Elaboration of Ceramics and Colloids

Week 6

A. Testino

2.3 Powder Treatment (1) Milling and Classification (p.127-142 *)

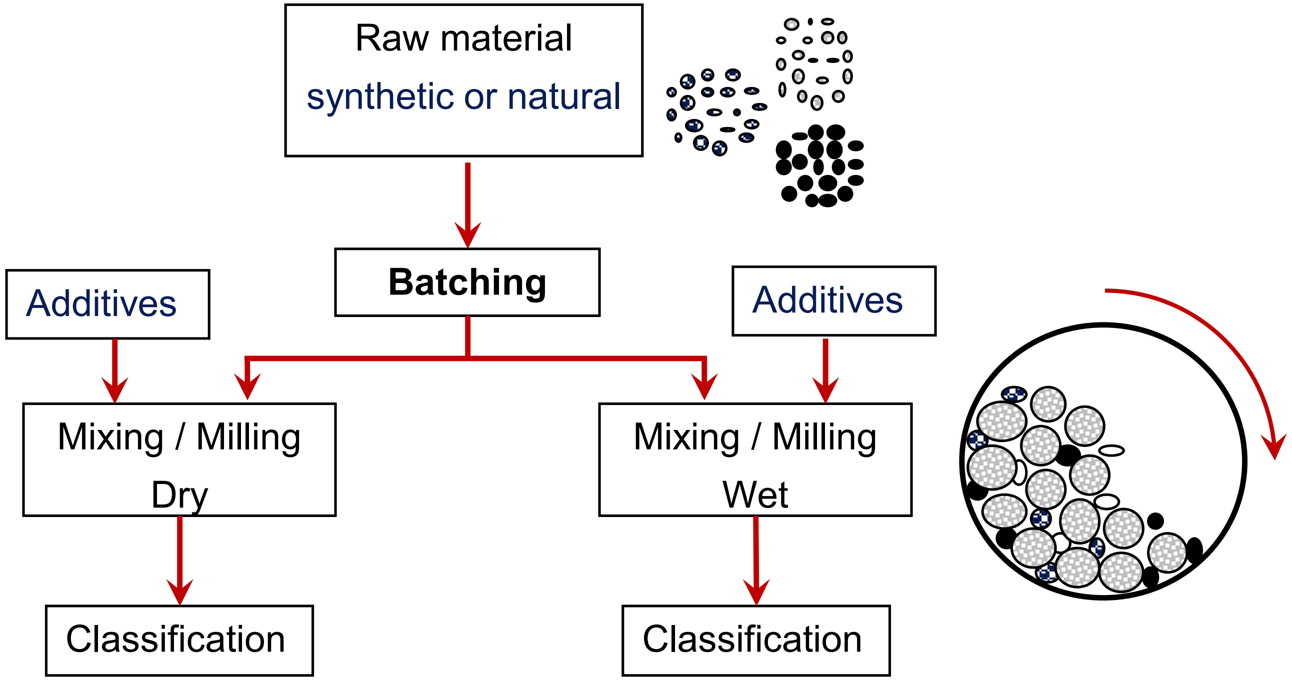
Crushing / Milling

→

Classification

* Les Traité des Matériaux, Volume 16 « Les Céramiques »

Manufacture of Ceramics - powders (1)



Raw material

synthetic or natural

Batching

Additives

Additives

Mixing / Milling

Dry

Mixing / Milling

Wet

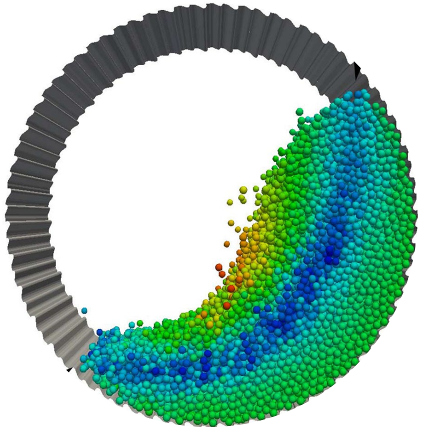
Classification

Classification

- 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

- high chemical purity,
- good reactivity
(size around 1-2 µm and specific surface around 5-15 m^2/ g) and
- good homogeneity - physical and chemical.

Chaper 2.4 Traitements des Poudres*



*Les Céramiques, J. Barton, P. Bowen, C. Carry & J.M. Haussonne, Les Traité des Matériaux, Volume 16, PPUR, 2005

Table 3.3.4. Commercial powders - Al_2O_3

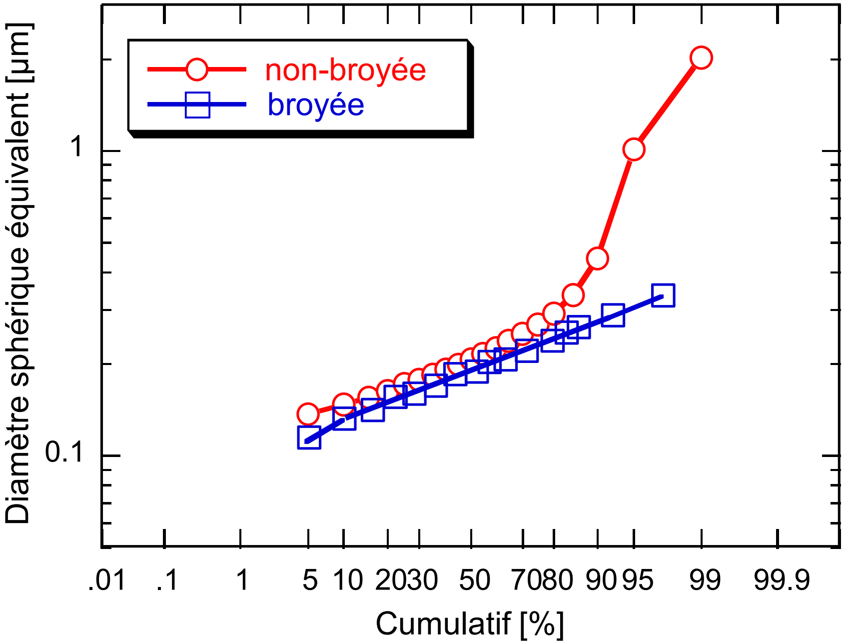
	Precipitation Alpha Gamma				Vapor phase
	Bayer	alum	alum	boehmite	chloride
Price (CHF – approx.)	10	70	70	20	10
Phase α (%)	-	98	0.5-3	-	2
Diameter (d_{v50}) (μm)	0.3	0.3	0.3-0.8	9.8	0.042
Distribution width (span)	2.92	1.53	2.2 - 1.5	1.56	0.8
Purity - Al_2O_3	99.5	99.99	99.99	99.94	99.6
Specific surface (m^2/ g)	9.0	9.8	104	144	107
d_{BET} (μm)	0.167	0.154	0.017	0.012	0.0165
F_{ag} (agglomeration factor)	1.8	1.95	20-50	816	2.5

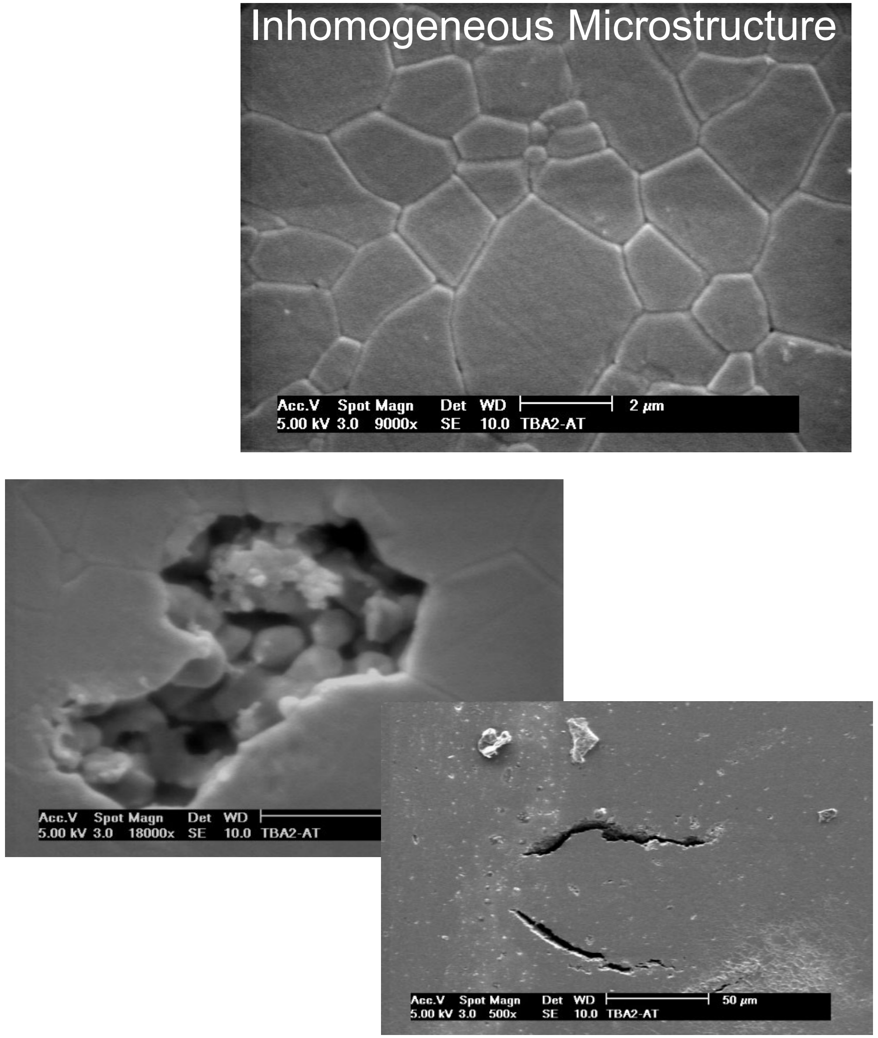
span $=(d_{v90}-d_{v10}) / d_{v50})$

$F_{ag} = d_{v50}/ d_{BET}$

Alpha alumina - effect of agglomerates

- Particle size distribution shows small tail of agglomerates - leads to defects in microcstructure and low sintered densities (94%)

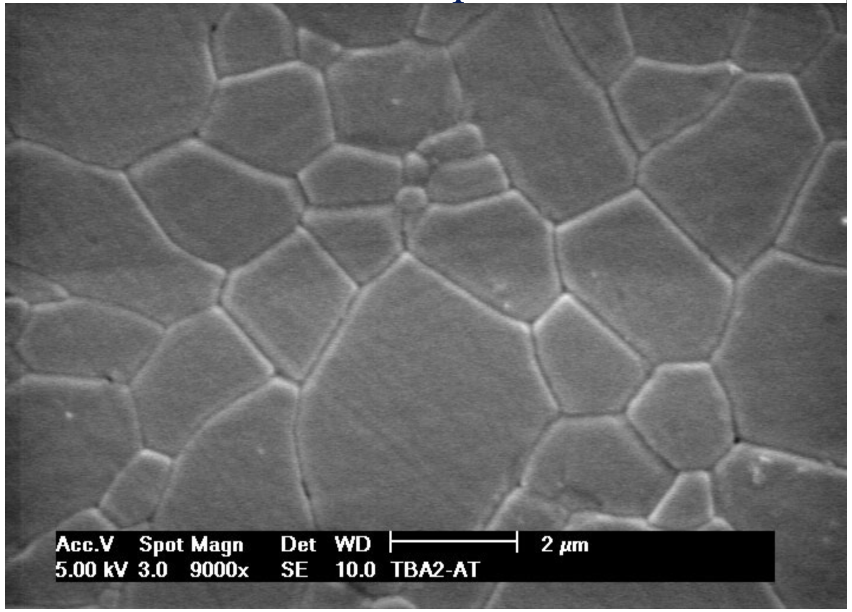




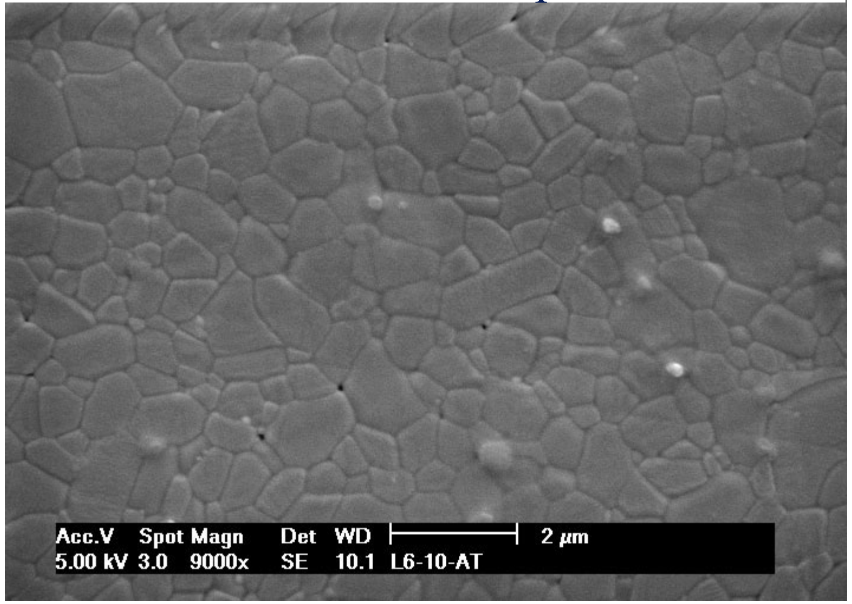
Alpha alumina - effect of agglomerates

- Attrition milling 1h agglomerates removed
- Improved sintered density & microstructure

As recived - slip cast - 94%

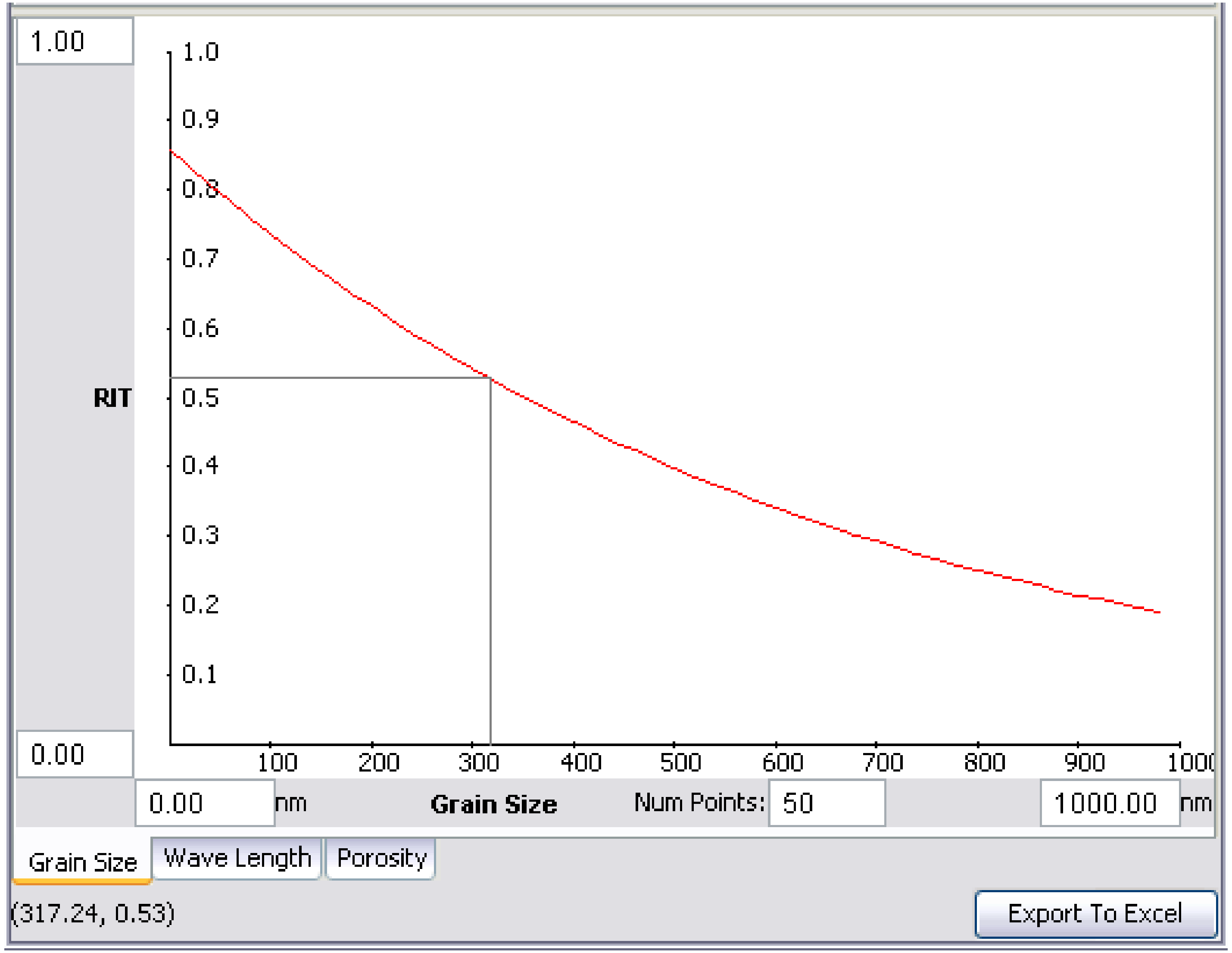


Attrition milled 1hr - slip cast - 99%



FS. Shiau, TT. Fang, TH Leu, Materials Chemistry and Physics, 57, 33-40 (1998).

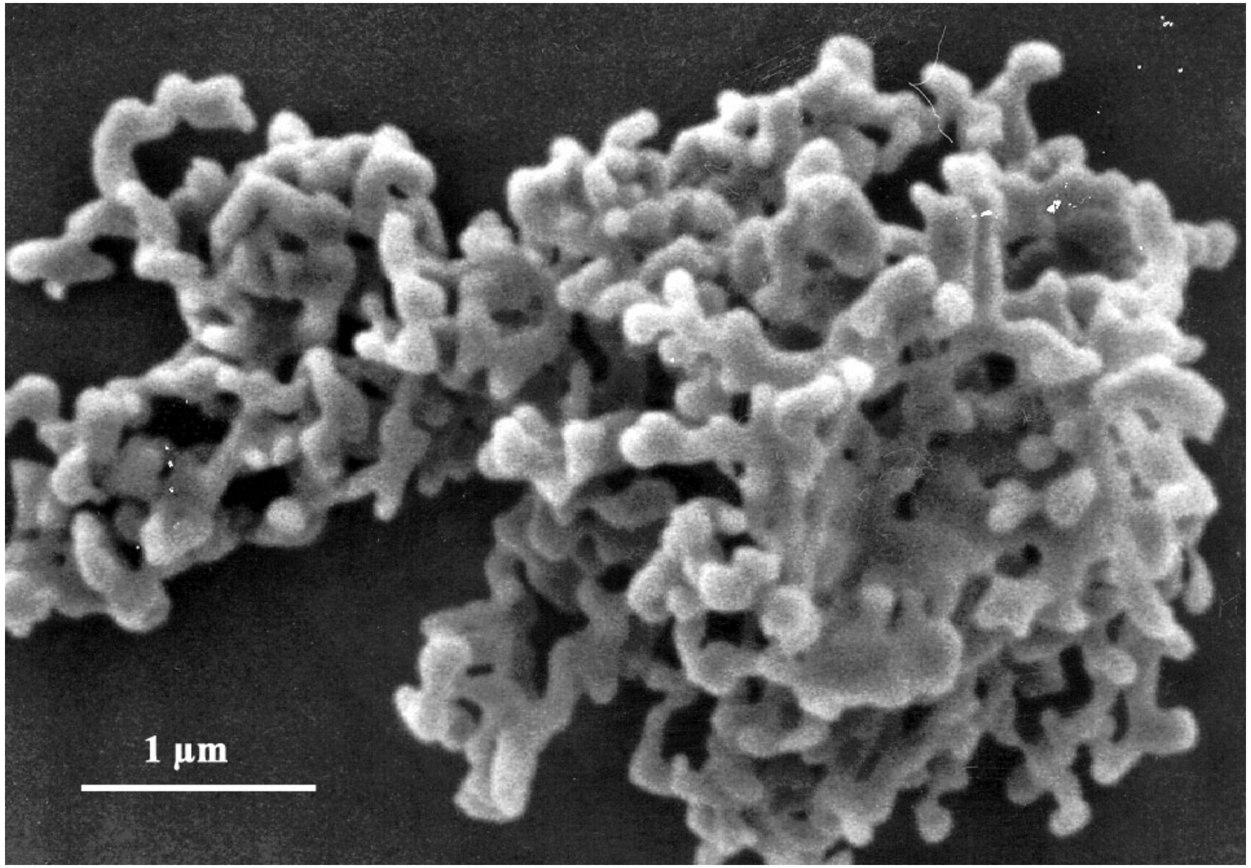
Alumina - Real In–line Transmittance (RIT) vs grain size



Plot RIT as function of grain size (diameter) for a given wavelength (640 nm) and porosity (0.01% volume) for alumina

Sol-Gel - Transformation of AlOOH - into γ Al_2O_3

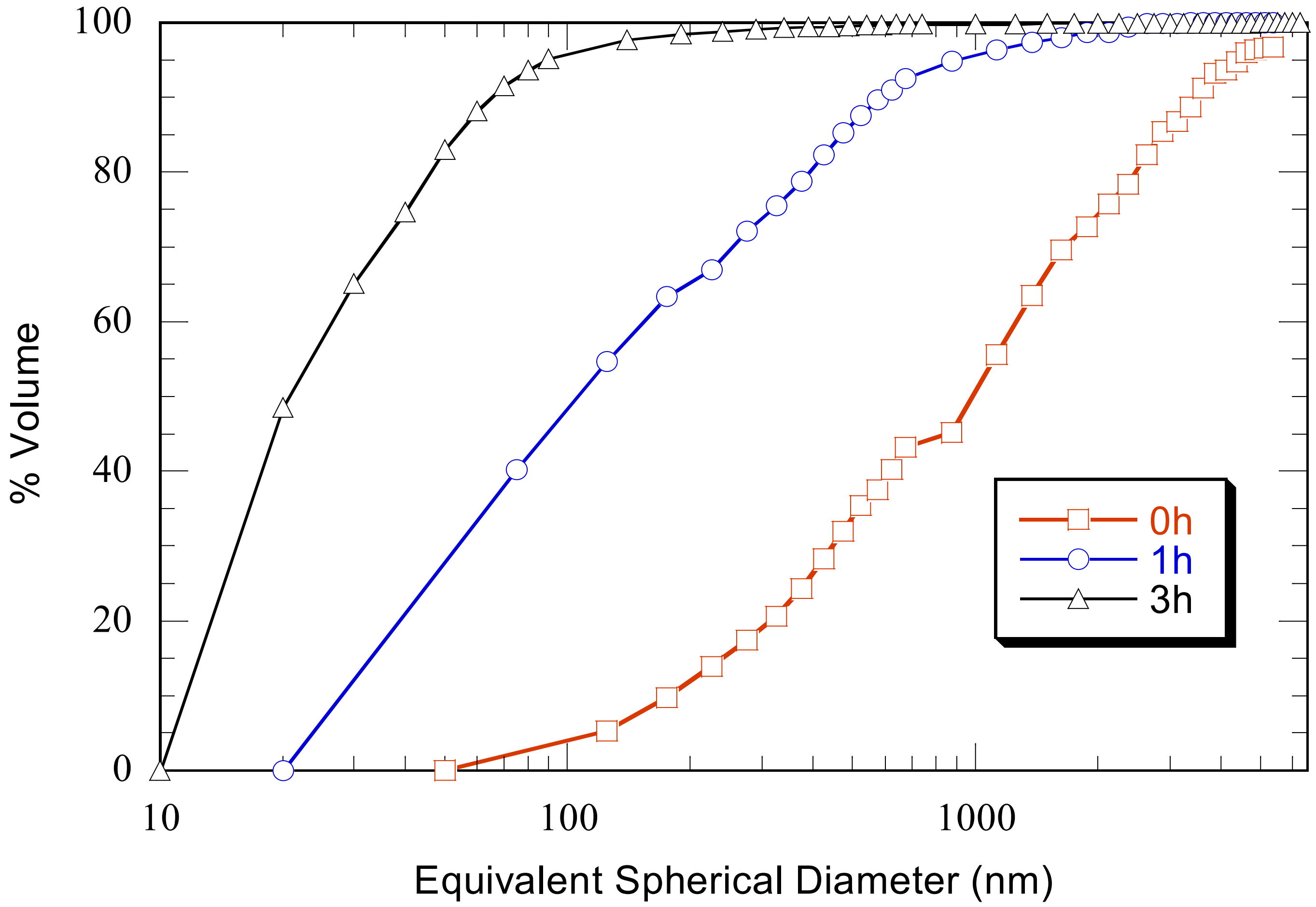
- $2AlOOH \Rightarrow Al_2O_3 + H_2O$ (500-1000 ° C)
- Agglomeration $D_{v50} = 1.22\ \mu m$, $d_{BET} = 12.2\ nm$, $F_{ag} = 100$



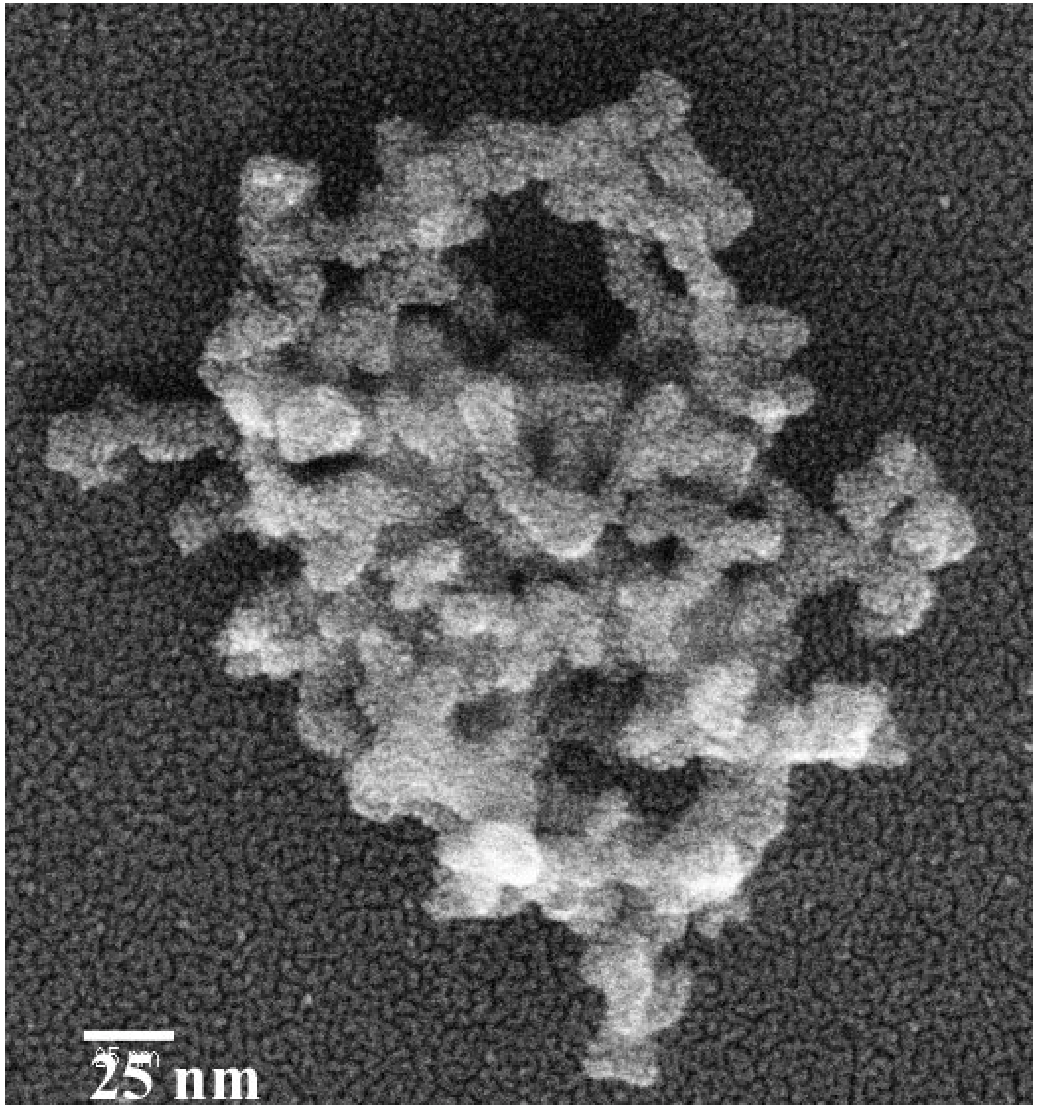
Micrograph of a gamma alumina powder produced by decomposing boehmite

Milling effect on a size distribution

Example of effect of milling for gamma alumina – heavily agglomerated Fag >>1

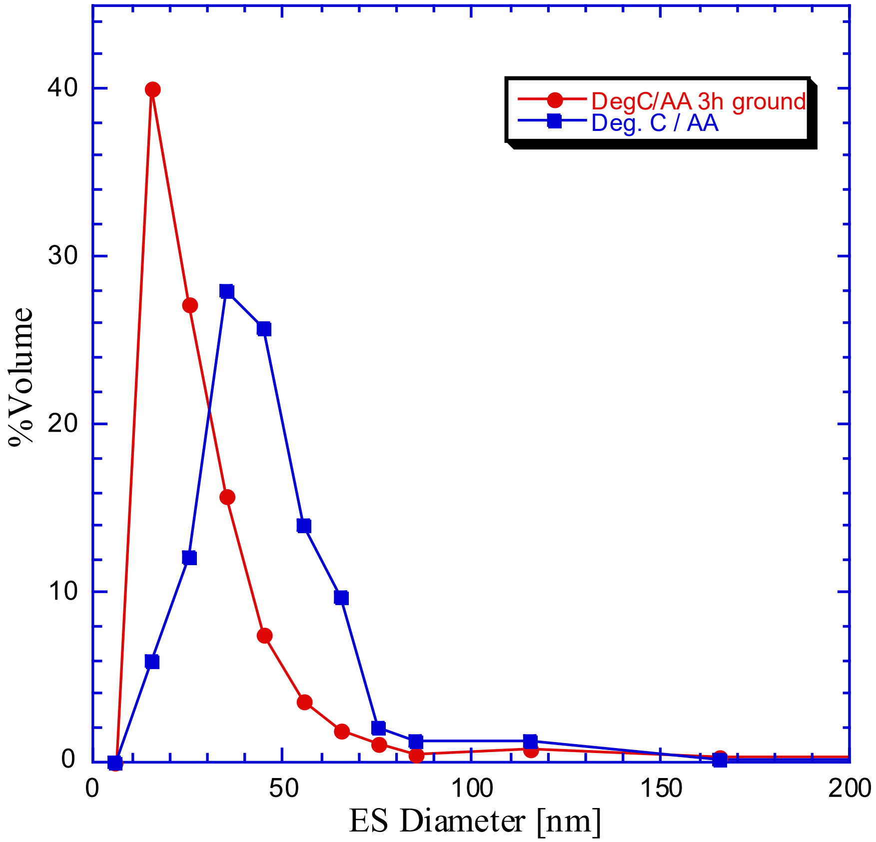


Vapor phase synthesis



gamma alumina,
d_{v50} = 40 nm,
F_{ag} = 2.5

Milling effect on a size distribution

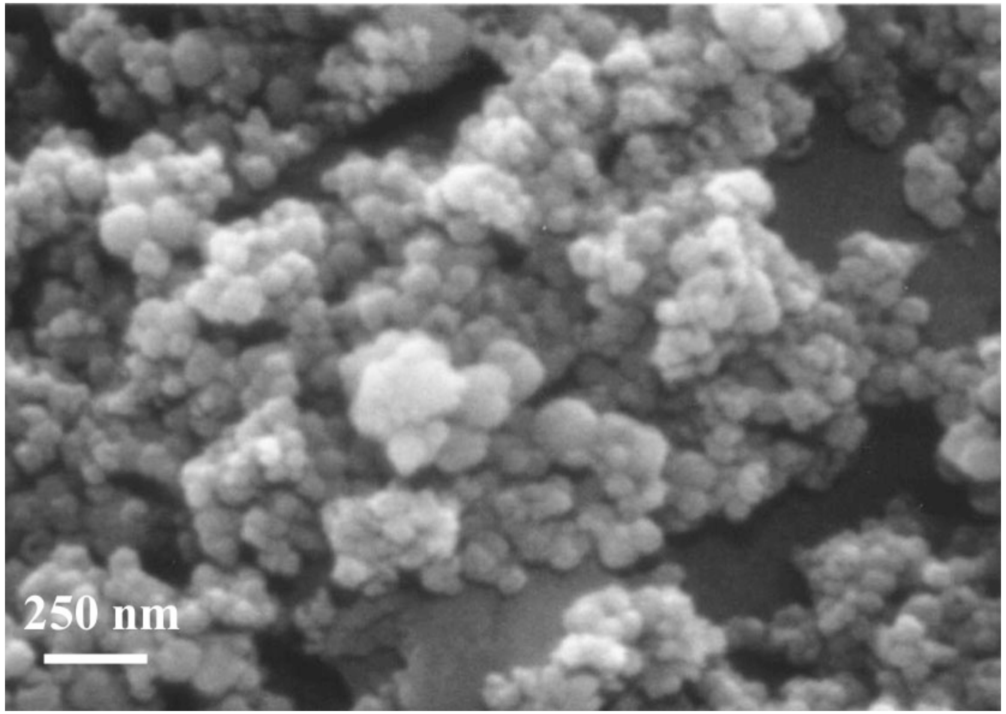


Gamma alumina,
d_{v50} = 40 nm,
F_{ag} = 2.5

Milled **Deg C**,
D_{v50} = 23.7 nm,
Fag = 1.62

Hydrothermal synthesis

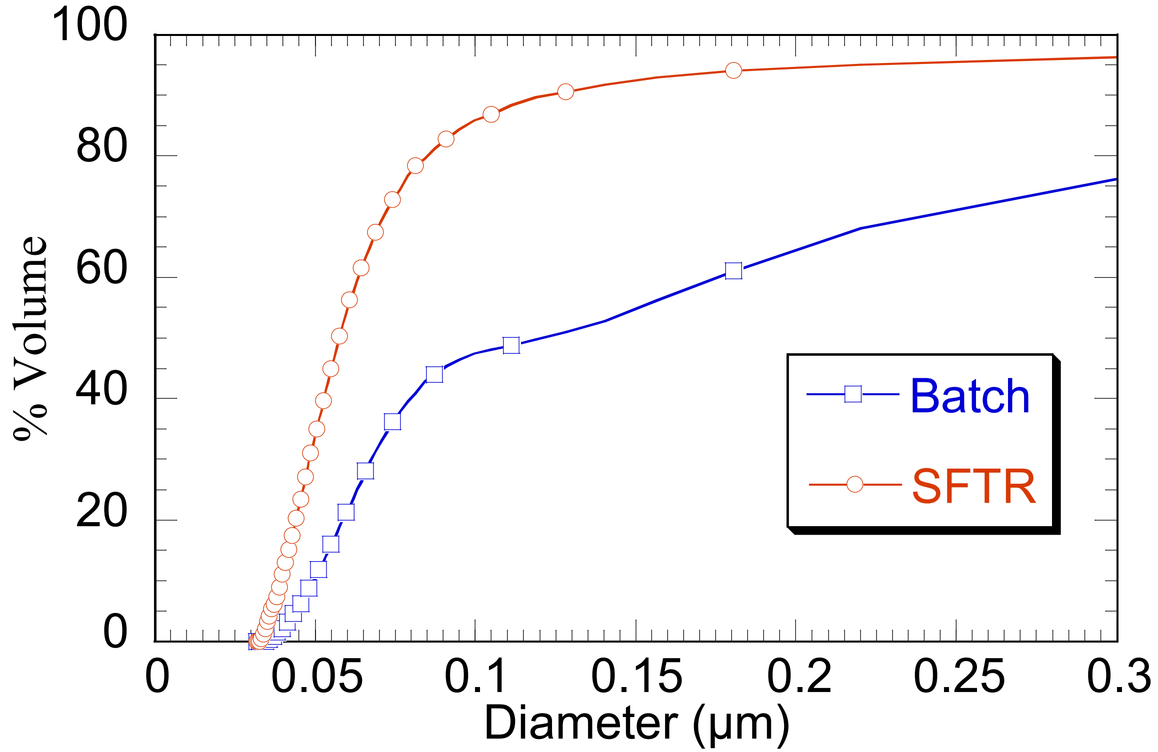
- $BaTiO_3$ hydrothermally produced



Powder	SSA (m2/g)	dBET (nm)	PSD (nm) dv16	 dv50	 dv84	Fag (dv50/dBET)
Batch synthesis	37.6	31	54	86	328	2.8

$BaTiO_3$ - SFTR - Batch - Granulometry

- ❖ SFTR powder
- ❖ Fine,
- ❖ High surface area
- ❖ F_{ag} - same value



Powder	SSA (m2/g)	dBET (nm)	PSD (nm) dv16 dv50 dv84	Fag (dv50/dBET)	dv84/dv16
Batch synthesis	37.6	31	54 86 328	2.8	**6.8**
SFTR synthesis	50.3	24	50 67 111	2.8	**2.2**

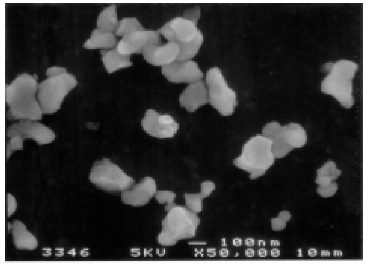
3.4.2 Crushing and Milling

- Comminution: particle size reduction by crushing or milling, is used for (almost) all raw materials. Different types of crushers and mills are classified according to material size

- Crushing: large particles - tens of cm

  - reduced to a millimeter or a few hundred μm.

- Milling: reduces such particles down to a few tens of μm



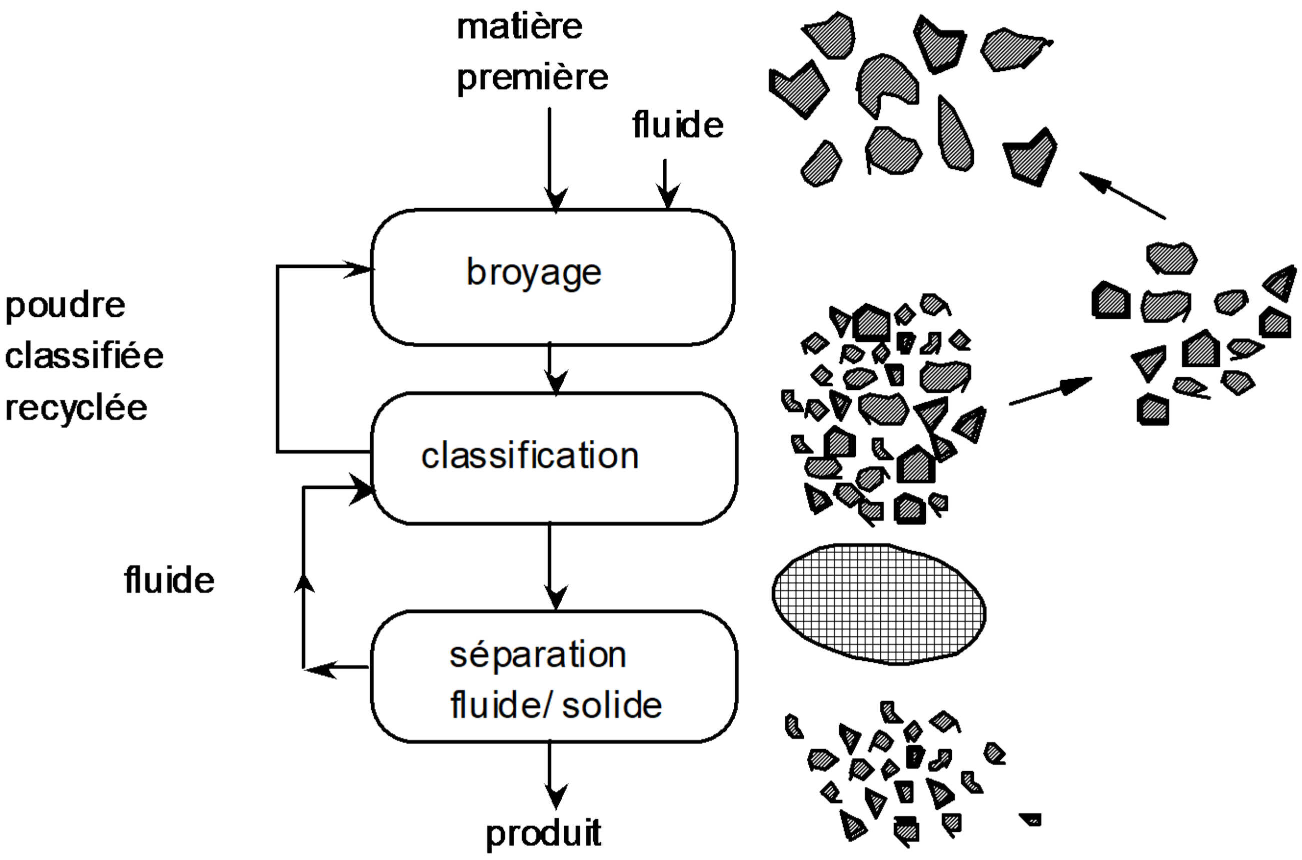
- Fine milling produces submicron particles,

  - typically between 1 and 0.1 microns.

Milling and crushing - definitions

- Often there is a classification step in addition to the size reduction step.
- In laboratory milling is essentially done in *batch mode*,
- In industry the continuous processes are often used.
- A classification step in a milling circuit
  - enables more efficient use of milling energy
  - removing the fraction of the product that has already reached the required size and
  - recycling the other, as shown in Figure 3.4.1.

Milling circuit - Fig 3.4.1



- at the end of the circuit, the particles must be separated from the gas or the carrier liquid.
- using either screens, sieves, centrifuges, cyclones or air classifiers.

Milling - general remarks - energy

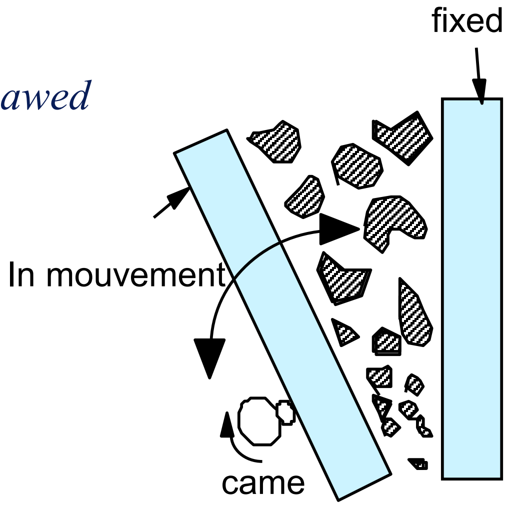
- Many industrial processes include particle size reduction (cement, ceramics, food, pigments).
- Despite the importance, the mechanisms of milling are poorly understood and difficult to model.
- The milling performance in terms of energy used to reduce the particle size is low. Only 1-7% of the energy supplied is actually used to break particles.
- This therefore represents a great waste of energy - around 6% of the world's electrical energy is used in milling operations.
- Improving our ability to predict and model milling, making it more efficient, would be of great economic and ecological importance.

Milling - generalities - modeling

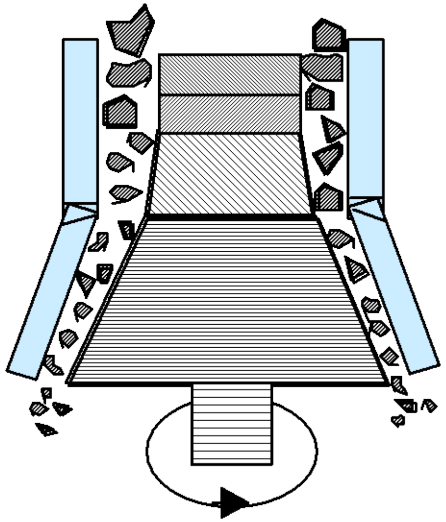
- Progress over the past 10-15 years with the use of population balance equation modelling.
- Modeling the size distribution of incoming and outgoing products for different types of materials
- Milling produces constraints both in compression and in shear which break the particles into smaller fragments.
- Several different mechanisms may be involved,
  - such as de-agglomeration of a porous aggregate,
  - abrasion, fracture or cleavage of single crystals.
- The fracture mechanisms depend on the type of mill, the milling material and incoming material.

Crushers

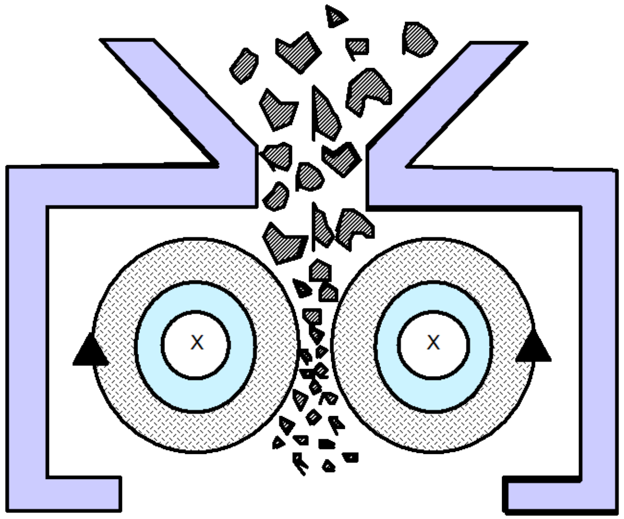
(at) *jawed*



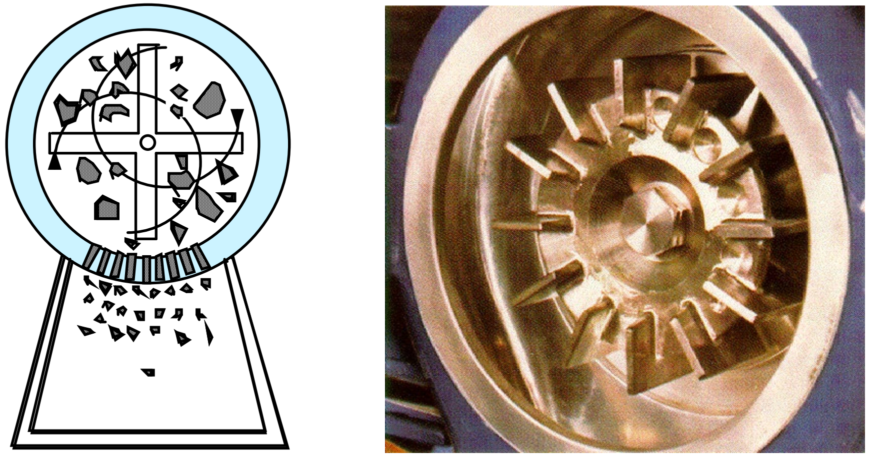
(b) *rotary*



(vs) *roller*

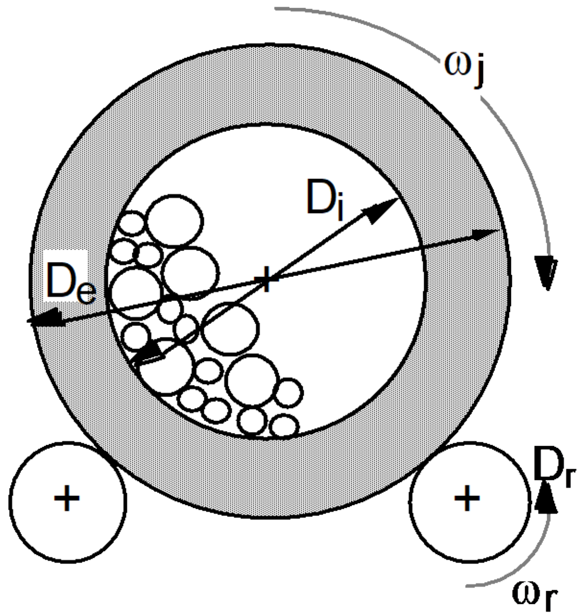


(d) hammer



Milling and fine milling

- Rotary bead mill
- Maximum rotation speed, ϖ_{vs} (rpm), at which all the beads are held against the wall by centrifugal forces
- When the external and internal diameters of the jar are known, this speed can be adjusted according to the speed of rotation of the rollers ϖ_r.
- If the wall of the jar is thin, Eq. 3.4.1 (c) can be used
- A speed of 60 to 80% of the maximum speed is used.

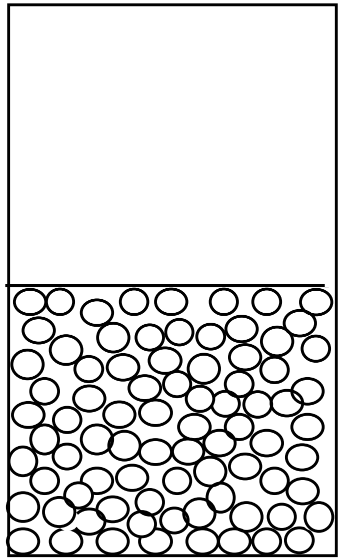


$$\omega_c = \frac{42.3}{\sqrt{D_i}} \quad \text{Eq. 3.4.1 (a)}$$

$$\omega_r = \frac{42.3 D_e}{D_r \sqrt{D_i}} \quad \text{Eq. 3.4.1 (b)}$$

$$\omega_r = \frac{42.3 \sqrt{D_e}}{D_r} \quad \text{Eq. 3.4.1 (c)}$$

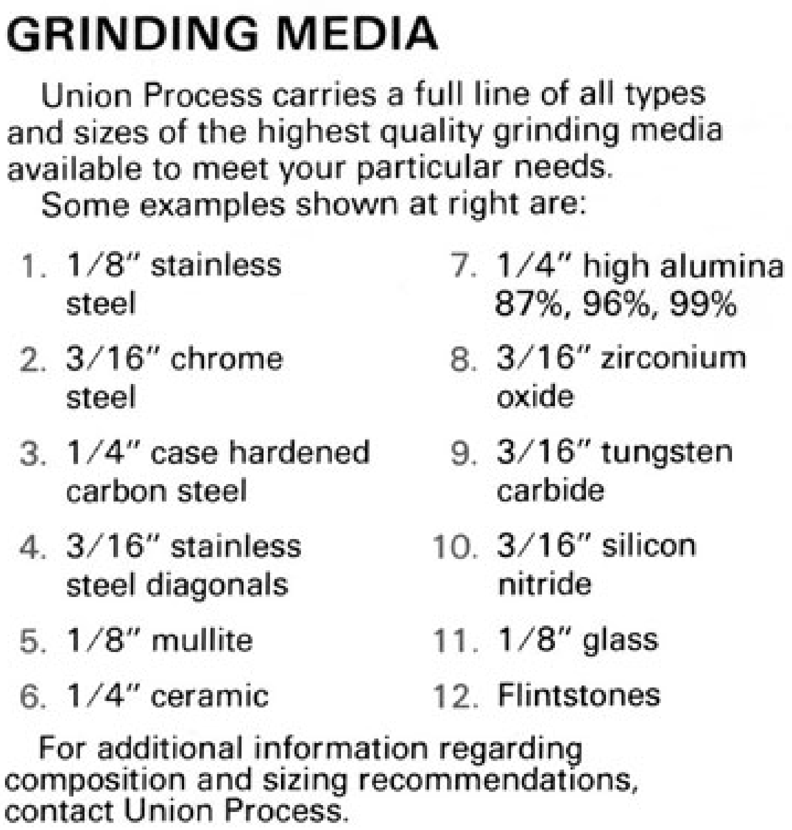
Milling and fine milling - beads



- The jar volume is usually about 50% full with the milling beads.
- The added milling powder is just enough to cover the surface of the beads and fill in the gaps, i.e. approximately 25% of the jar volume.
- The size of the beads used ranges from approximately 1cm to 10cm.
- Its size must be approximately 25 times the size of the material to be ground for milling to be effective.
- A mixture of sizes can be used to increase the number of collisions, keeping a few large beads to produce large impact forces (in some case, not in general. Large beads strongly increase contamination due to abrasion of small beads).

Milling and fine milling - materials

- Several materials are used for milling ceramics:



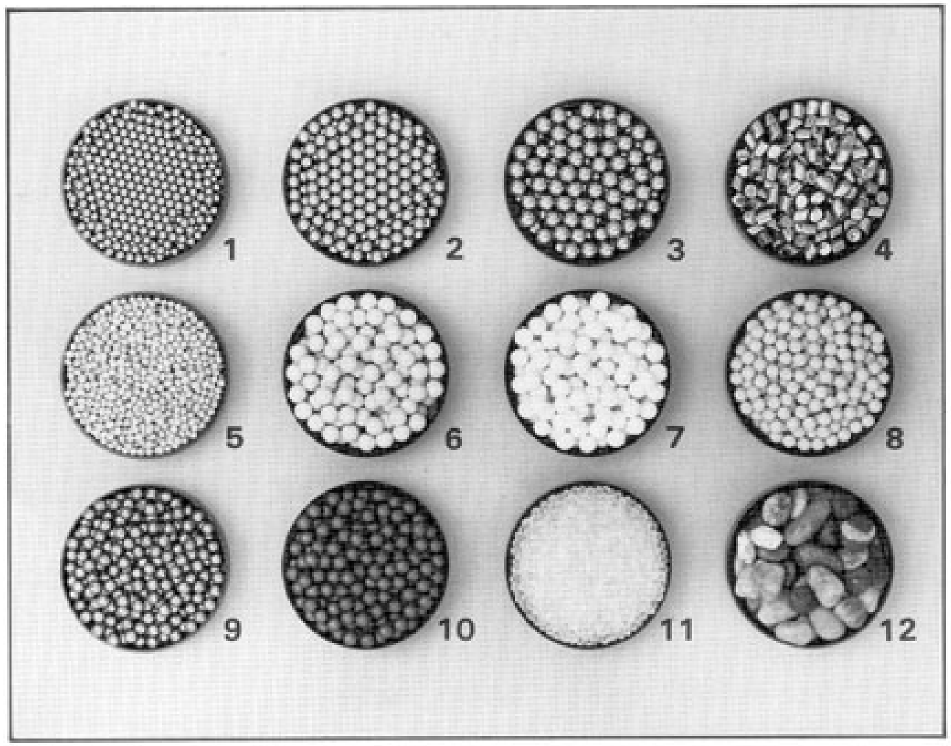
GRINDING MEDIA

Union Process carries a full line of all types and sizes of the highest quality grinding media available to meet your particular needs.

Some examples shown at right are:

1. 1/4″ stainless steel
2. 3/16″ chrome steel
3. 1/4″ case hardened carbon steel
4. 3/16″ stainless steel diagonals
5. 1/8″ mullite
6. 1/4″ ceramic
7. 1/4″ high alumina 87%, 96%, 99%
8. 3/16″ zirconium oxide
9. 3/16″ tungsten carbide
10. 3/16″ silicon nitride
11. 1/8″ glass
12. Flintstones

For additional information regarding composition and sizing recommendations, contact Union Process.



12. Flint or Flintstone (Fr: silex, It: selce) is a sedimentary cryptocrystalline (crypto: hidden) form of the mineral quartz.

Milling and fine milling – materials - YTZ

- Yttrium stabilized zirconia which is particularly popular at the moment because of its high hardness and good fracture toughness (3-6 times more than "normal" ceramics)
- Typical ceramic fracture toughness: 2-5 MPa $m^{1/2}$
- Partially Stabilized Zirconia fracture toughness: up to 15 MPa $m^{1/2}$

  - Impurities from the wear of the milling bodies is an important factor
  - Zirconia impurities in alumina can have minor consequences on forming and subsequent sintering, but
  - Can be catastrophic for dielectric materials such as $BaTiO_3$ because the liquid phase which forms early in the sintering cycle generates an exaggerated grain growth.

YTZ® - yttria stabilized (tetragonal) zirconia

Toughness: ability of absorb energy and plastically deform without fracturing.

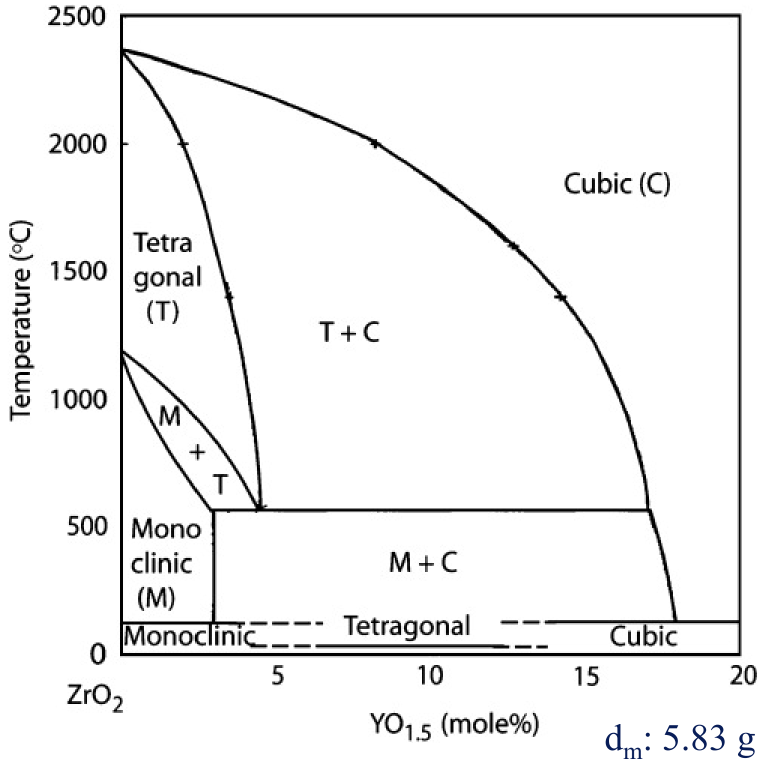
Fracture toughness: stress intensity factor for crack propagation.

Hardness: resistance to localized plastic deformation induced by e.g. indentation or abrasion.

1

Transformation - Toughened Zirconia

- Zirconia is monoclinic between 25 – ~1000 °C
- T>1000 °C Tetragonal (size dependent): 1-4% percent change in volume.
- Higher temperatures: cubic.
- With proper chemical additions and heat treatments, conserve tetragonal at RT
- Tetragonal Zirconia Polycrystal (TZP) doped with yttria (Y-TZP) has nearly every crystallite in the tetragonal form at RT

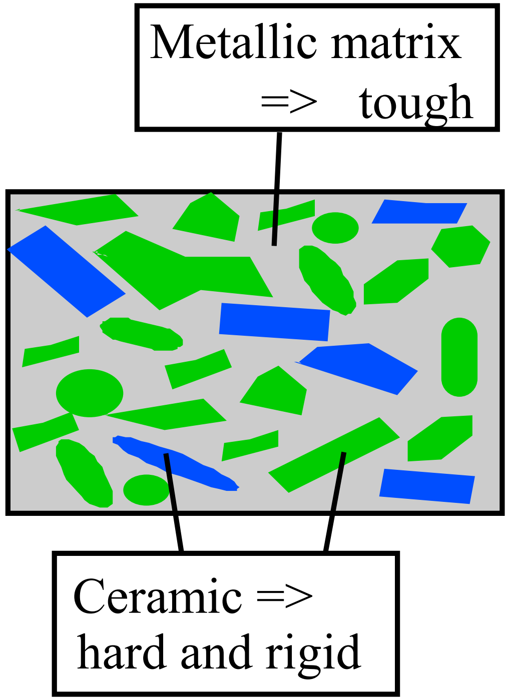


d_m: 5.83 g cm^{-3}
d_t: 6.10 g cm^{-3}
d_c: 6.09 g cm^{-3}

- Normally, tetragonal transforms to the monoclinic on cooling, but it must expand to do so.
- Tetragonal precipitates next to the crack are now able to expand and transform back to their stable monoclinic form.
- This expansion adjacent to the crack presses against the crack and stops it.
- This is the mechanism of transformation toughening.
- It is similar to the toughening mechanism in some forms of steel, so the TZP has sometimes been called “ceramic steel”.

Milling - wear

- Milling of a mixture of TiC, TiN, Mo_2C and Ni for the production of a cermet.
  - WC-Co beads - steel pots with isopropanol
  - Wear of pot →0.3% steel in the product
  - with additives to improve milling efficiency
  - stearic acid for Ni and
  - polvinylpyrrolidone (PVP) for ceramics,
  - Wear increases up to 2.3%.
- For this application the steel does not seem to be harmful for the properties of the sintered cermets*.



Metallic matrix => tough

Ceramic => hard and rigid

*Bowen,P. Bonjour,C. Carry,C. Gonseth,D.R. Hofmann,H. Mari,D. Mulone,R. and Streit,P. "Novel Alumina Titanium Carbonitride Nickel Composites" JOM, **47**(11) 56 (1995)

Wet milling

Some advantages over dry milling:

- Handling and pumping of slurries of fine particles - easier than dry state – dust formation (fine particles 20nm - 10µm - enter and can be retained in the body - harmful to health)
- Wet milling uses about 30% less energy for an equivalent size reduction - but
- the wear of the beads can be significantly higher for the same material - up to a factor of 5
- For forming methods which uses suspensions e.g. slips casting - dip coating

dip coating

Funeral wreath

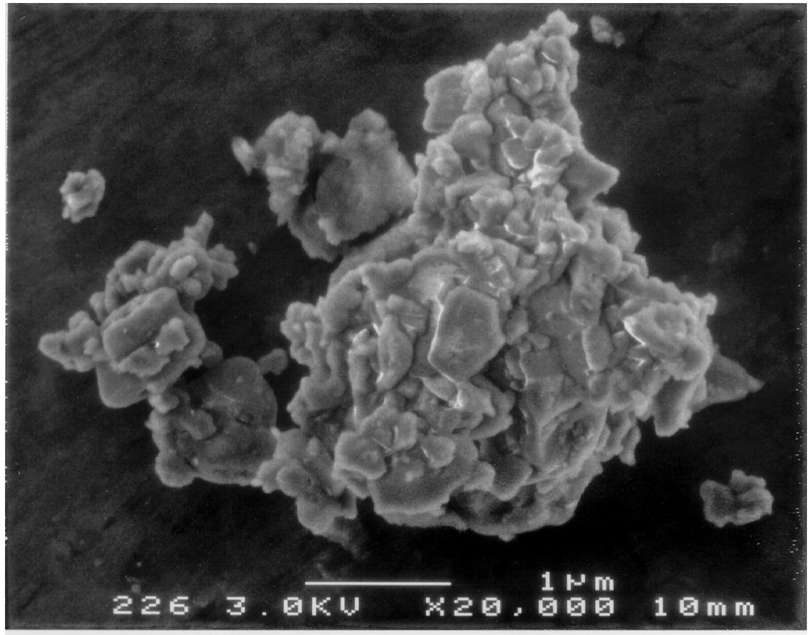
Dry milling

Generally used when

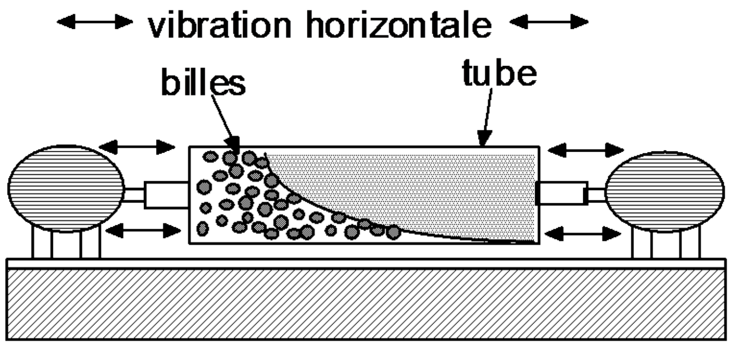
- materials react with water
- other fluids are too expensive, or
- the material must be used in a dry state and
- energy used to dry the ground slurry adds excessive expense to the overall process

Alumina alpha - Alcoa A16SG

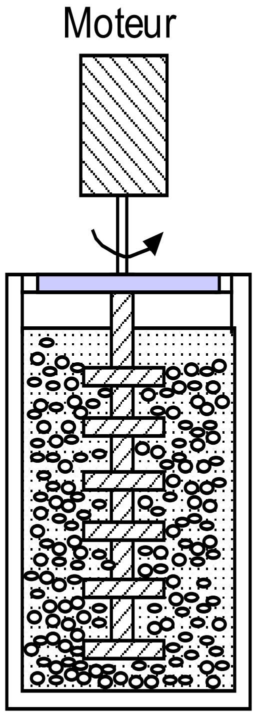
- dry milled



Fine milling

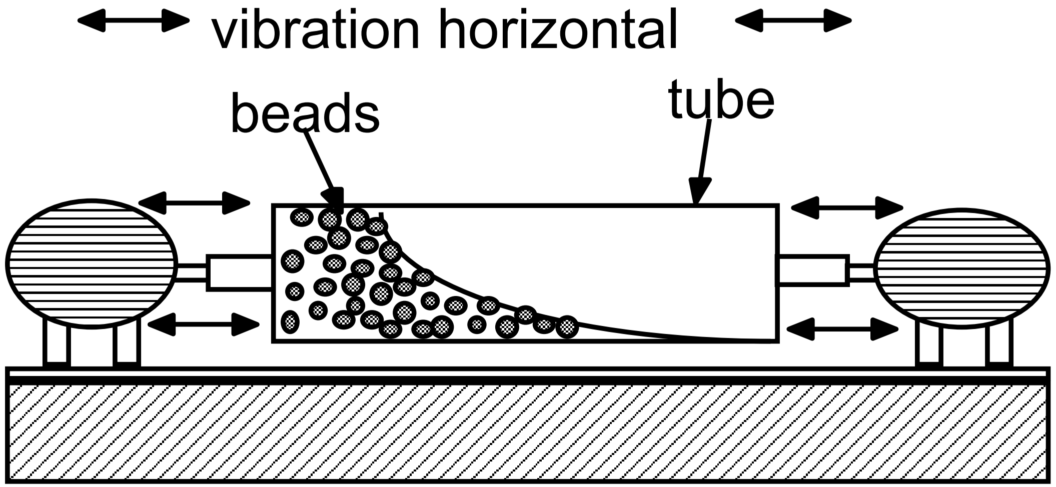


- Fine milling is associated with greater energy input by
  - vibration,
  - high shear, like in agitated bead mills or
  - high speeds, as in fluid impact crushers
- The main difference of these mills from the simple rotary bead mill is the **number of collisions per unit of volume and time**.



Attrition mill

Vibrational mills



- The vibratory bead mill can be filled with milling beads
  - spherical or cylindrical
- Cylindrical bodies increase the impact surface and are generally used for low energy vibratory crushers.
- The size of the spherical beads also has an influence on the frequency of collisions
  - more collisions for smaller sizes.
- In practice, the smallest beads reach about 1mm
- (0.3mm – very high wear observed in practice)

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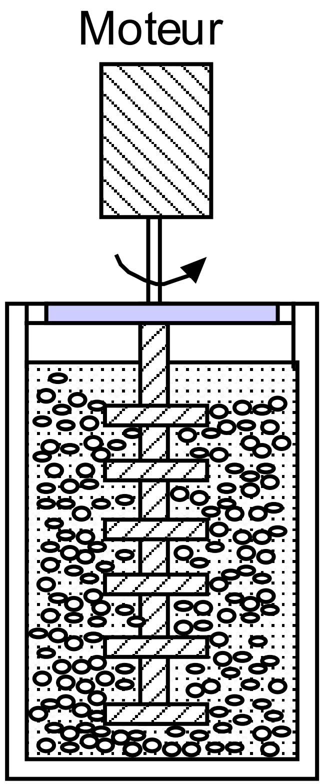
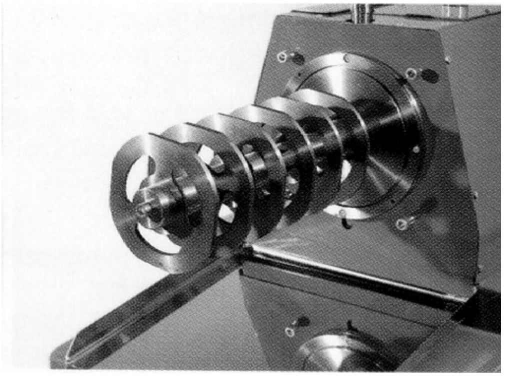
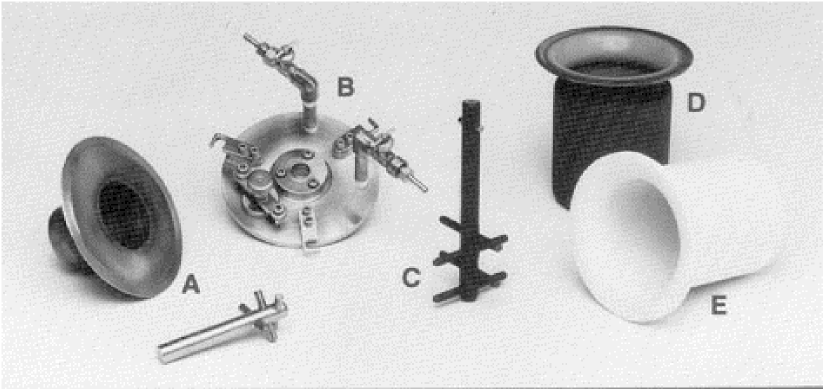
Agitated bead mills – Attrition mills



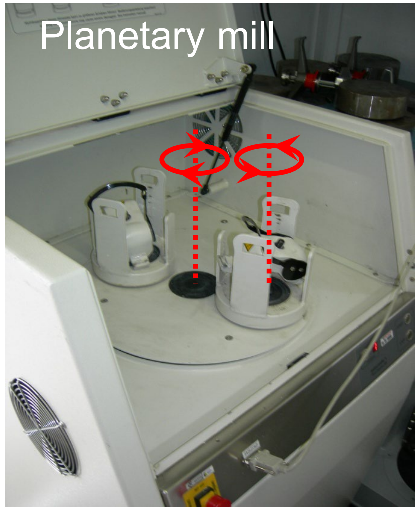


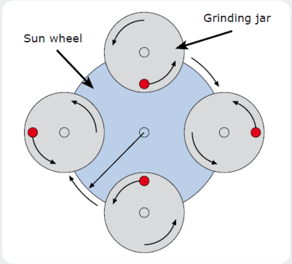


- High turbulence produces high compressive and shear stresses - high collision frequencies and fast milling kinetics.
- Significant stress is produced by the friction of particles between the beads, causing attrition - as much as by the compressive and shear stresses resulting from direct collisions.

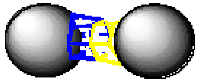
Planetary ball milling

- Decrease the milling time to a certain point to obtain a homogeneous nanopowders with increased reactivity for further processing.
- Especially attractive for the preparation of complex compositions.

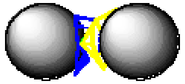




elastic deformation

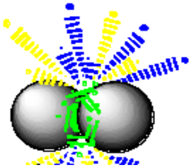


plastic deformation



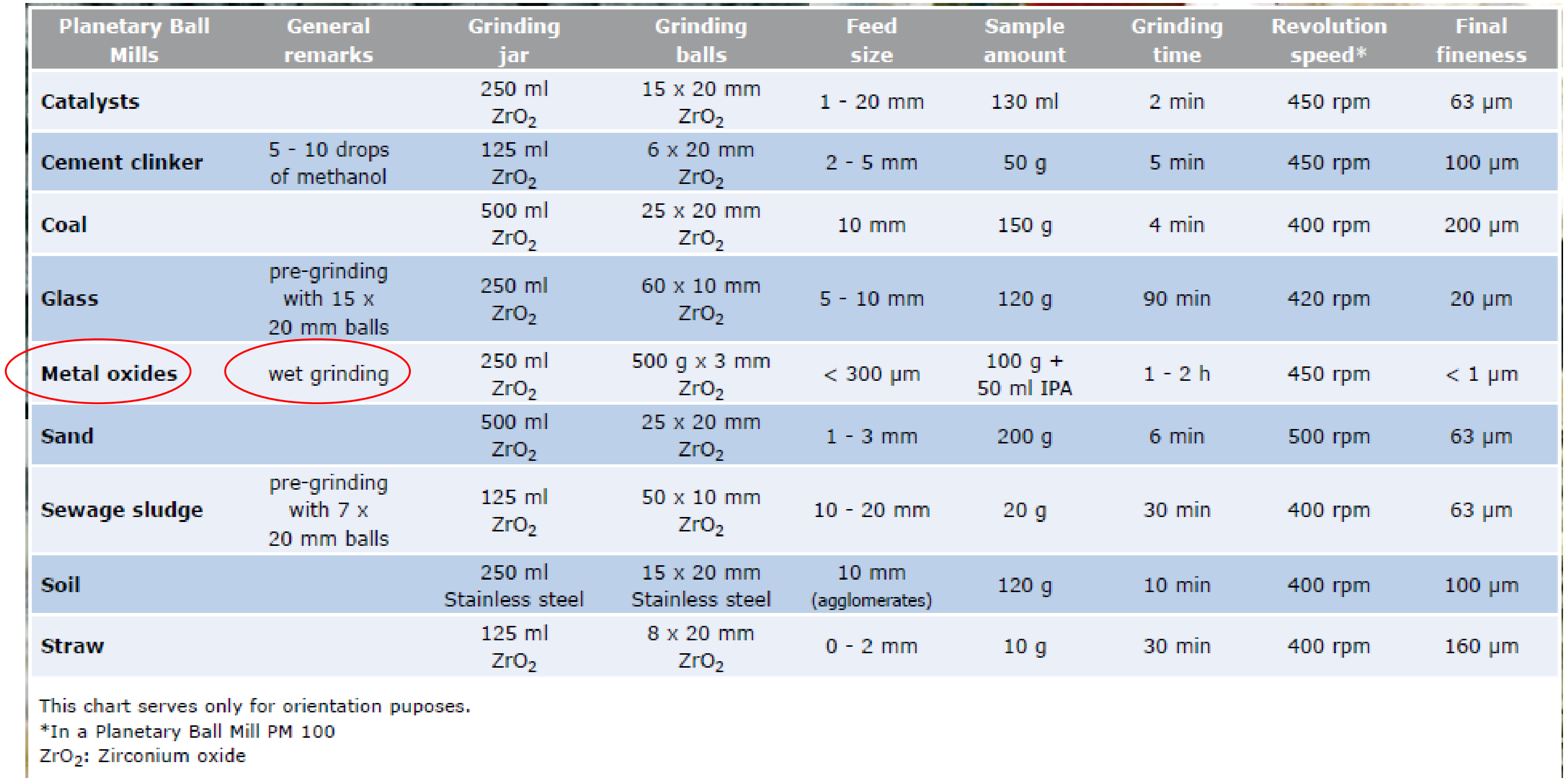
fracture, amorphisation,

chemical reactions



with P, T sensors

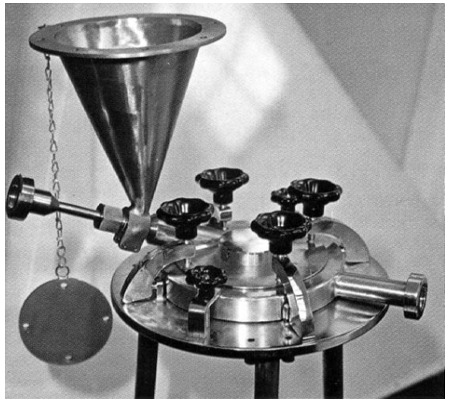
In order to understand the processes which occur during grinding with ball mills (e.g. chemical reactions, phase changes), it is helpful to record the most important thermodynamic parameters: pressure and temperature.

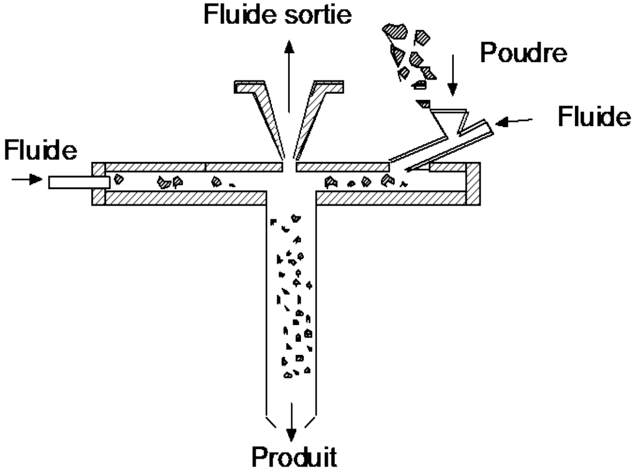


Planetary Ball Mills	General remarks	Grinding jar	Grinding balls	Feed size	Sample amount	Grinding time	Revolution speed*	Final fineness
Catalysts		250 ml ZrO_2	15 x 20 mm ZrO_2	1 - 20 mm	130 ml	2 min	450 rpm	63 µm
Cement clinker	5 - 10 drops of methanol	125 ml ZrO_2	6 x 20 mm ZrO_2	2 - 5 mm	50 g	5 min	450 rpm	100 µm
Coal		500 ml ZrO_2	25 x 20 mm ZrO_2	10 mm	150 g	4 min	400 rpm	200 µm
Glass	pre-grinding with 15 x 20 mm balls	250 ml ZrO_2	60 x 10 mm ZrO_2	5 - 10 mm	120 g	90 min	420 rpm	20 µm
Metal oxides	wet grinding	250 ml ZrO_2	500 g x 3 mm ZrO_2	< 300 µm	100 g + 50 ml IPA	1 - 2 h	450 rpm	< 1 µm
Sand		500 ml ZrO_2	25 x 20 mm ZrO_2	1 - 3 mm	200 g	6 min	500 rpm	63 µm
Sewage sludge	pre-grinding with 7 x 20 mm balls	125 ml ZrO_2	50 x 10 mm ZrO_2	10 - 20 mm	20 g	30 min	400 rpm	63 µm
Soil		250 ml Stainless steel	15 x 20 mm Stainless steel	10 mm (agglomerates)	120 g	10 min	400 rpm	100 µm
Straw		125 ml ZrO_2	8 x 20 mm ZrO_2	0 - 2 mm	10 g	30 min	400 rpm	160 µm

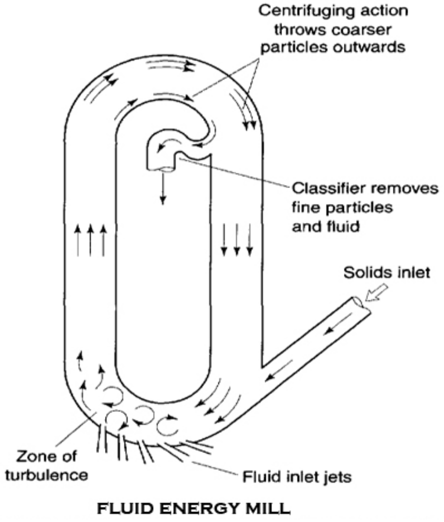
This chart serves only for orientation puposes.
*In a Planetary Ball Mill PM 100
ZrO_2: Zirconium oxide

Fluid Energy Mills





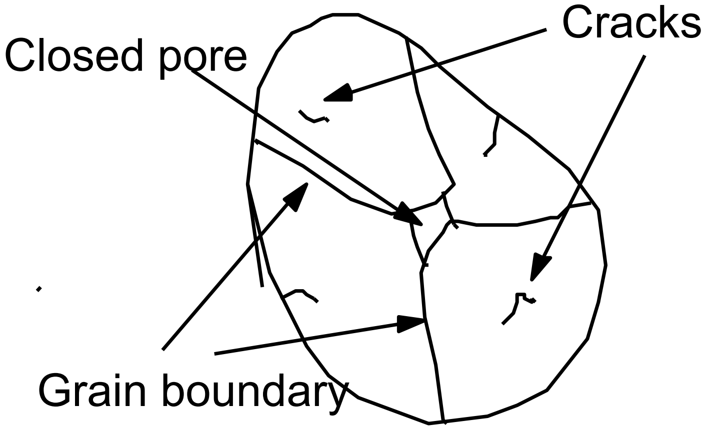

Jet Mill MC 300 KX-TD

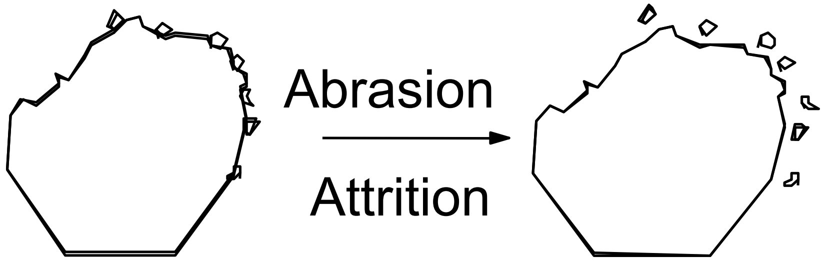


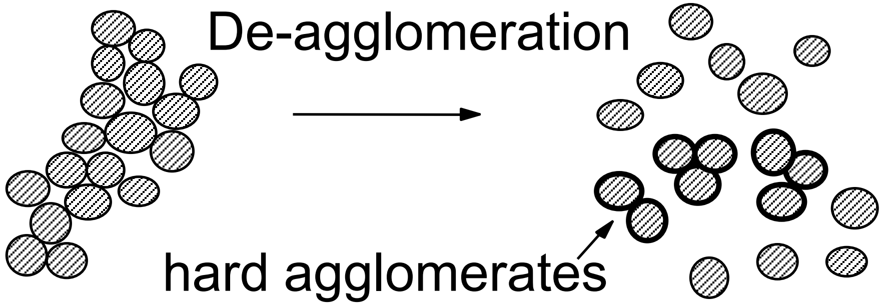
- Often used for high purity products (Baikowski 99.995% gamma alumina - synthetic rubies),
- Virtually all of the collision energy is used to break up the particles
    - the crusher coating must resist abrasion by the product, but
    - wear is generally low.
- These mills are often and easily combined with turbo-classifiers and
- The desired product can therefore be withdrawn and
- Only the excessively large fraction returns to the milling chamber with the incoming flow of product to be ground.
- Also known as “micronizer” and used in pharma industry

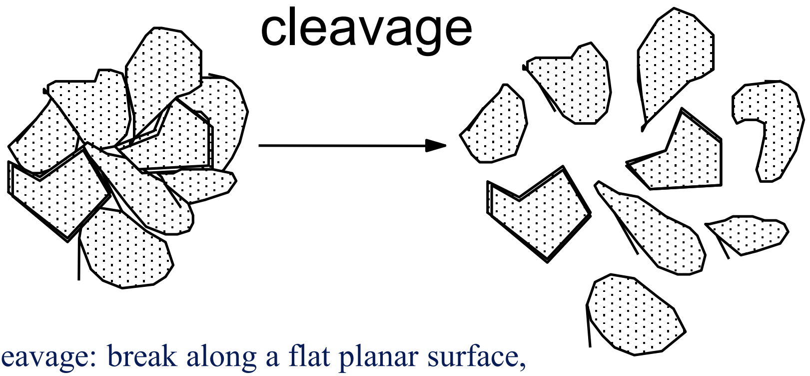
Particle breakage 1

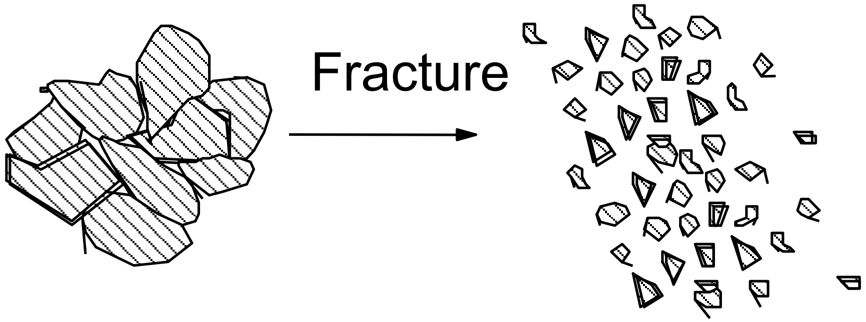
- Particle fracture is produced by forces of compression, shear, and friction.











Cleavage: break along a flat planar surface, e.g. in a specific crystal lattice direction

Particle Breakage 2

- The constraint at the breaking of a particle tends to increase when the size decreases and we approach dense monocrystalline materials.
- Different approaches exist and involve Griffith's law relating defect size to modulus and elastic energy (Ceramics properties).
- There exists a size limit for a perfect single crystal
  - of about 1µm for quartz and
  - of 4µm for calcite
- Below these limit values, it is no longer possible to accumulate sufficient elastic energy in a particle, which can therefore only deform plastically.
- At this time, the attrition because of the large stresses produced during the friction between the particles, becomes an important mechanism to allow further size reduction.
- Reality - small defects - depending on the synthetic route
- SiC from a carbothermal route milled down to 40 nm (prof. H. Hofmann, LTP-EPFL)

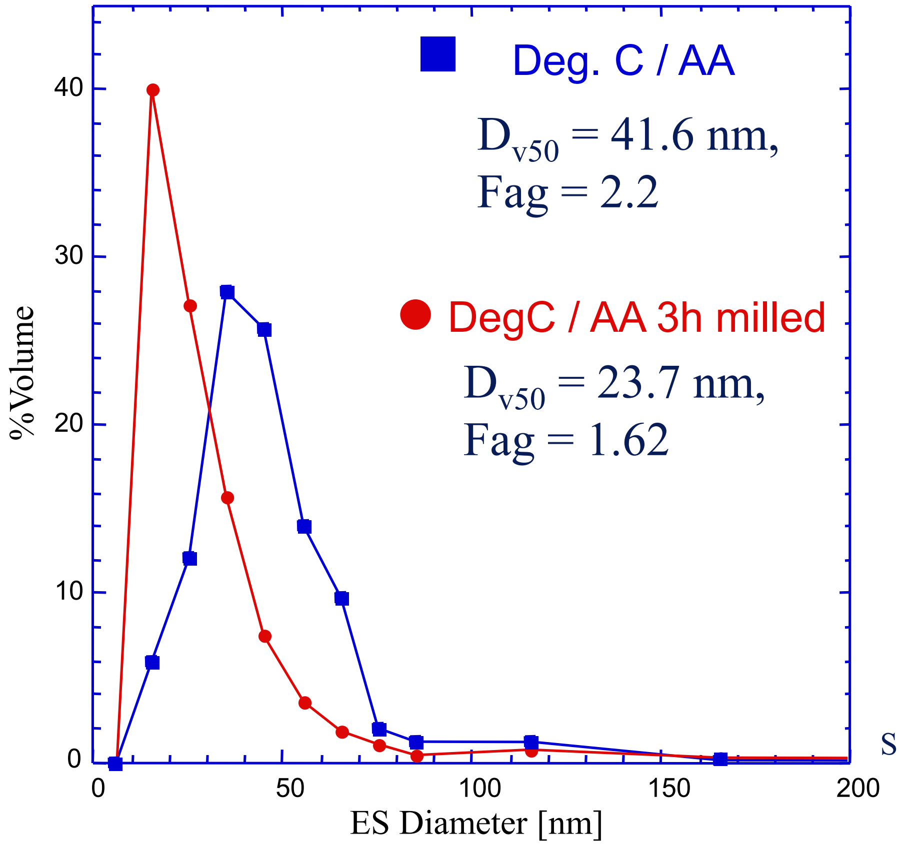
Griffith's law on crack propagation: see specific course on material properties

Particle breakage 3

- During milling very high local temperatures can be reached from
  - heat dissipation at the tip of propagating cracks,
  - friction in attrition.
- It may soften the material and lead to a more plastic behavior.
- This heat can lead to local transformations of the material, e.g. producing an amorphous layer, or even a phase transformation,
- An example is the transformation of typical transition alumina γ to α by high energy vibration milling (with heat it happens at around 1000 ° C).
- The defects which remain in the powders after milling can also have a positive influence on the sintering, by facilitating the diffusion of the different species according to the sintering mechanism.

Milling effect on sintering - Gamma alumina

Photocentrifuge PSDs (Horiba)



See slide 12

Relative Densities	DegC - AA Acetic Acid	DegC - AA 3hrs - milled	CR125 -PAA 3hrs - milled
Green Body (NAD)*	30.5±1.5%	40.1±2%	41.8±2.1%
Green Body (Archimède's)	31.0± 1.1%	41.2±0.9%	41.5±1.3%
Sintered	56.6±7%	99.1± 0.4%	98.7±0.4%

NAD: N_2 ads/desorb, after Binder Burnout

- Size reduction
- More contact points
- Defects produced by milling facilitates transformation from γ to α.

CR125: https://www.baikowski.com/en/serie/cr/

Deg C (Degussa) -> AEROXIDE® Alu C (Evonik)

Particle breakage - 4

- The amount of energy used during milling is consumed by
  - the moving parts of the system,
  - transfer of material to the milling zone
  - the fragmentation of the material to be ground,
  - the collection, separation and transfer of the product.
- The amount of energy actually used to break up the particles,
  - is often 1% to 7% of this total.
- There have been many attempts to relate the energy consumed during milling to the properties (size) of the final product.
- In 1867, Ritinger suggested that the energy used to reduce the particle size should be proportional to the energy of the newly formed surface.

Particle breakage - 5

- The energy consumed to produce this new surface can be expressed as the integral between the initial size L_0 and the final size L_f, Eq. 3.4.2

$$E = -\int_{L_o}^{L_f} \frac{K}{L^m} \, dL$$

- Where K is a constant and m = 2.
- For particles between 10 and 1000μm this simple approach works relatively well, as for the fragmentation of cement clinkers.

Particle breakage - 6

- Kick's Law
- m = 3 to relates the energy consumed to the energy stored per unit volume

$$E = -\int_{L_o}^{L_f} \frac{K}{L^m} dL$$

- Bond’s Law
- m = 1.5 for the empirical approach of Bond
  - very popular works with a lot of different materials
- <10µm, it is more complex and the energy used to deform, can lengthen a crack, but does not necessarily lead to the rupture of the particle.

- For fine milling, a simple and adequate relationship has not yet been developed, but the modeling of specific combinations of mills and product has shown some success.

See section 2.3.4* for a treatment using population balance approaches.

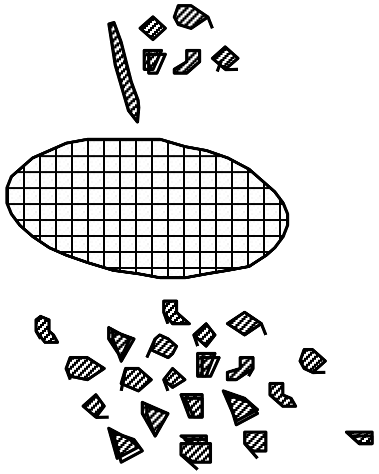
* Les Traité des Matériaux, Volume 16 « Les Céramiques »

2.4.2.5 Classification

- Another way to change the size distribution is to classify the particles into two or more fractions.
- Classification is normally done by size, but can also be based on other criteria such as
  - shape,
  - density or
  - magnetic or electrical properties.
- Equipment for classification
  - the upper limit up to 20cm with screens or sieves,
  - the lower limit down to a few nm with ultra-centrifuges;
  - air classifiers cover the intermediate range 1000 and 0.1 µm.

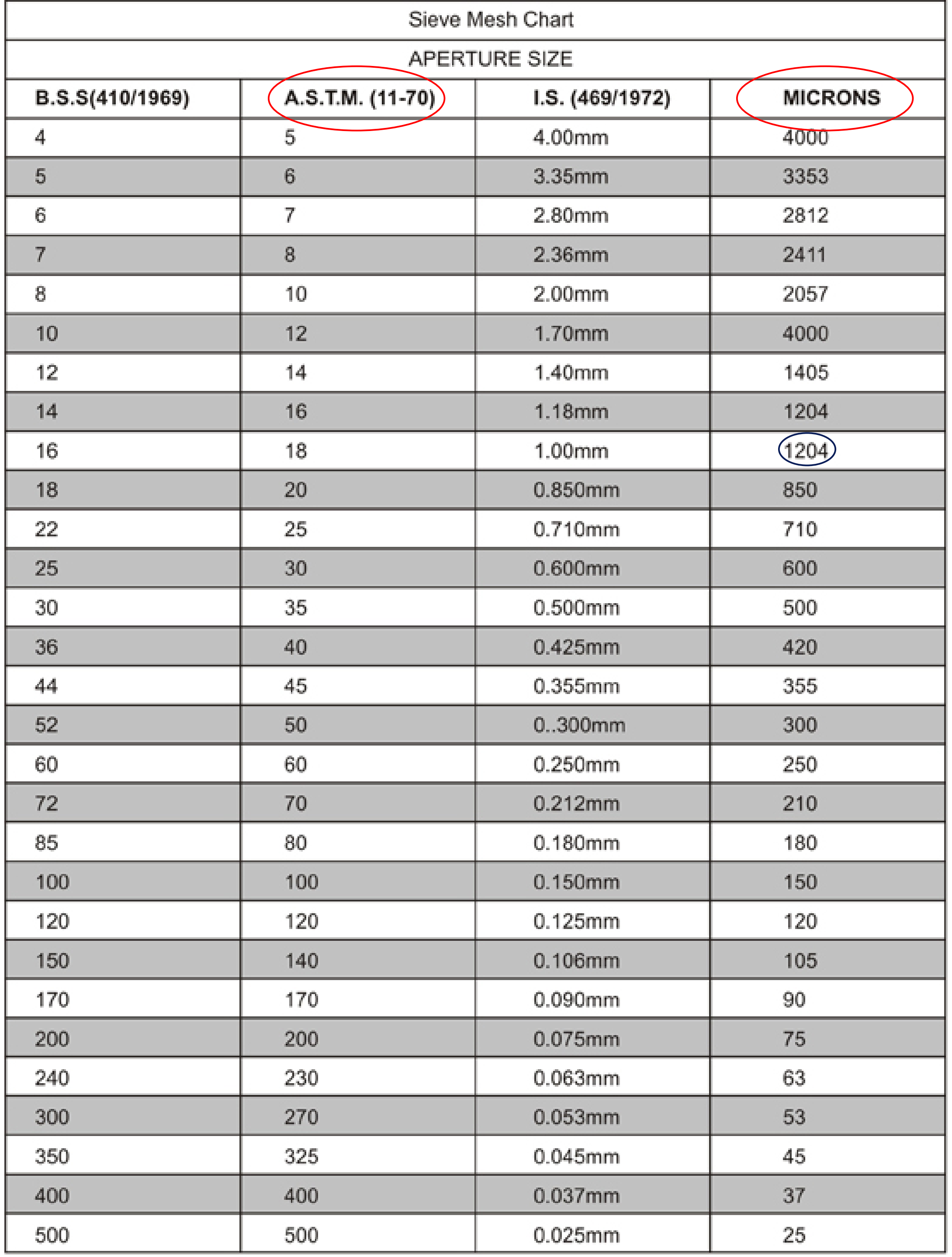
Sieving

- The diameter of the sieve d_T, is a minimum size that can fit through the square opening.
- When using sieves, great care must be taken not to deform the mesh and create large openings which decrease the selectivity.
- One of the most frequent questions regarding sieves is to know what size (aperture) corresponds to a certain mesh number.
- The mesh number corresponds to the number of threads per unit length and varies between Europe and the US.
- The ISO standard which gives the size of the opening and the size of the wires is easy to follow, unlike the American standards (ASTM) whose definitions are listed in Table 3.4.1 for those who will meet this standard in their future activity.



Sieving size

3



Sieve Mesh Chart

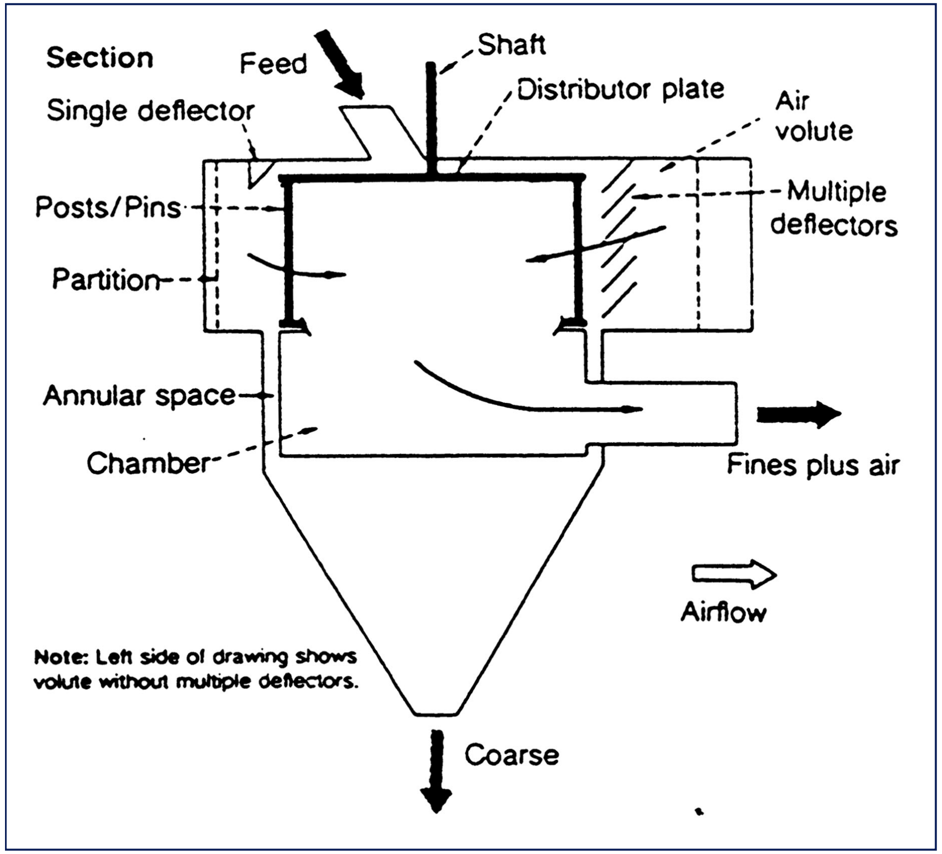
APERTURE SIZE

B.S.S(410/1969)	A.S.T.M. (11-70)	I.S. (469/1972)	MICRONS
4	5	4.00mm	4000
5	6	3.35mm	3353
6	7	2.80mm	2812
7	8	2.36mm	2411
8	10	2.00mm	2057
10	12	1.70mm	4000
12	14	1.40mm	1405
14	16	1.18mm	1204
16	18	1.00mm	1204
18	20	0.850mm	850
22	25	0.710mm	710
25	30	0.600mm	600
30	35	0.500mm	500
36	40	0.425mm	420
44	45	0.355mm	355
52	50	0..300mm	300
60	60	0.250mm	250
72	70	0.212mm	210
85	80	0.180mm	180
100	100	0.150mm	150
120	120	0.125mm	120
150	140	0.106mm	105
170	170	0.090mm	90
200	200	0.075mm	75
240	230	0.063mm	63
300	270	0.053mm	53
350	325	0.045mm	45
400	400	0.037mm	37
500	500	0.025mm	25

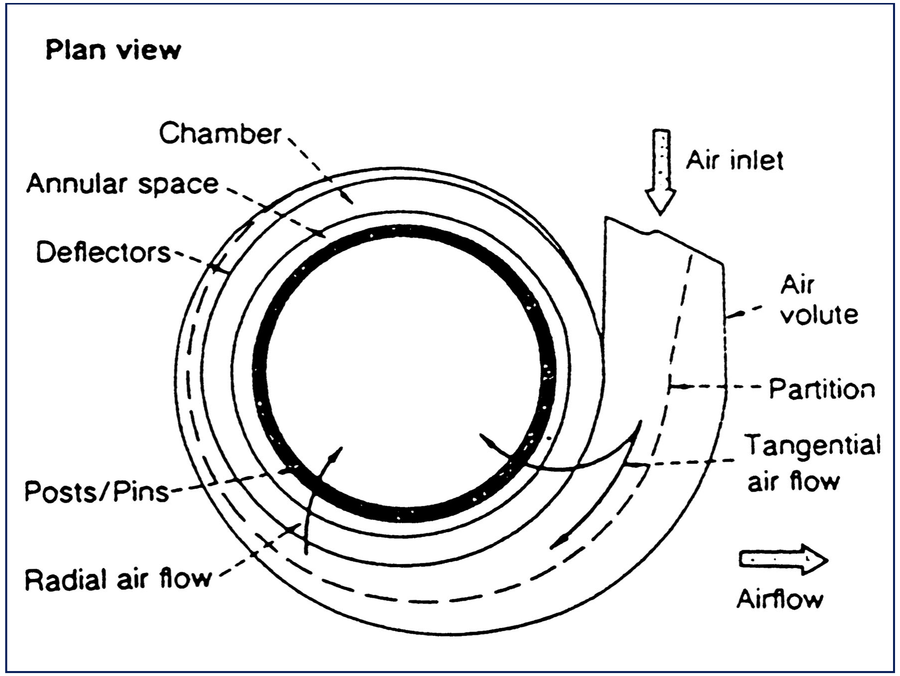
≈1000

Air classifiers

- Air classifiers are very popular for high flow rates where several hundred kg must be classified.



Note: Left side of drawing shows volute without multiple deflectors.



Characteristics of classifiers

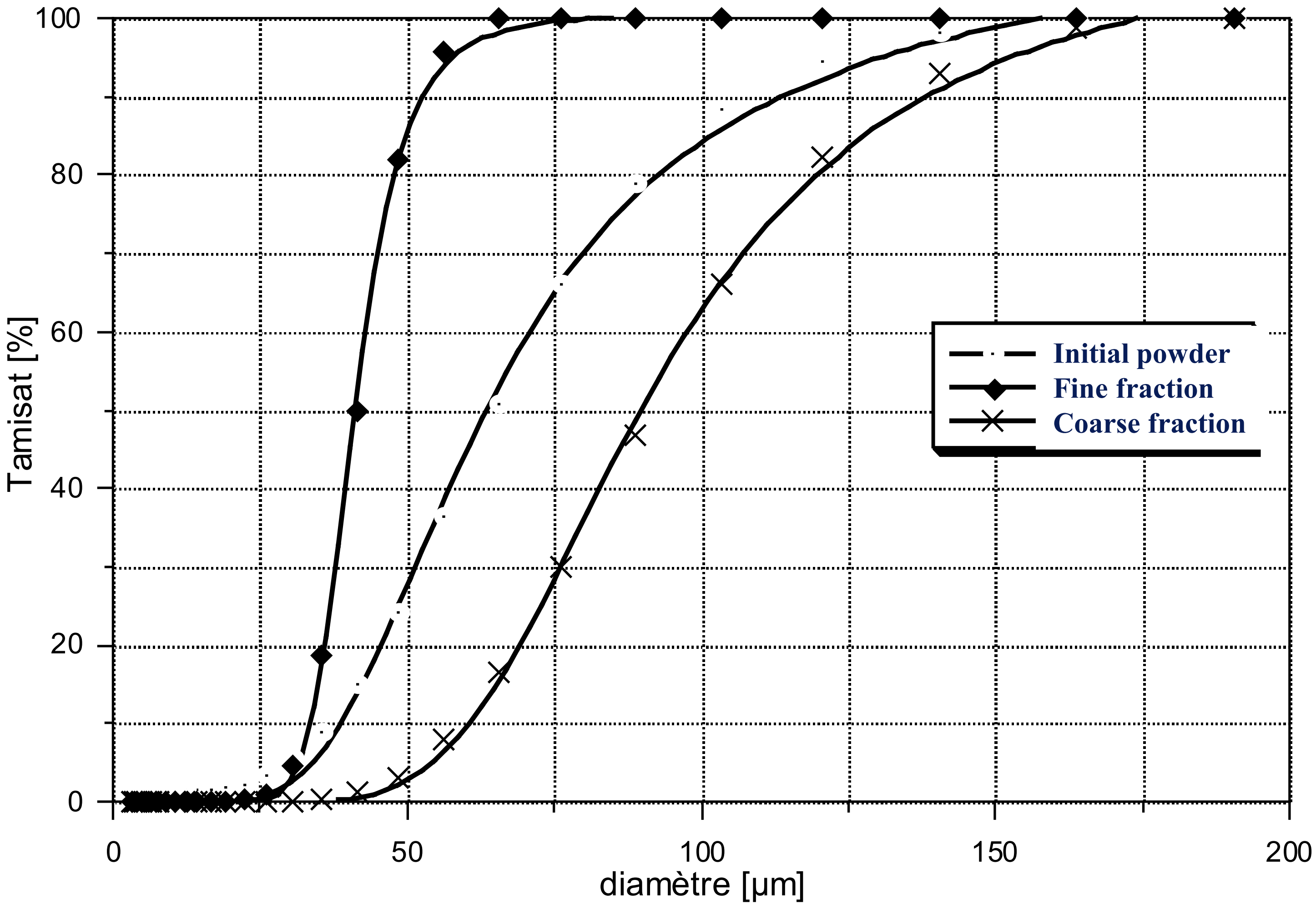
- The selectivity S, expressed as:

$$S(d) = \frac{W_c M_c(d)}{W_c M_c(d) + W_f M_f(d)} \qquad \text{Eq 3.4.5}$$

- W_c and W_f are the masses (or flow rates for continuous systems) of the collected fraction and
- $M_c(d)$ is the cumulative percentage, by mass, of particles smaller than *d* in the coarse fraction and
- $M_f(d)$ is the cumulative percentage, by mass, of particles larger than size *d* in the fine fraction.

Characteristics of classifiers -2

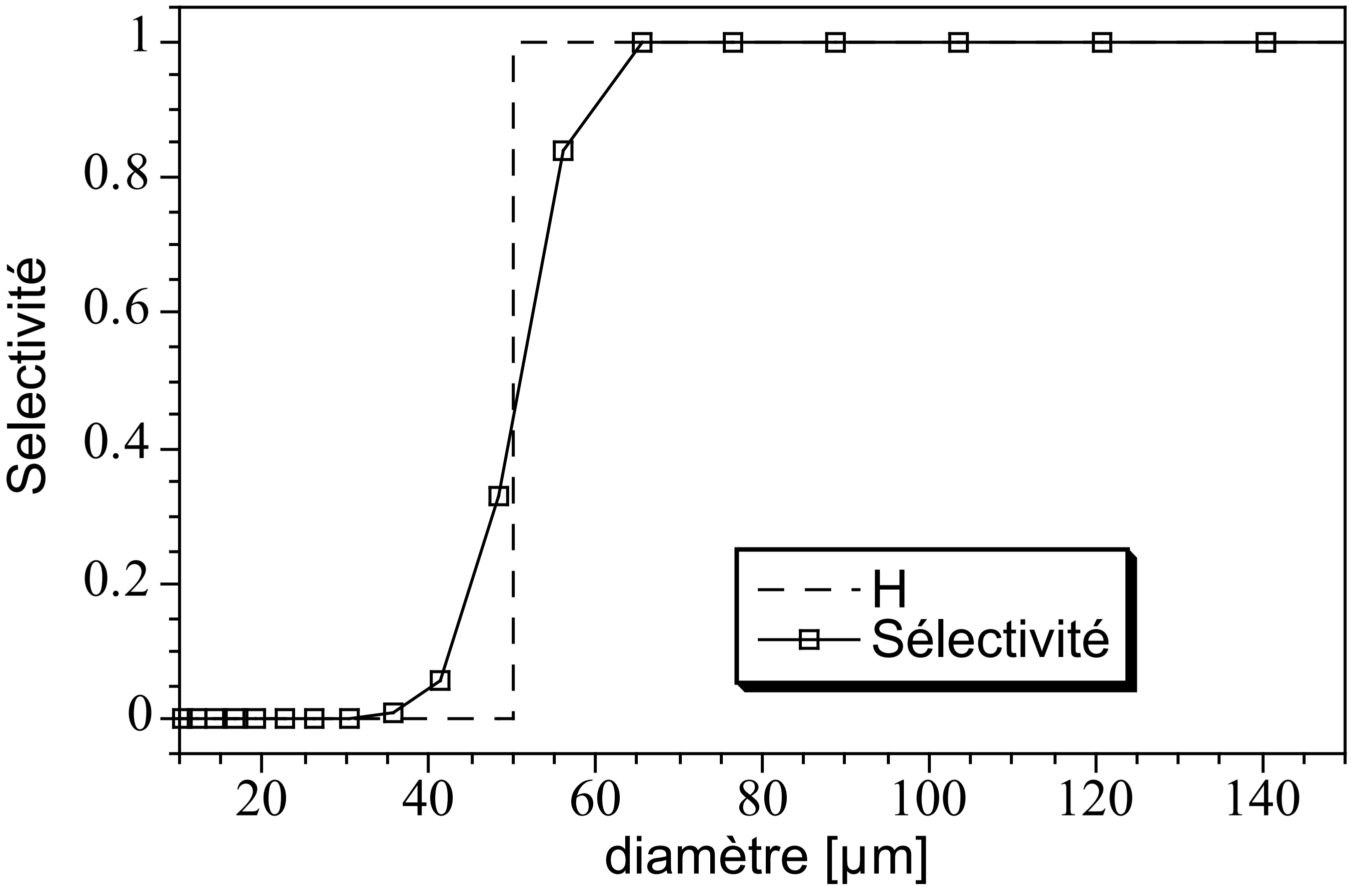
Cumulative size distributions of a granulated (spray dried) zirconia powder before and after sieving into two fractions using a 50 micron sieve



Classification - selectivity 1

- Selectivity curve for a 50 µm sieve and atomized zirconia powder

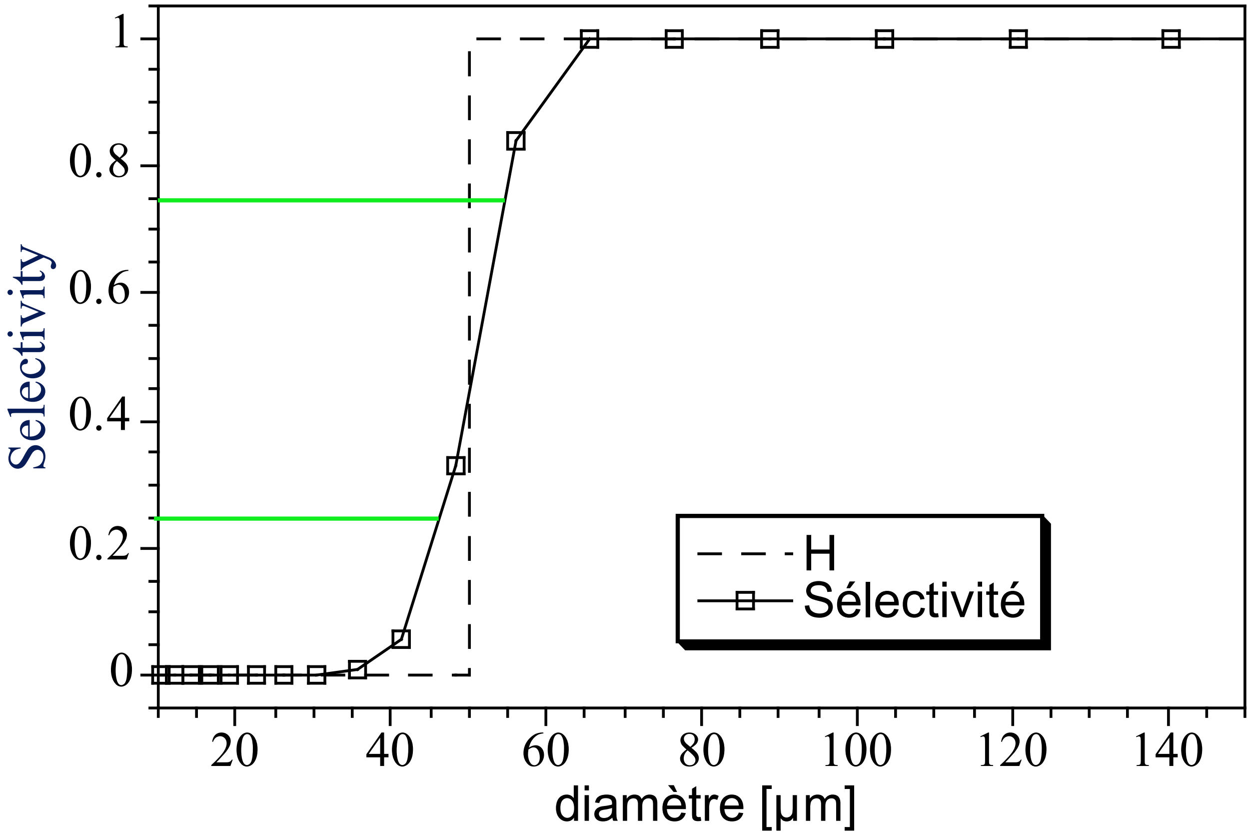
$$S(d) = \frac{W_c M_c(d)}{W_c M_c(d) + W_f M_f(d)}$$



Classification - selectivity 2

- One method of quantifying the degree of classification is to calculate the sharpness index s_c,

$$s_c = \frac{d(S_{0.25})}{d(S_{0.75})}$$ Eq. 3.4.6



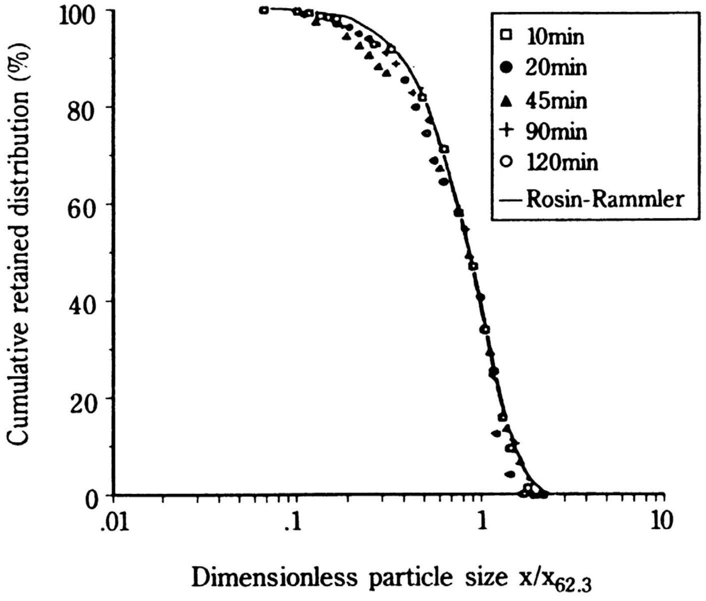
Classification - selectivity 2

- Fines may remain in the large fraction because of
  - agglomeration (dry sieving and size analysis in suspension),
  - because of the blocking of certain meshes by a few large particles
  - insufficient sieving time to allow these particles to find a free mesh.
- When the presence of large particles in the fine fraction,
  - the presence of holes or
  - distorted mesh is possible.
  - all size measurement methods assume the particles are spherical, resulting in spherical equivalent diameters (ESD) – if the particles are elongated they can pass through the sieve and will give an ESD > sieve size
- In the case of friable powders (easily crumbled), fines can be produced during sieving, which would modify the selectivity curve (e.g. spray dried ceramic powders)

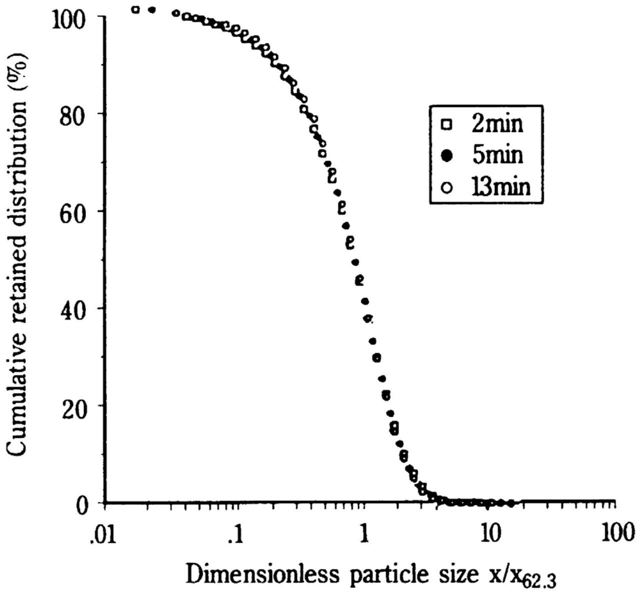
Modelling

- Milling on an industrial scale is sometimes carried out for up to 100 hours and for volumes of several cubic meters.
- A successful approach to predicting particle size distribution has been to use population balance equation
- Batch and continuous grinding can be predicted successfully for given materials and given crushers. See section 2.4.2.4 p.138-140 for more details
- E.g. Figure 2.4.5 – work of Dodds et al (1995) for hydro-argillites ($Al(OH)_3$)

(a) Rotary ball mill

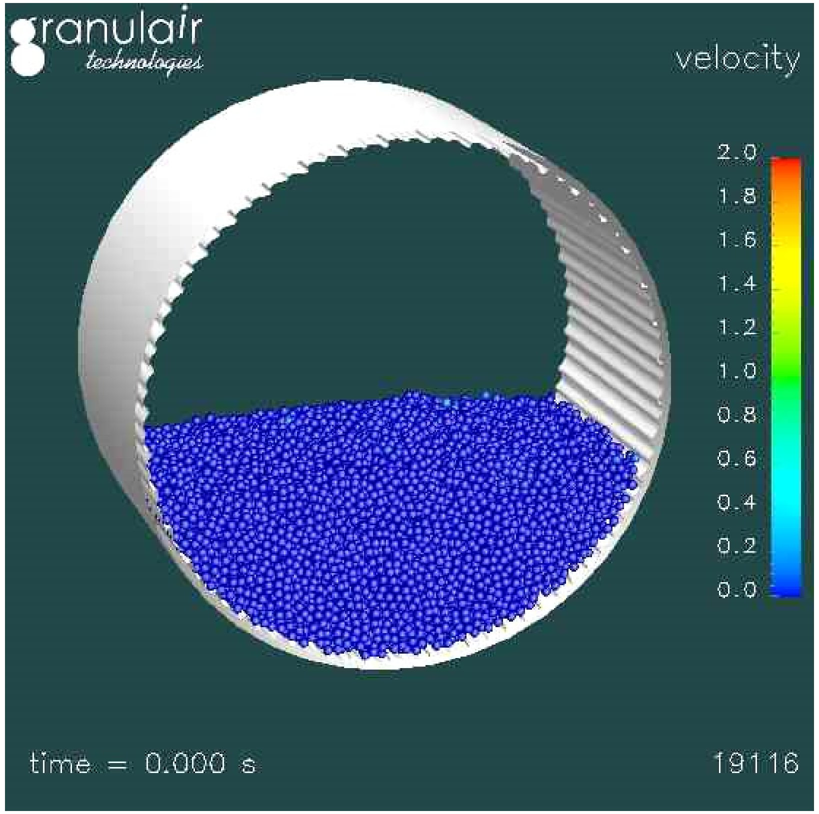


(b) Attrition mill

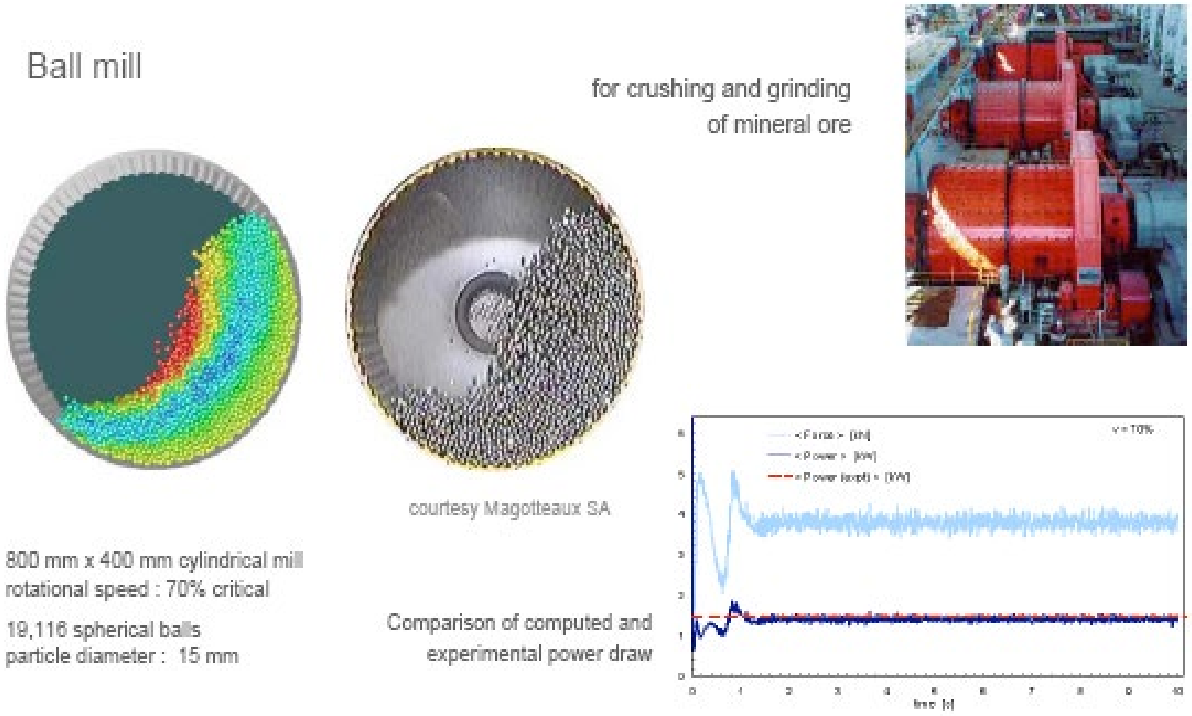


Modelling (DEM)

- Discrete Element Modelling (DEM)
- Can follow the behavior of each particle during grinding - progress - 0.5 - 2 million particles….and can evaluate the energy consumed in industrial mills – by simulation rather than trial and error – and look at the effect of milling parameters such – loading (beads and powder), rotational speed etc.



Dr. Mark Sawley – EPFL



for crushing and grinding of mineral ore

courtesy Magotteaux SA

800 mm x 400 mm cylindrical mill
rotational speed : 70% critical

19,116 spherical balls
particle diameter : 15 mm

Comparison of computed and experimental power draw