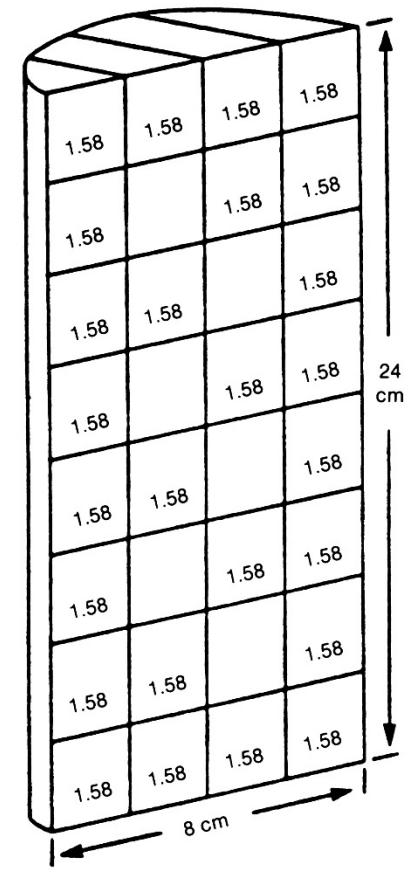
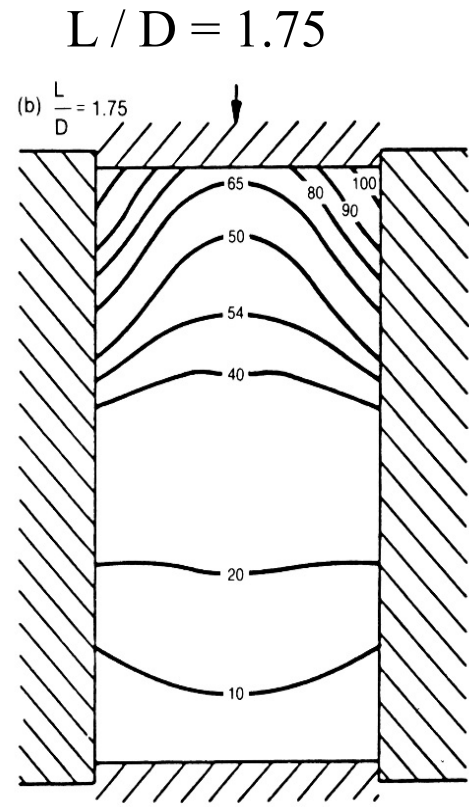
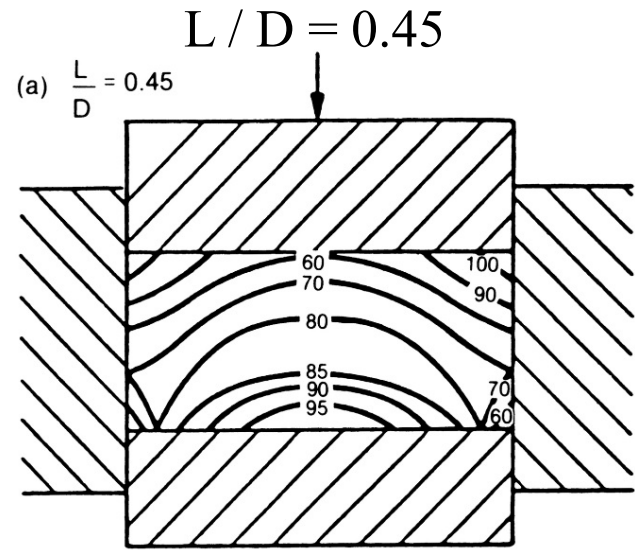
https://www.youtube.com/watch?v=77fu_aiEJkM

Dry Pressing - Density gradients in green bodies

Uniaxial - simple

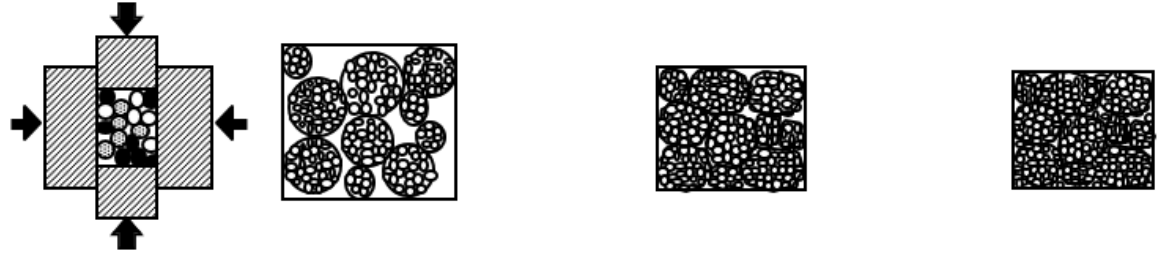
Uniaxial - simple

Cold Isostatic Pressing
- Very homogeneous densities
CIP



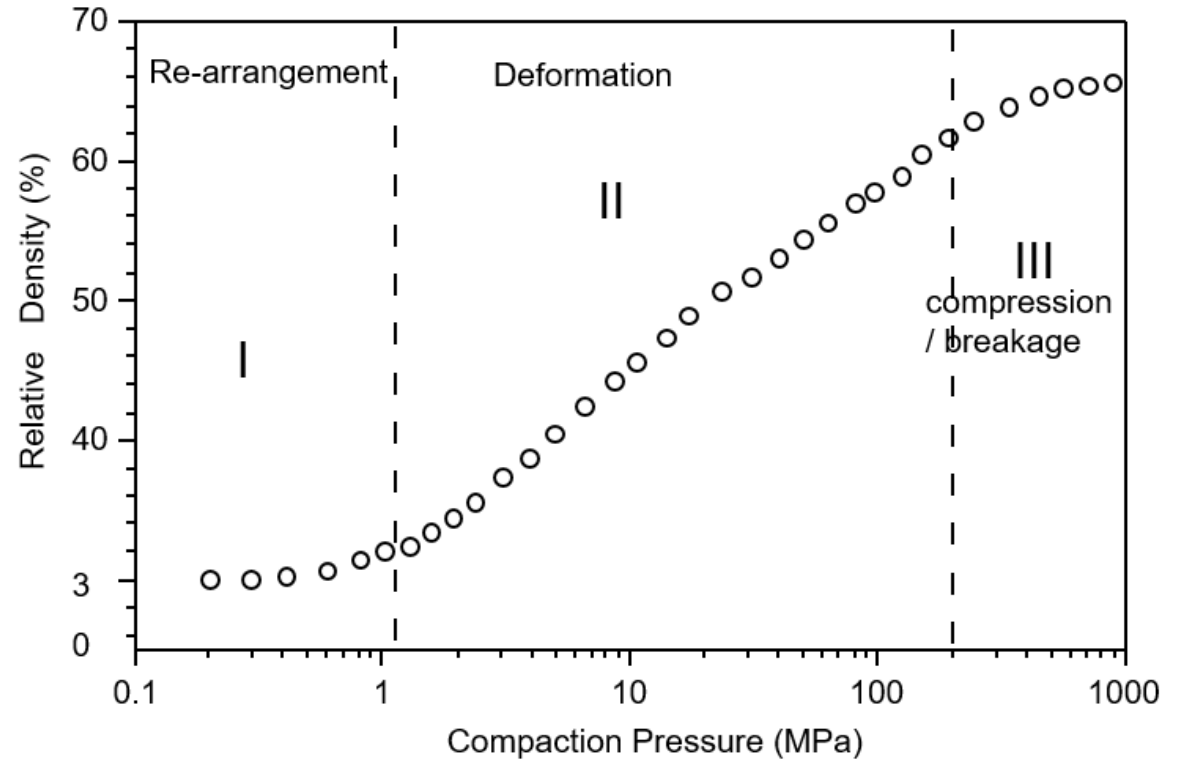
- ◆ Significant density gradients
- ◆ Can lead to defects on ejection
- ◆ - See slides- 21-22
- ◆ And loss of dimensional stability after sintering – poor dimension precision – needs machining to rectify

Dry Pressing – stages of compaction



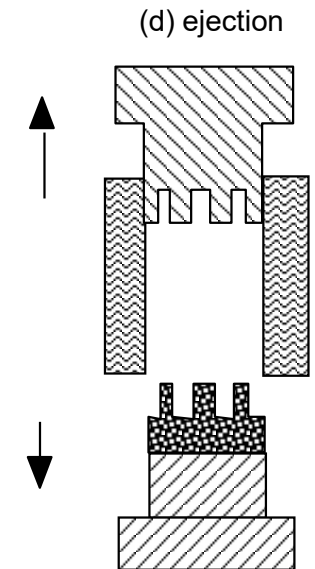
Compaction takes place in 3 stages

- ◆ Re-arrangement (0.5 MPa)
- ◆ Deformation of granules
- ◆ Fracture and densification of granules (rare for applied pressures < 200 MPa)

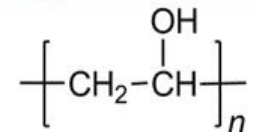
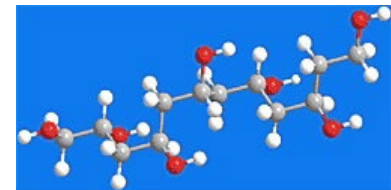


Ejection

- ◆ Stored elastic energy is released when the compact is withdrawn – creates a spring back - if this is too large, defects may appear
- ◆ We want a linear spring back of less than 0.75% to avoid defects
- ◆ Lubrication of the walls and granules - important (e.g. oleic acid)
- ◆ Compact must be strong enough for subsequent handling, e.g. robots
- ◆ Normally ensured by the use of an organic additive or binder
 - e.g. polyvinyl alcohol - PVA with Mw 50'000-100'000
 - increased resistance for higher molecular weights (but hardness also increases so we use plasticizers like polyethylene glycol,
 - PEG (PEG $[-\text{CH}_2-\text{CH}_2-\text{O}-]_n$) – give the granule plasticity for pressing
- ◆ Higher pressures can give higher mechanical strengths and higher green densities,
 - but the residual stresses during ejection are then increased, giving rise to more defects.
- ◆ An optimum must be found between applied pressure, quantity and type of organic additive, as well as resistance and compact (green body) density.



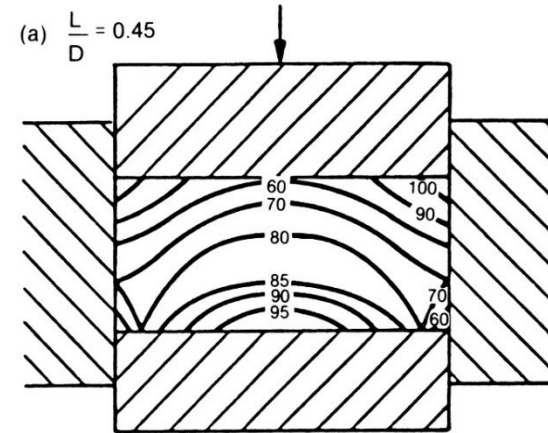
PVA



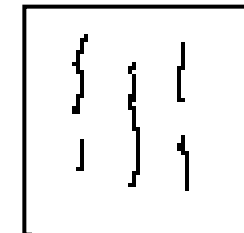
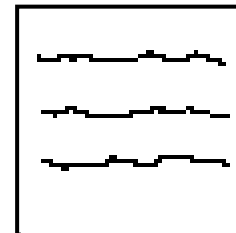
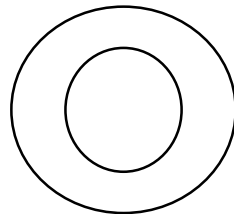
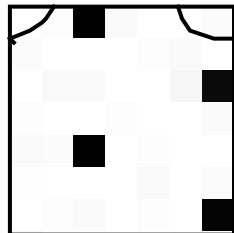
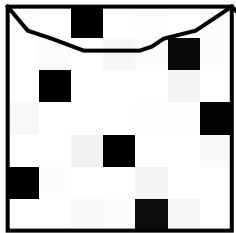
Gray - carbon
 Red - oxygen
 White - hydrogen

Dry pressing Ejection – Density Distribution and Defects

- ◆ Density distribution – because of friction between granules – and between the granules and the walls leads to a loss of pressure transmission...certain areas are pressed at a lower pressure than that applied macroscopically by the press.
- ◆ This can cause a loss of dimensional stability because of
- ◆ Differential shrinkage during sintering or
- ◆ Ejection defects



(a) end capping (b) ring capping (c) lamination (d) vertical cracking



Typical additives - for spray drying granules

Component	Function	% wt powder
Polyvinyl alcohol	Binder – green body strength	1-3
Poly ethylene glycol	Plasticizer – deformability	0.5-1
Oleic acid or ammonium stearate	Lubricant - friction reduction	0.05
Polyacrylic acid	Dispersant for spray drying suspension	0.5-1
Octanol	promotes degassing of the suspension to atomize	<0.1
humidity	acts as a secondary plasticizer	1
De-foamer	prevents foaming during degassing	<0.1

Slip Casting

- ◆ Porcelain – wash basin, cups, fine china
- ◆ Complicated shapes and large size
- ◆ Slip casting – uses concentrated suspensions (the slip) with 45% vol powder –
- ◆ 80 minutes per mould for a wash basin
- ◆ Pressure casting - 2 mins! 40x faster
- ◆ Modern plants are semi-automatic
- ◆ 1 week for mixing, homogenization and milling of the slip
- ◆ Slip casting with sub-micron alumina powders can achieve very high green densities of 68% very close to the maximum packing fraction
- ◆ But have to dry before sintering – wash basin 6 days in ambient!

Limitations

- wall thickness ~1cm max
- Slow - drying ...



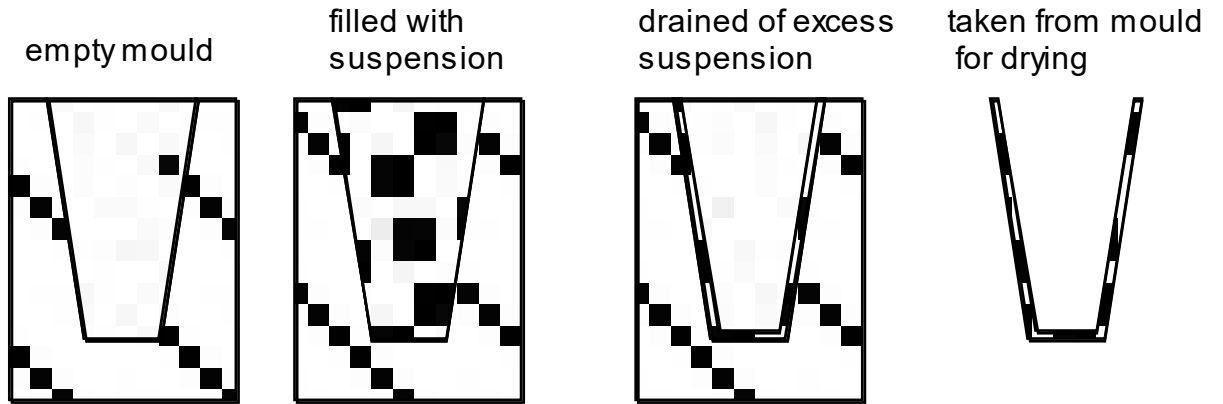
LAUFEN - Switzerland

Slip casting – practical aspects

Drain casting

- by emptying the excess slip

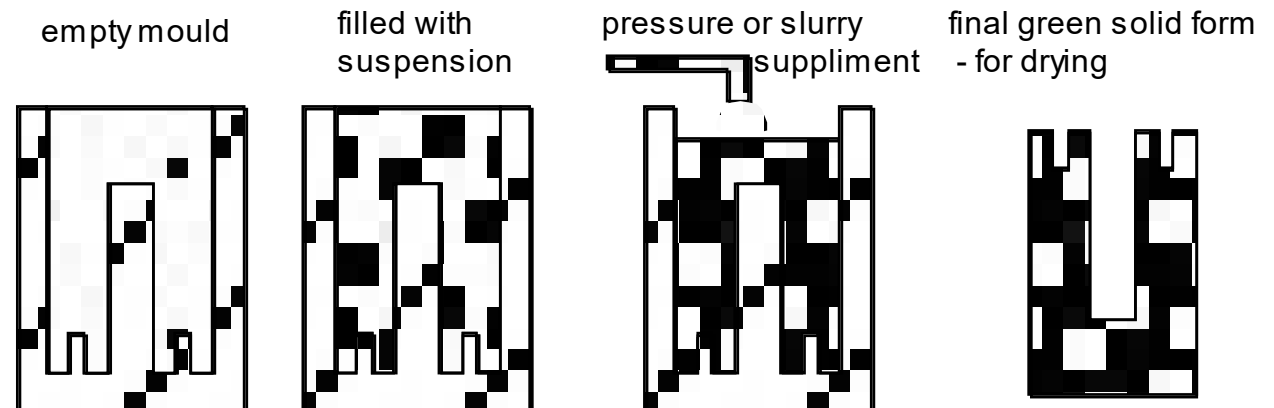
The slip needs to be poured easily - i.e. a low viscosity – e.g. with Newtonian rheology – no yield point....



Porous mould absorbs water by capillary action - ceramic particles form a layer on the mold and become themselves a barrier for the flow of the liquid because the pores in the ceramic layer are smaller than those in the plaster mould – with parabolic kinetics – next slide

Solid casting

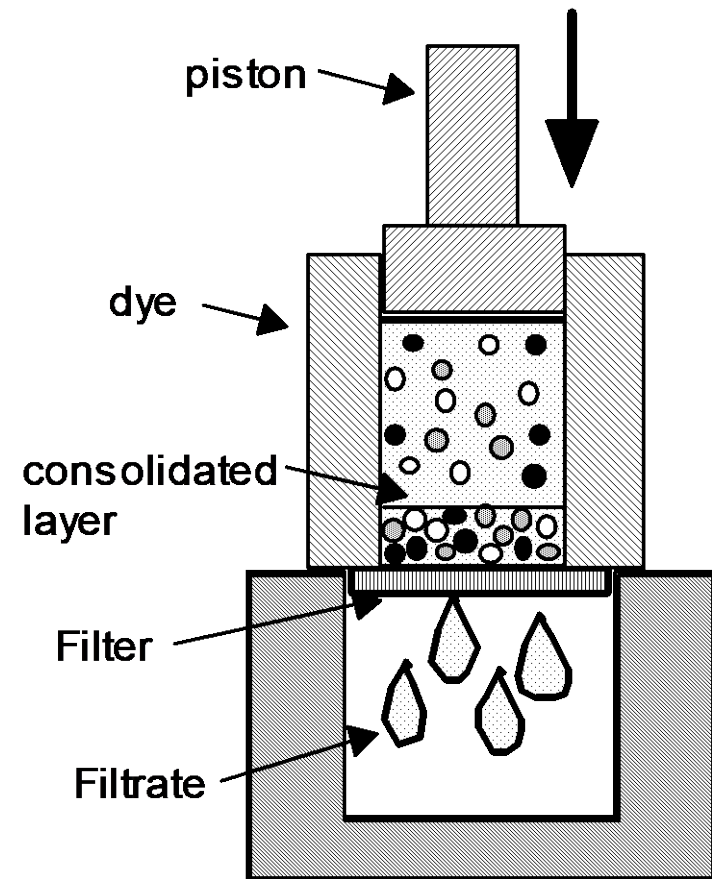
- Solid form by topping up slip



VIDEO _slip casting vase... <https://www.youtube.com/watch?v=FZzOTX9Ihqs>

Filter Pressing

- Filter pressing is used for example to produce ferritic magnets, and sometimes the suspension is
 - **flocculated** (with high molecular weight polymers) or
 - **coagulated** - addition of salts, calcium nitrate for porcelain,
 - to increase the filtration speed
- Flocculation or coagulation can also limit segregation of components of different sizes for mixed powder suspensions
- Coagulation or freezing can also be used for casting into non-porous molds
- Suspensions with as high a solids loading as possible very very important to produce high density green bodies ...which means
- = very good initial colloidal stability....



Casting / Filtration Kinetics

Filtration kinetics - also applicable for casting with the capillary pressure being the applied pressure.

- ◆ Kinetics follow a parabolic law derived from Darcy's law

$$d = \left[\frac{2K_p P t}{\eta} \left(\frac{v_1}{v_0} - 1 \right) \right]^{\frac{1}{2}}$$

d - is the thickness of the consolidated layer,

K_p - the permeability of the consolidated layer,

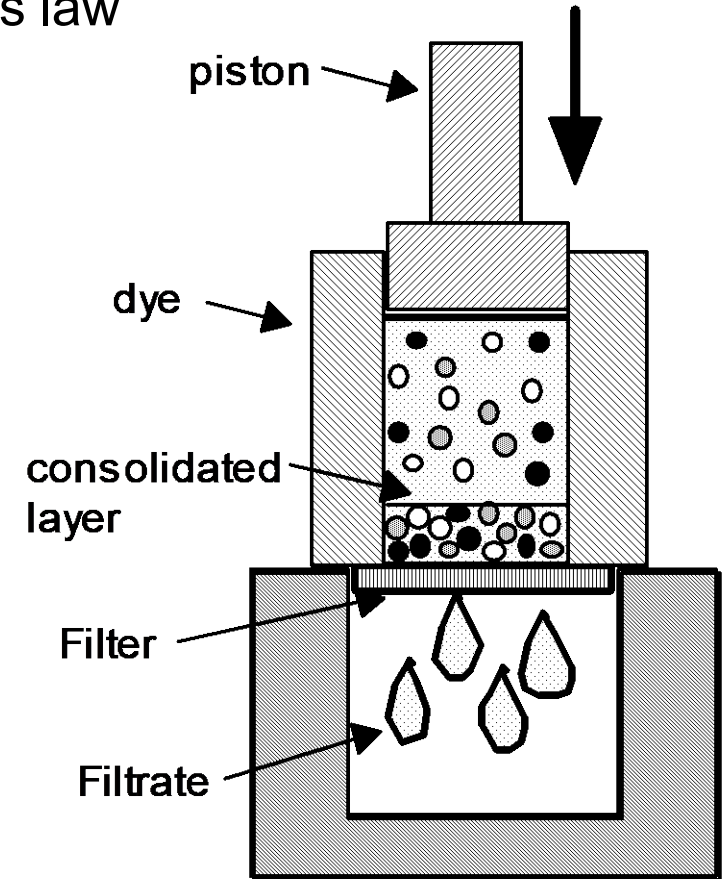
t - filtration time,

P - the applied pressure (gas, piston, or capillary),

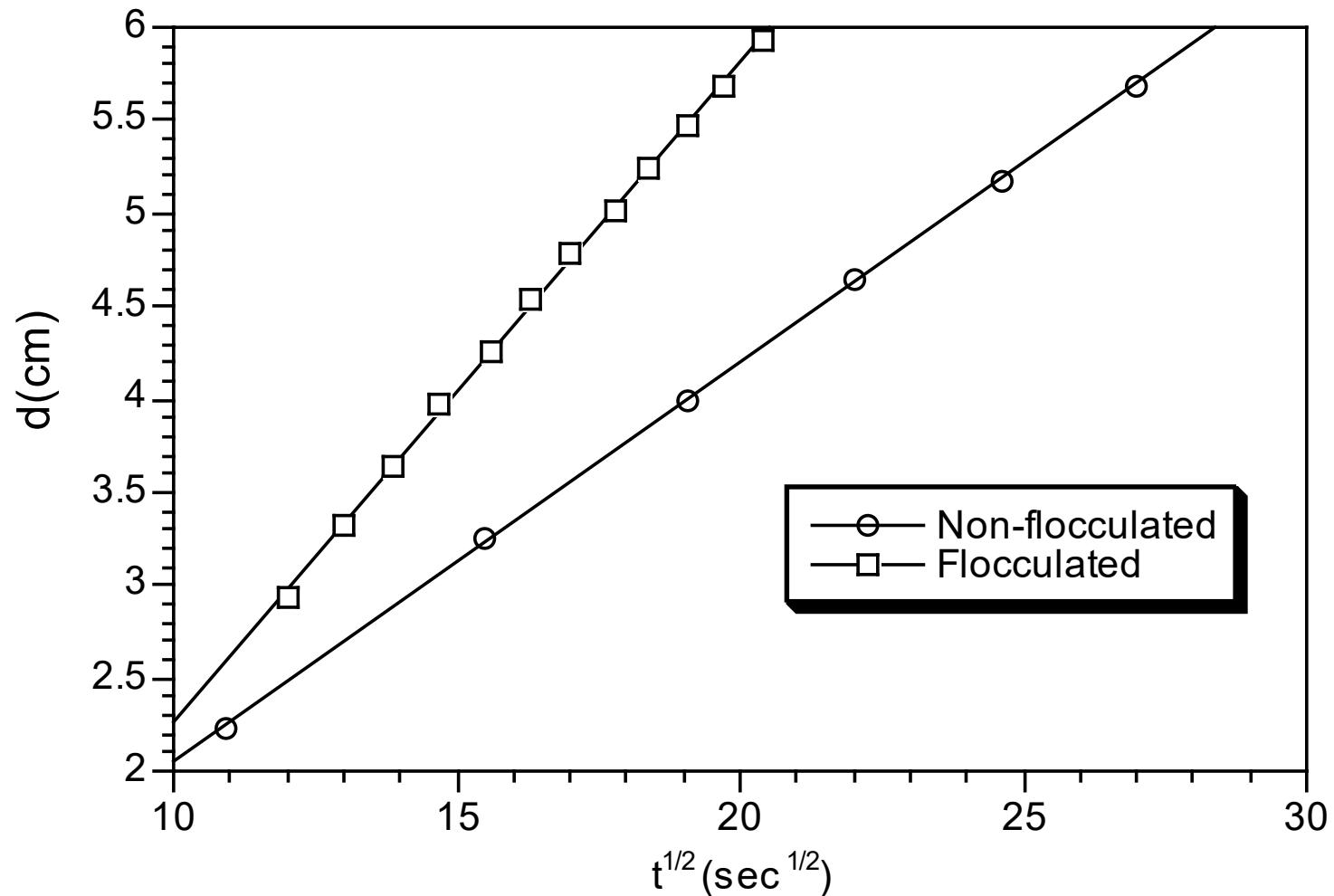
η - the viscosity of the fluid (filtrate),

v_1 - the volume fraction of solid in the consolidated layer and

v_0 - the volume fraction of solid in the suspension



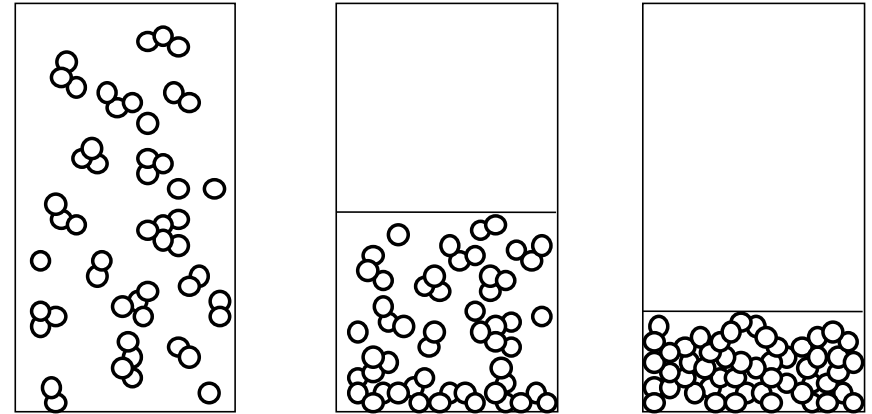
Filter press kinetics - AlN-TiO₂ suspensions



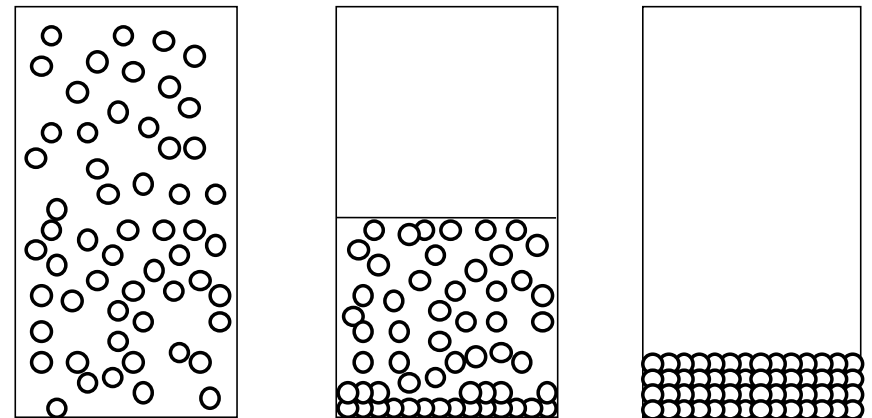
Suspensions - Interparticular Forces

Poorly dispersed - fast network formation
- low green density (30%)

- ◆ Suspension
- 1. Surface wetting
- 2. De-agglomeration
- 3. Stabilization against re-agglomeration
- 4. Modification / rheology control



Well dispersed - slow network formation
- high green density (70%)



Interparticle Forces

◆ Attractive

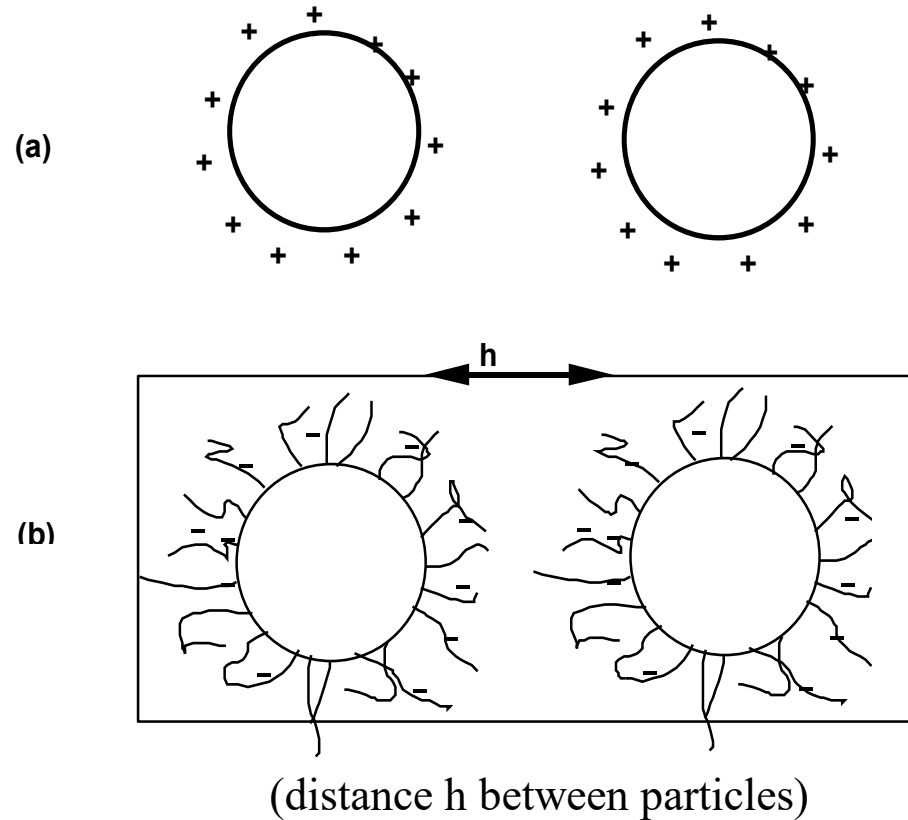
Van der Waals forces

◆ Repulsive

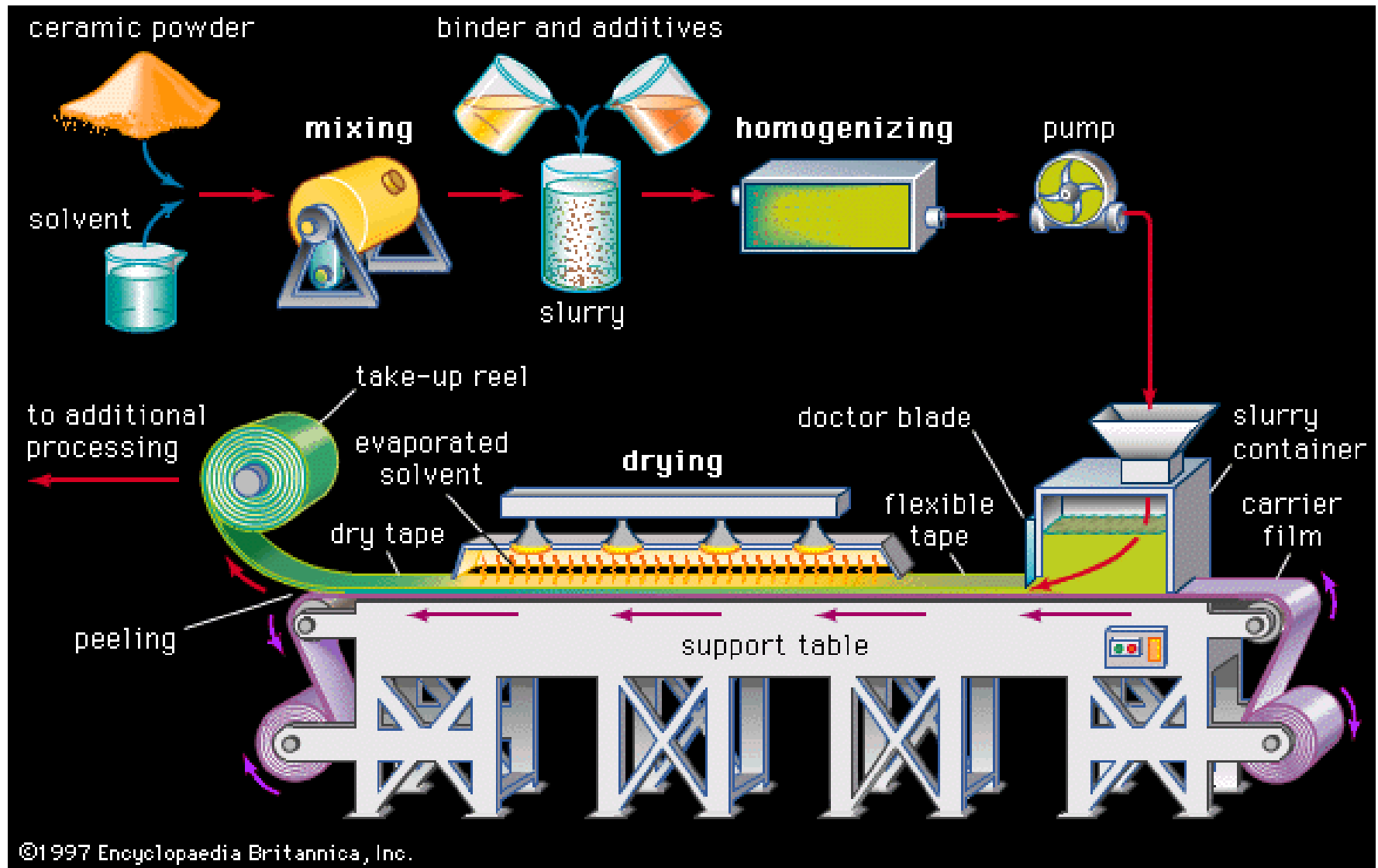
(a) electrostatic,

(b) soluble polymers - steric
polymer adsorption

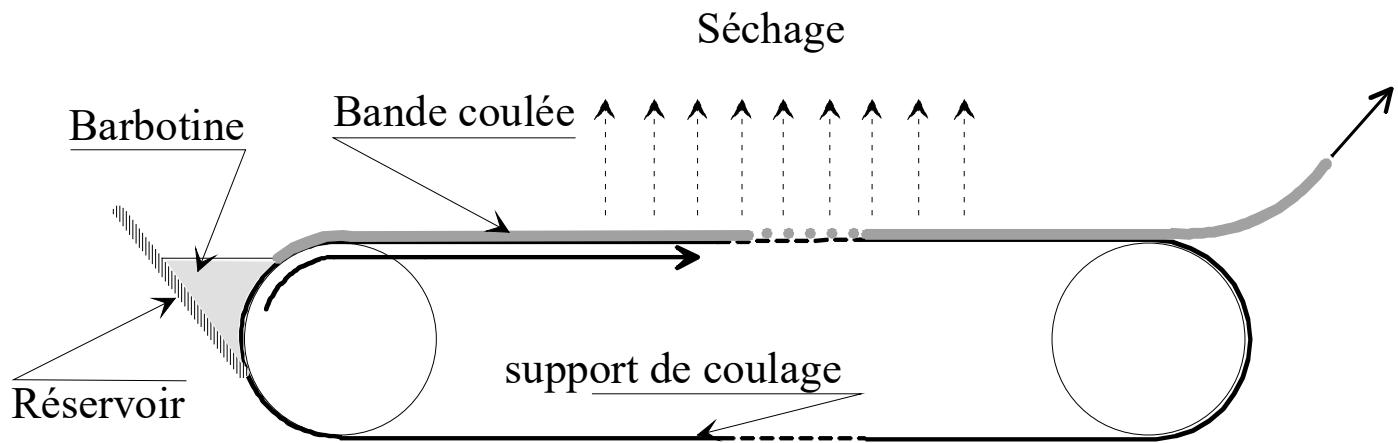
(c) charged polymer **electro-steric**



Tape Casting – “thick” ceramic films



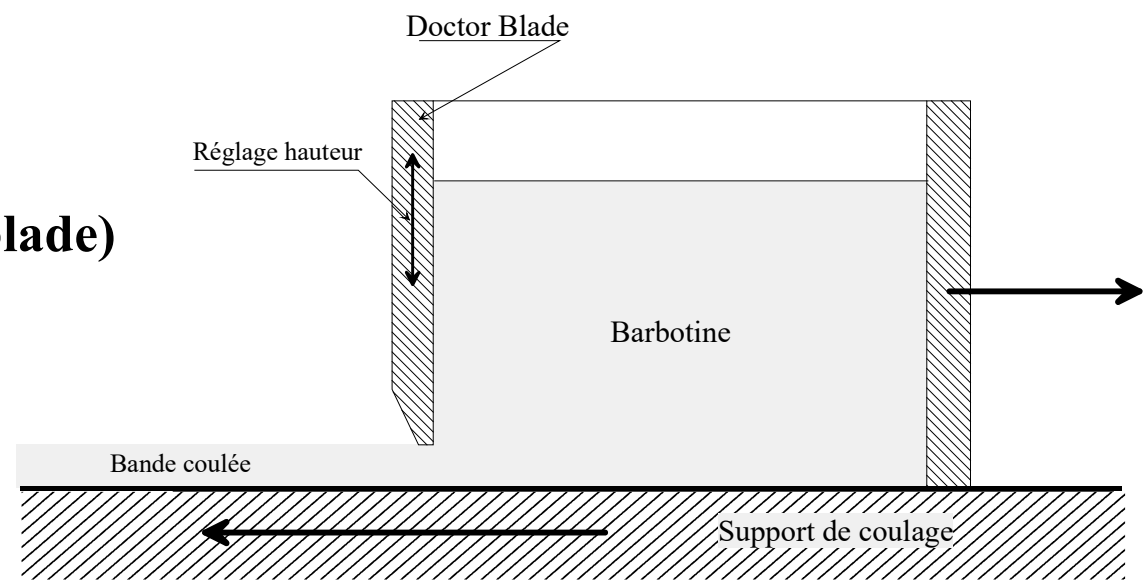
Tape Casting – “thick” ceramic films



Training



Calendering or (doctor blade)

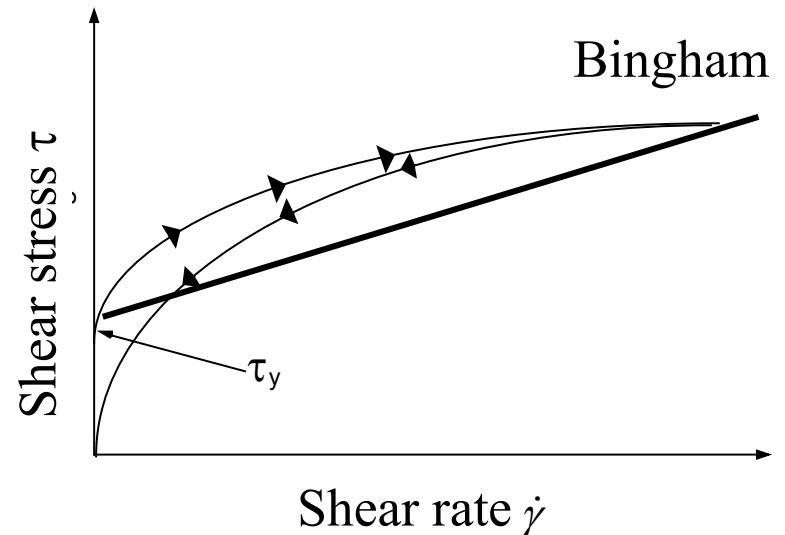


Tape casting - rheology

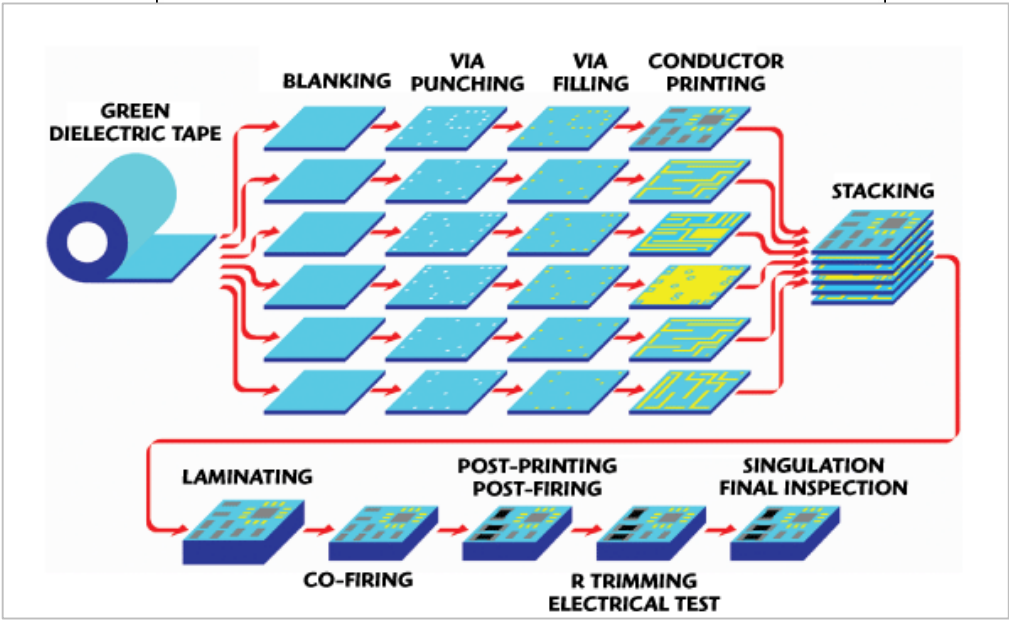
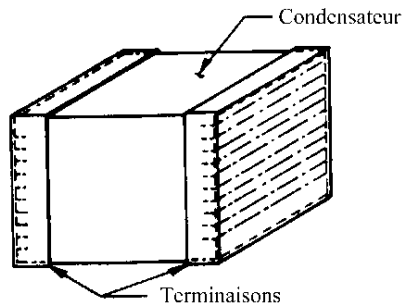
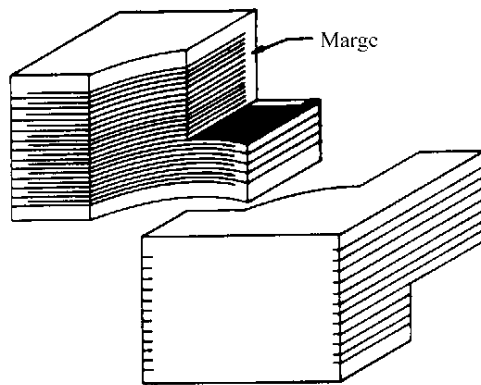
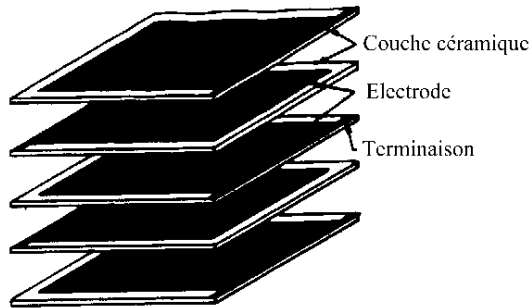
- ◆ Tape casting is used to produce "thick" ceramic films - 25(5) -1250 microns.
- ◆ large smooth surfaces, where pressing, slip casting and extrusion have difficulty with this thickness and large areas.
- ◆ The films thus obtained are often very flexible and are used as
- ◆ substrates, multi-layered capacitors, piezoelectric actuators, and sometimes for porous structures such as filters, catalysts and absorbents
- ◆ Rheology of suspension needs **shear thinning behavior**... .with small yield stress – application of shear needed to flow....e.g. tooth paste
- ◆ E.g. via an attractive secondary minimum

Limitations

- Thickness
- Binders-organic solvents (expensive)
- De-binding - co-sintering

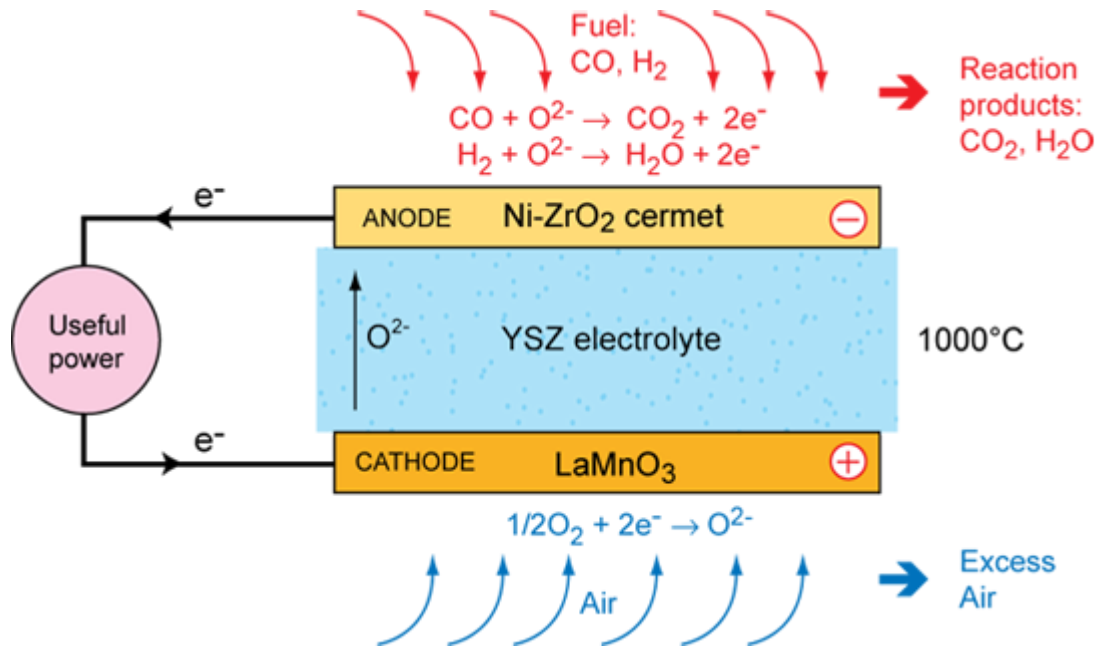


Multi-layer capacitors – BaTiO₃



SOFC - Solid Oxide Fuel cell - example

- http://www.youtube.com/watch?v=zE_t5Lsyex8

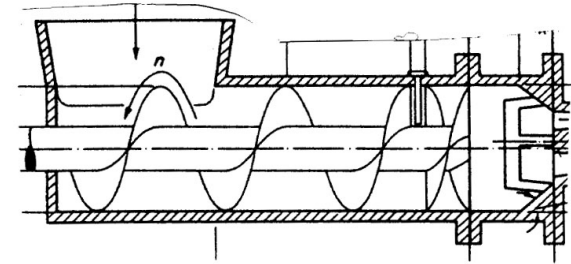


http://www.doitpoms.ac.uk/tlpli/b/fuel-cells/high_temp_sofc.php

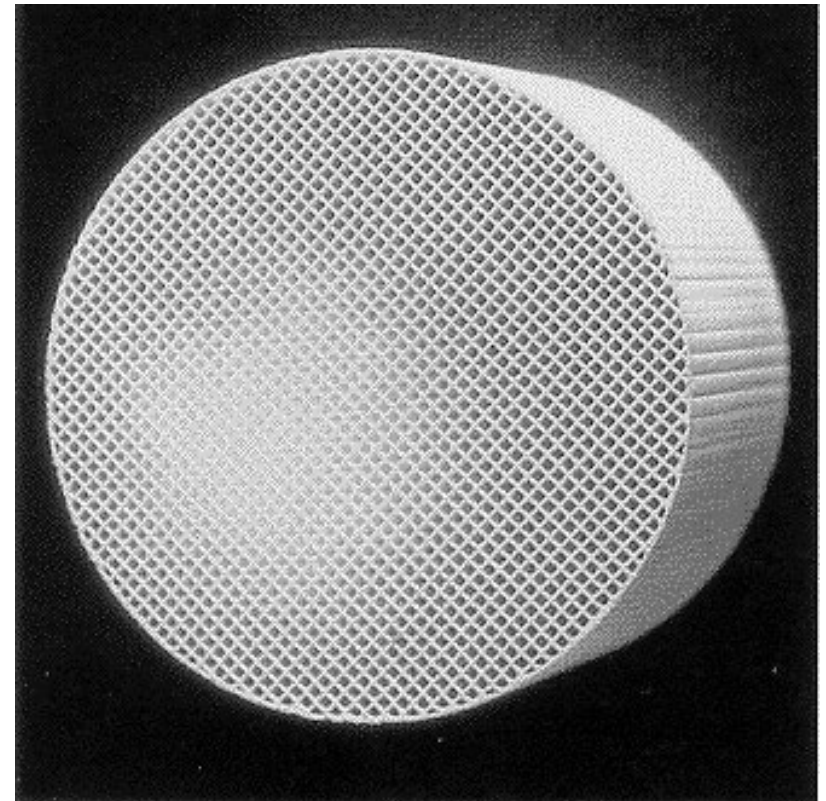
The operation of the solid oxide fuel cell is straightforward: oxygen atoms are reduced on the porous cathode surface by electrons. The oxide ions diffuse through the electrolyte to the fuel rich and porous anode, where they react with the fuel (hydrogen) and give off electrons to an external circuit. A large amount of heat is produced by the electrochemical reaction, which can be used by an integrated heat management system. Since it takes a long time to reach its operating temperature, the best applications for SOFCs are ones that use both the heat and electricity generated: stationary power plants, auxiliary power supplies.

Plastic Forming - Extrusion

- ◆ Extrusion - as for polymers ...e.g. screw extruder or
- ◆ Bricks* – iron oxide impurities...red brick...
- ◆ Automobile catalyst support (cordierite = 30% talc & 70% kaolin)
- ◆ Talc = $3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$ kaolinite - $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$



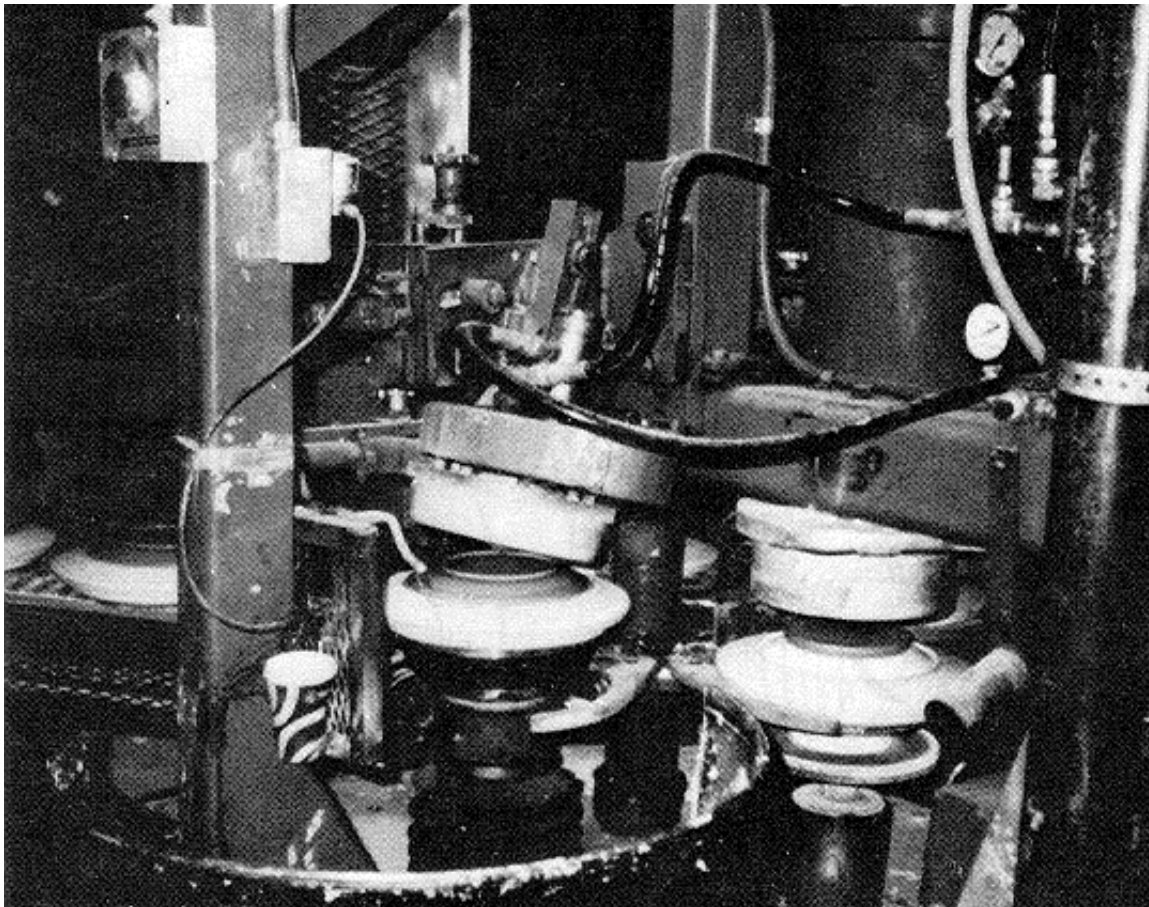
www.shutterstock.com · 705553



*<https://www.youtube.com/watch?v=GEvoXuFKSA0>

Plastic shaping - Pressing

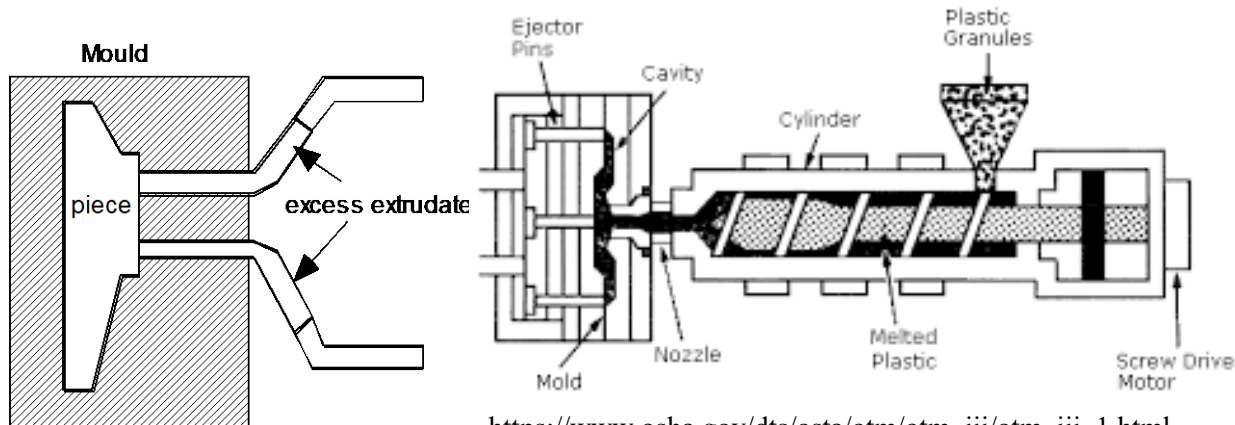
- ◆ Plastic pressing - dishes
- ◆ Filter pressing - plastic dough disc... like modeling dough...play dough...simple plastic forming...see video on ceramic mugs...below...



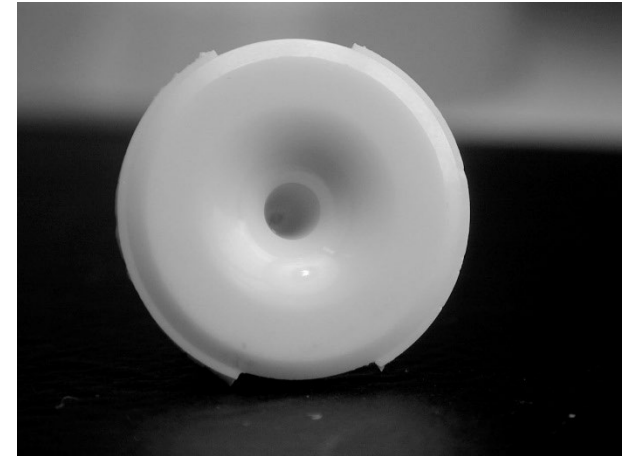
Ceramic mugs -
<https://www.youtube.com/watch?v=pYw5zUyiS7M>

Injection molding - SPT Roth SA, Lyss

- ◆ Small precision parts - very complex shapes
- ◆ Powder - polymer mixture (20% weight 50% volume of polymer) heated to around 200 °C
- ◆ Limitations - expensive - part sizes limited to cm
- ◆ De-binding - slow 2-3 days... or 2-4 h with new technology BASF HNO₃ at 120 °C



https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_1.html

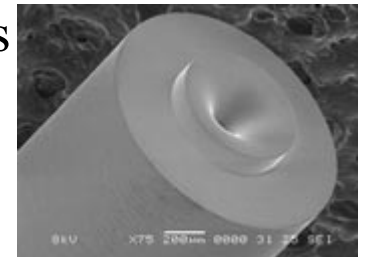
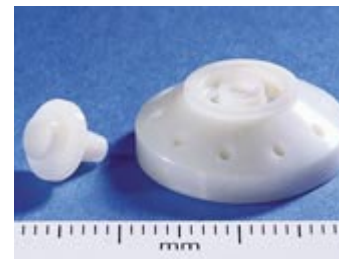


SPT Roth SA- Ceramic injection molding (CIM) of small complex & precise components in micron tolerances. [Materials](#) include Alumina, Zirconia, Zirconia-toughened Alumina and polycrystalline Ruby.

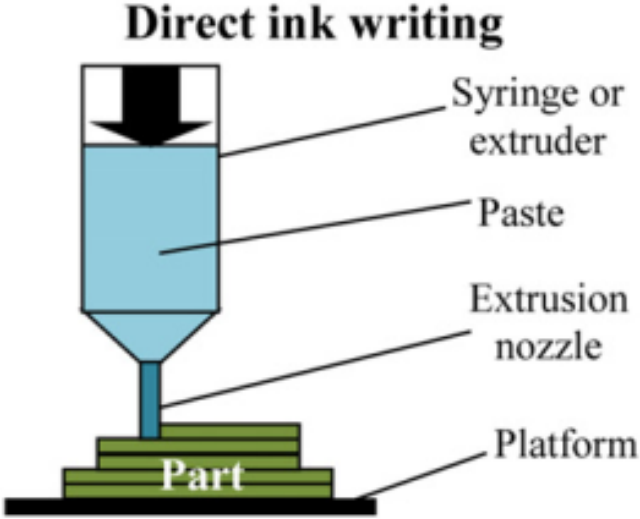
Limitation of cut max cm...expensive....

- [Medical tools & implants](#)
- [Dental applications](#)
- [Industrial](#) and [Electronic](#) components
- [Nozzles](#) with hole diameter less than 15µm
- <http://www.smallprecisiontools.com/>

Nozzles- nozzles



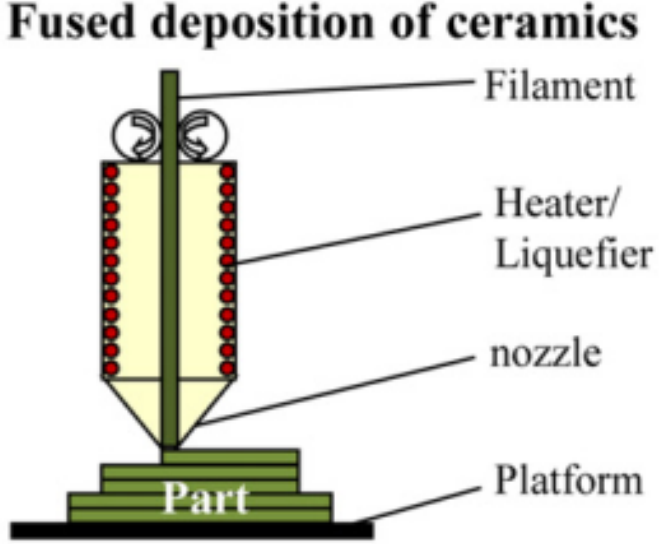
Additive manufacturing - 3D printing techniques for ceramics * - direct technologies



DIW

Lewsi et al J. Am. Ceram. Soc., 89 [12] 3599 (2006)

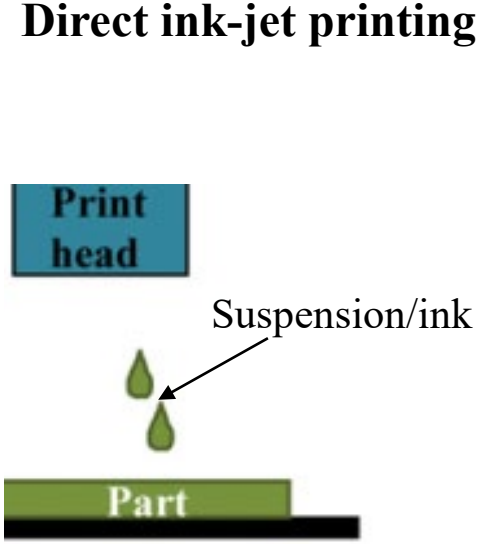
Ink is continuously extruded through a fine cylindrical nozzle



FDC

Lous et al J. Am. Ceram. Soc., 83 [1] 124 (2000)

Ceramic particles in appropriate thermoplastic binders



Dip

Ink-jet printing of material in the form of droplets in a desired pattern via a layer-by-layer build sequence

<https://www.youtube.com/watch?v=NILF14QhNyY>

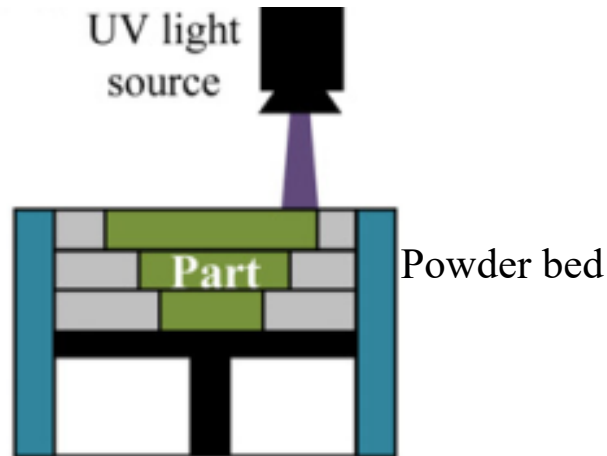
* Franks et al. J Am Ceram Soc 2017; 1-33

* Zocca et al. J. Am. Ceram. Soc., 98 [7] 1983-2001 (2015)

Additive manufacturing - 3D printing techniques for ceramics - powder beds - indirect technologies

Stereolithography

<https://www.youtube.com/watch?v=NM55ct5KwiI>

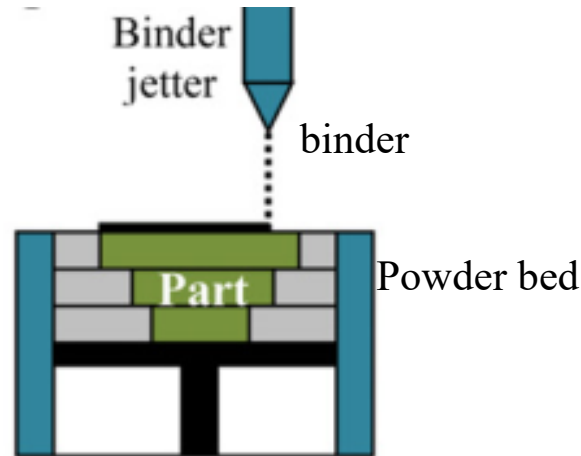


DLP / SLA

Stereolithography (SLA) and Digital light processing (DLP)
-similar principles - different possible outputs.

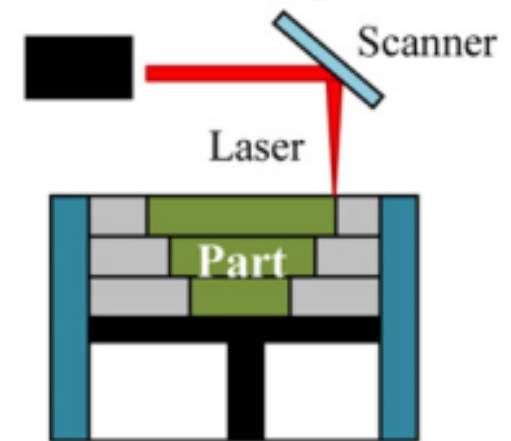
Both use UV or light curable resins
SLA - laser that travels over the cross sectional area of each layer of the part

DLP uses digital light projector screen to flash a single image of each layer all at once



3DP

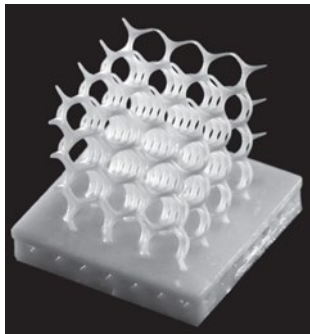
Powder-Based 3D Printing - an inkjet printing head spits a binding liquid onto a powder bed, thus defining the cross section of the object in that layer.



SLS

Selective Laser Sintering local densification of the powders by directly sintering. Direct laser sintering of ceramics is complicated by the poor resistance of this class of materials to thermal shock. But good with metals

European leaders – 3D printing of ceramics



https://www.youtube.com/watch?v=_jdMcKuJCh8



https://www.youtube.com/watch?v=_aIO-5iAqq0

Lift-up DLP

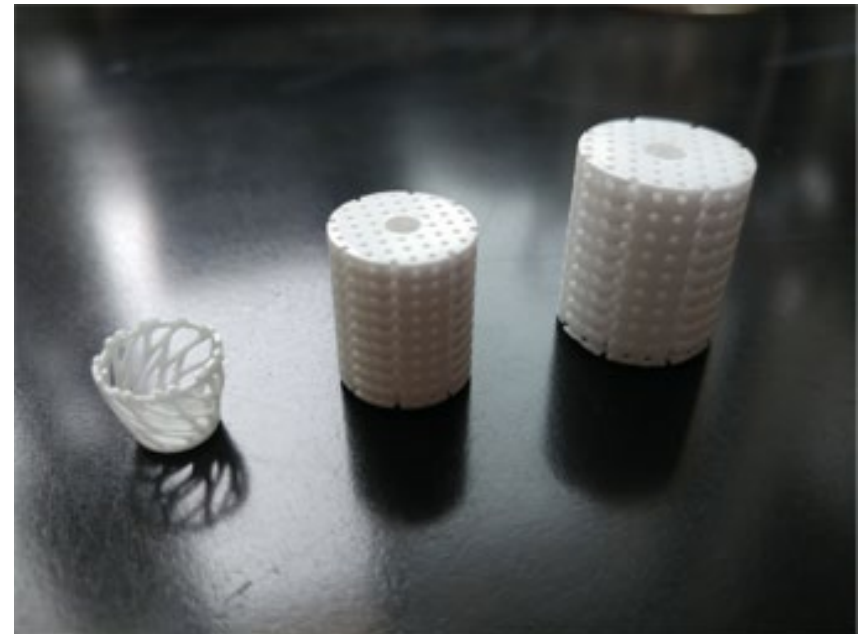
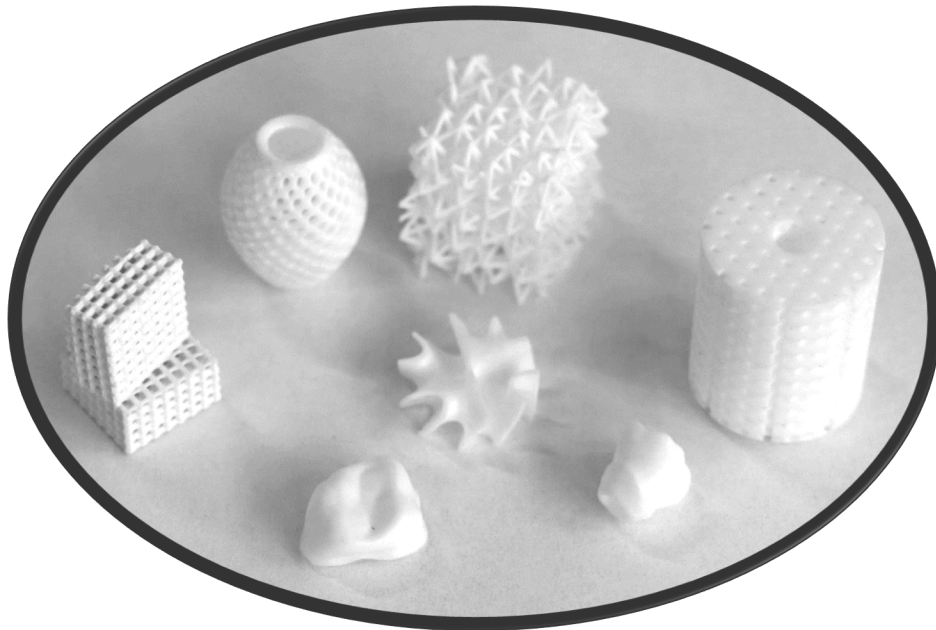


<https://www.youtube.com/watch?v=yWanrzUyi4Y>

Common Strategy: flocculated ceramic resin with very high viscosity!

CeramicPlus Shanghai (China) (Prof. Zhao Zhe)

- **Low shrinkage during printing, the thin sheet of 300 μ m can be sintered without noticeable deformation**
- **Low viscosity which lead to potential applications with desk-top machines**
- **Easy to be burned resin design which is critical for fast processing and also low post-processing cost**



**Top-Down DLP and SLA;
Low Viscosity dispersion-type ceramic resins**

Drying

- ◆ Drying is an important step in many of the shaping processes discussed above.
- ◆ Often a shrinkage of the ceramic part.
- ◆ The degree of shrinkage depends on the method and the amount of liquid to provide the rheological properties suitable for the process.
- ◆ For slip casting - linear shrinkage is between 1.5 and 7%.
- ◆ For tape casting or sol-gel films, it can be much higher, around 50-90% in the thickness (Z) of the layer (X-Y less than 1 %)
- ◆ Defects not always visible in a wet compact may appear during drying.



- ◆ Slip casting - 80 mins
- ◆ Die casting - 2 mins !!
- ◆ wall thickness 1cm max
- ◆ **Drying 6 days**

Drying - methods

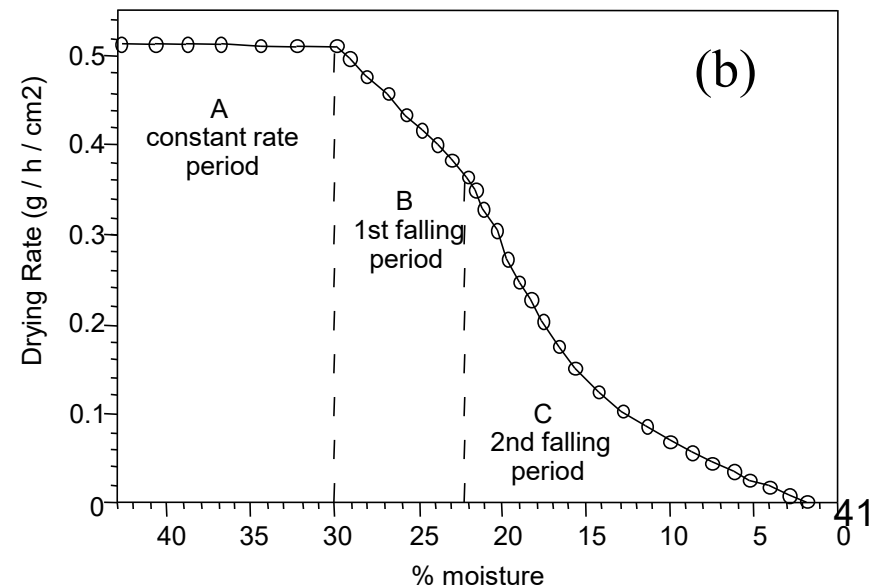
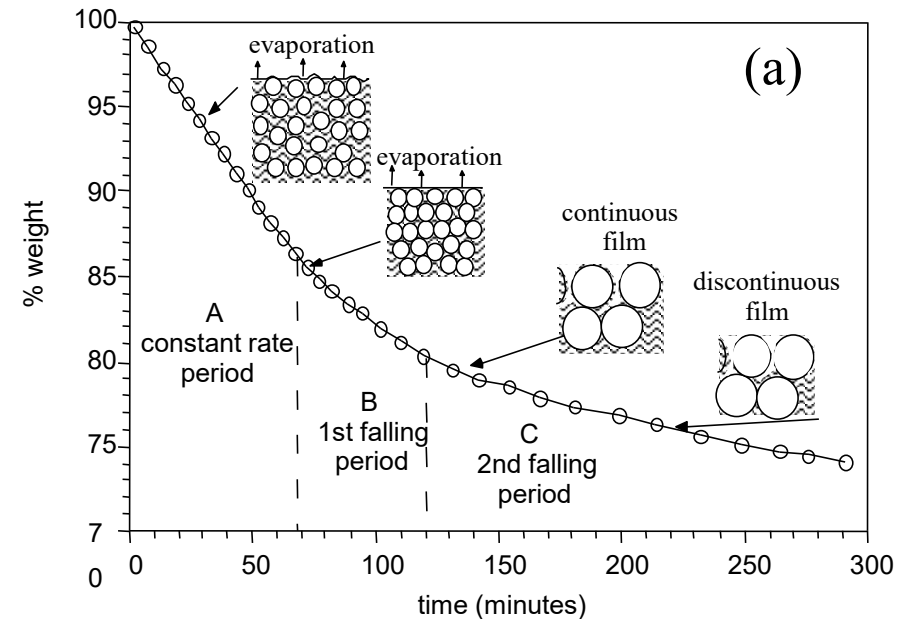
- The removal of the liquid depends on the transport of the liquid through the porous structure - followed by evaporation into the atmosphere.
- Evaporation can be accelerated by the application of heat
- The heat transport is done by
 - convection,
 - conduction (heated substrate) or
 - radiation (infrared lamps (coated surfaces), microwaves).
- Conductivities of ceramic, liquid and substrate play in heat transport.
- Replacing wood substrates with steel - reduce drying time by 40%.
- ◆ Porous materials e.g. aerogels for insulation - **supercritical drying** is used.
- ◆ Point where no more difference between liquid and gas states - eliminates the liquid-vapor meniscus.
- ◆ The critical point of water, located at 374 °C and 220 atm, is not really practical ... but
- ◆ CO₂ is at 43 °C and about 73 Atm.
- ◆ The only disadvantage with CO₂ is that it may take several hours to remove the original synthetic fluid.

Drying kinetics - weight vs time

- Drying of ceramics - followed by loss of mass over time (a)
- Often presented in relation to the final mass of the dry body, as a function of the humidity level (b) and rate of loss of weight

Two regimes

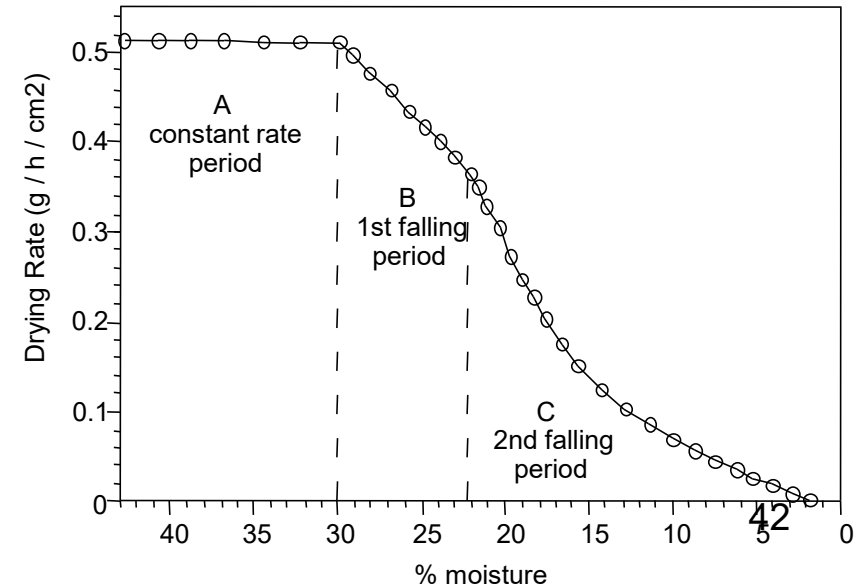
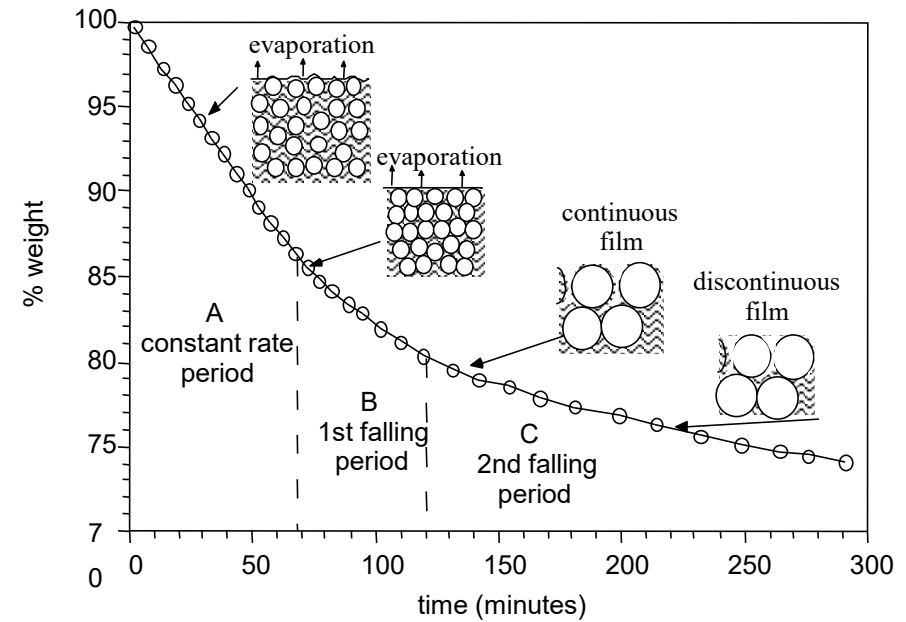
- constant evaporation rate,
- falling rate period
- Constant rate A is associated with the direct evaporation of the liquid from the surface of the green body with the pores still saturated with liquid.
- ◆ because of the surface tension of the liquid, the compact is in compression when the shrinkage takes place.



Drying kinetics - weight vs time

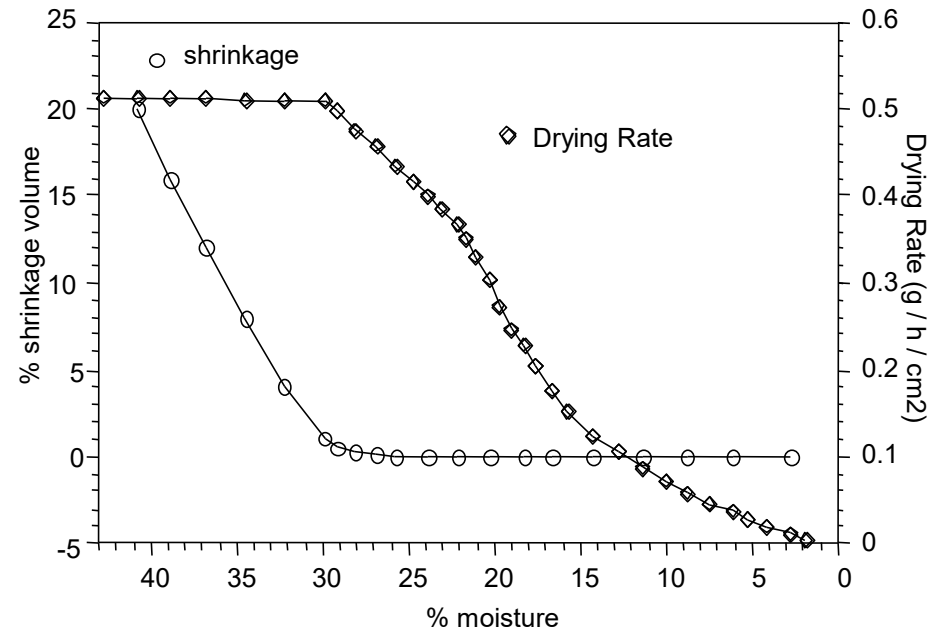
- The particles rearrange and come into contact (maximum packing fraction),
- a critical humidity level is reached
- the piece is just saturated with the liquid.
- Cracks often appear just after this critical point
- In the falling rate period there are two discernible regimes:

- 1 - still has a continuous liquid film on the surface of the powder, transport of liquid to the surface - by capillary migration or by evaporation of the meniscus. (B)
- 2 - the film is no longer continuous and the capillary transport stops - evaporation and diffusion through the pores control the rate of evaporation - then decreases again. (C)



Shrinkage - cracks

- As the meniscus passes through the porous network, the dry part of the part is no longer in compression and cracks can appear.
- Attributed to the differential shrinkage associated with the transport of liquid through the porous network, which creates stresses greater than a critical value – creates cracks
- The macroscopic stresses produced are dependent on the pressure gradient in the fluid which depends on the permeability of the porous structure which depends on
- the packing of particles.



- ◆ Stress is \propto capillary pressure, P_c ,

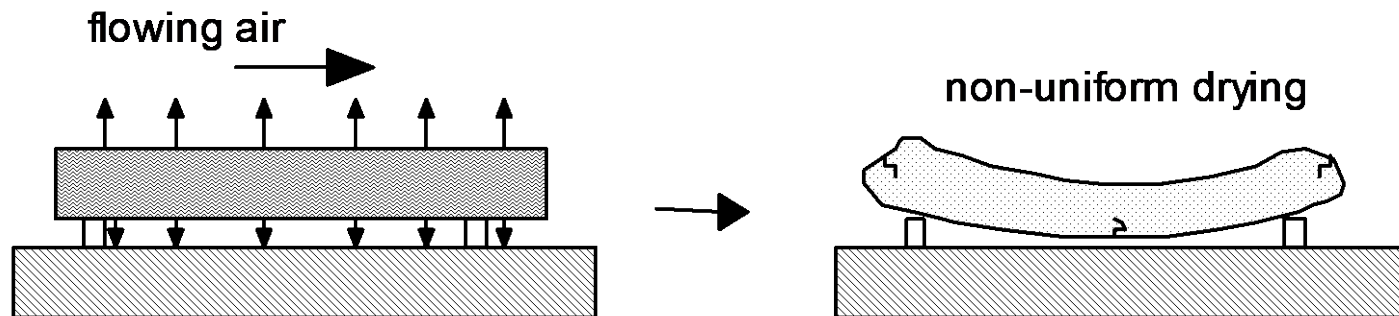
$$P_c = \frac{-2\gamma_{lv} \cos \theta}{r}$$

γ_{lv} surface tension - liquid-vapor,
 θ is the wetting angle (solid/liquid)
 r the cylindrical pore radius

- ◆ Chiu & Cima have shown that the drying stresses in films of alumina particles of 0.35 μm are ~ 2 MPa
- ◆ Produced cracks.....
- ◆ Stress was reduced to 0.9 MPa with 0.005% wt of surfactant – reducing the surface tension of the liquid from 7.2 to $3.2 \cdot 10^{-2}$ N / m.
- ◆ Cracks no longer observed

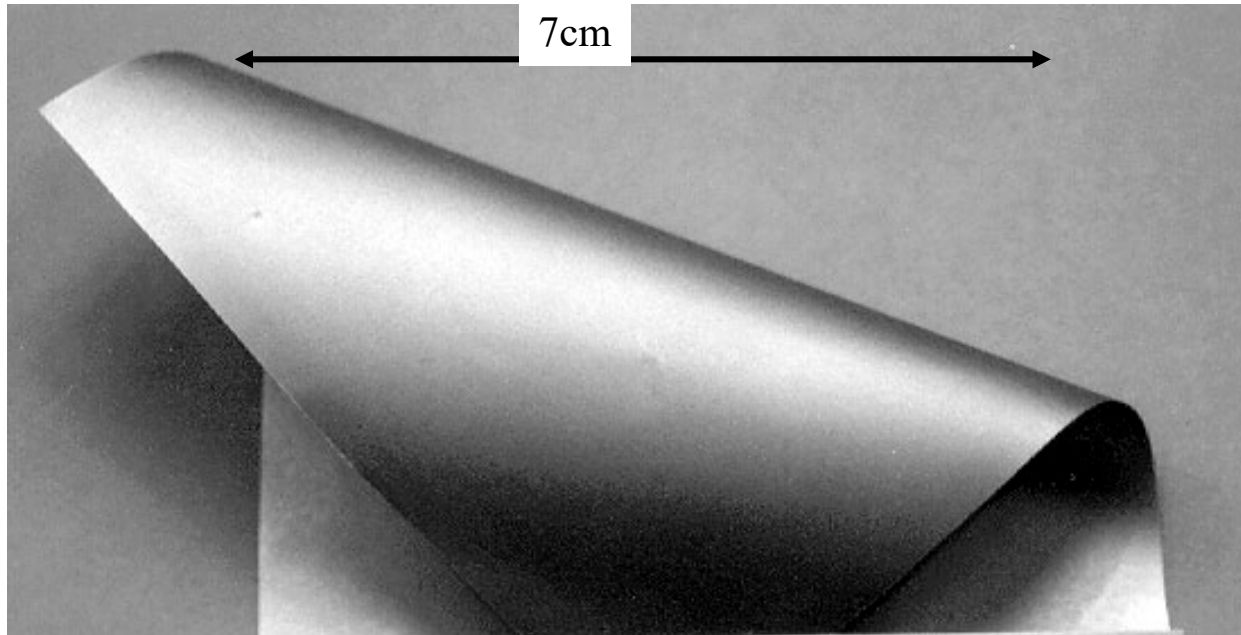
Drying - crack deformation

- If the transport of liquid to the surface is not the same for all faces, internal stresses can appear and the parts can then deform.
- This can be observed when a pressure gradient appears during the transport of liquid to the surface due to a low permeability of the porous network - p. ex. using fine ceramic powders
- The part to be dried is then subject to a more marked compression due to capillary pressures, and deforms (figure 3.5.20).



Drying – thick films

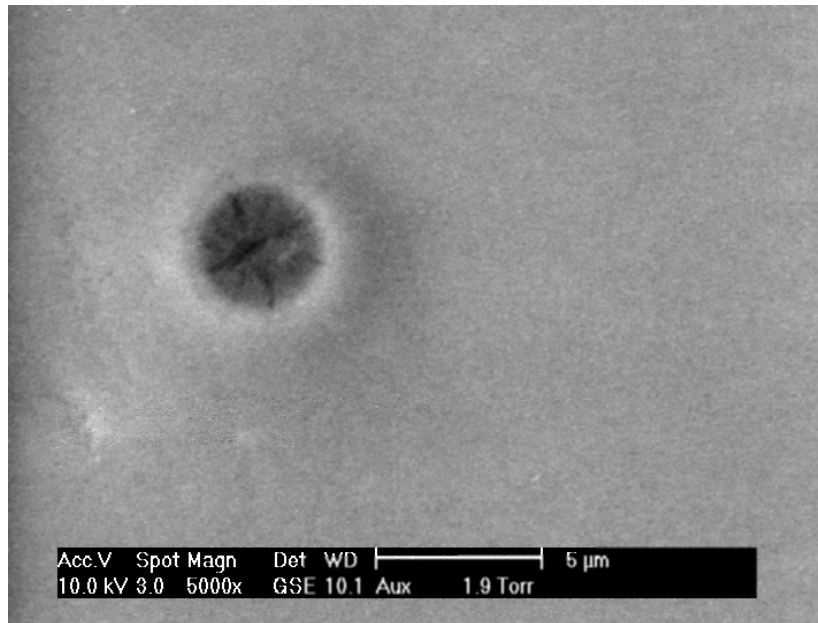
- The rate of evaporation can also be made more uniform by using higher vapor pressures of the liquid in the initial gaseous environment.
- Figure 3.5.21 shows vermiculite films (30-60 μm) dried at 80 °C for 4 hours at constant humidity of 90%. (application - electrical insulation - flexible)
- Dried at 25 °C took 48 hours.



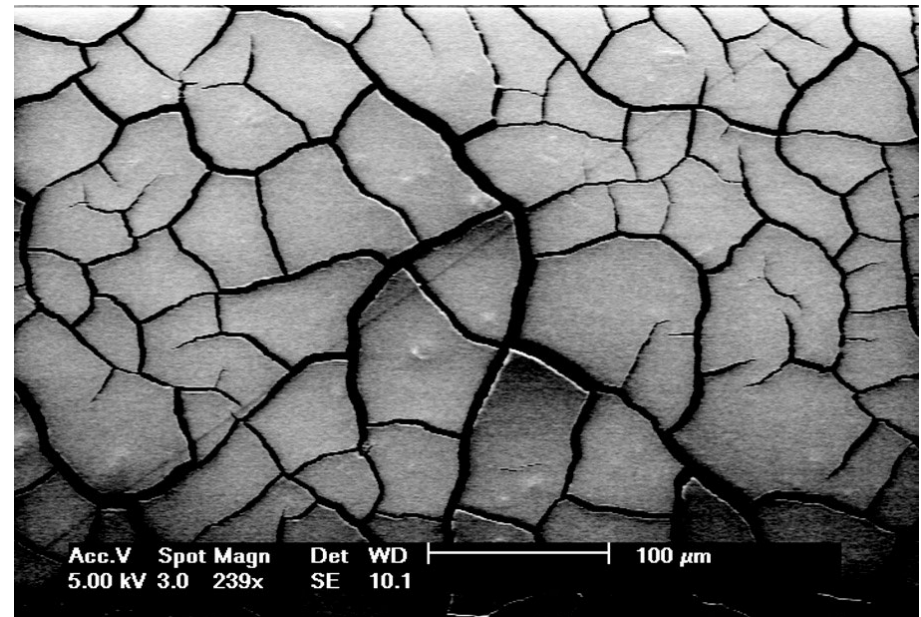
Drying - cracking

- Another possibility is to add larger amounts of binder (figure 3.5.21).
- Caution - any binder or other additive not adsorbed on the surface of the powder can migrate with the liquid towards the surface, be deposited in pores near the surface and restrict vapor diffusion (e.g. explosion of spray dried granules slide 44 Week 10)

Alumina films from 0.04 μm (dv50) particles (around 30 μm thick)



(b) with organic binder (PVA-PEG) showing an air bubble defect



(c) without organic binder showing severe macro-cracks.

Binder Removal – Binder Burnout

- Additives (organic) must be removed before sintering.
- The most common method is by decomposition and pyrolysis in air at around 500 °C - slow heating rates of 0.5-1 °/ min are essential.
- Mechanisms – include evaporation, oxidation and decomposition
- The phenomenon to be avoided is the crosslinking of carbon bonds, which can give carbon residues which are difficult to remove.
- If the removal of the binder is incomplete the carbon residues can react with oxygen in the ceramic forming CO/CO₂
- the ceramic may swell and even crack due to the pressure of the gases produced at sintering temperatures (> 1000 °C)

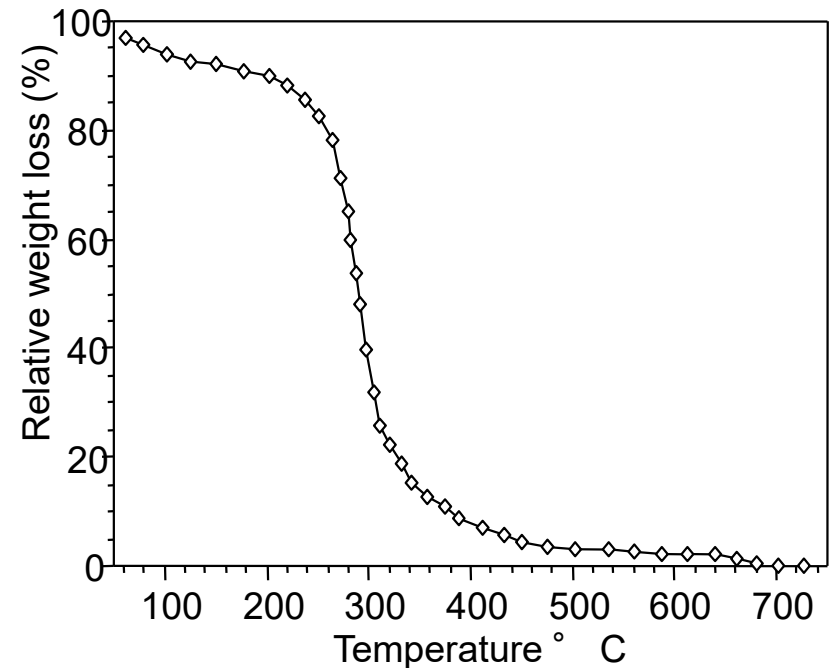


Figure 3.5.22 Typical decomposition weight loss curves for slip cast barium titanate green body with PAA as dispersant.

- ◆ Other methods, by capillary flow (waxes) and by solvent (normal or supercritical fluids (CO₂)) dissolve the binders – sometime more than one binder is used – one removed by solvent and one removed by pyrolysis

Forming – general remarks

- Lots of variations – new specific methods under development
 - e.g. additive manufacturing - 3D ink-jet printing - lithography - selective laser melting-sintering... .
- Questions to ask when choosing the forming method are
 - the size of the piece,
 - the complexity of the shape,
 - dimensional tolerances needed 1-2 microns or 50 microns or 0.5 mm,
 - the final density (95, 98 or 99.9%) and
 - the production rate.
- All of these factors must be weighed against **the final cost of the part.**
- Then, a powder suitable for the shaping method should be chosen.
- New shaping methods will not find widespread use in the mature ceramic industry,
- but when a young engineer is looking for a shaping process for a specific new product,
- an open mind and an imaginative use of new methods can then make the difference between business success and failure... ..