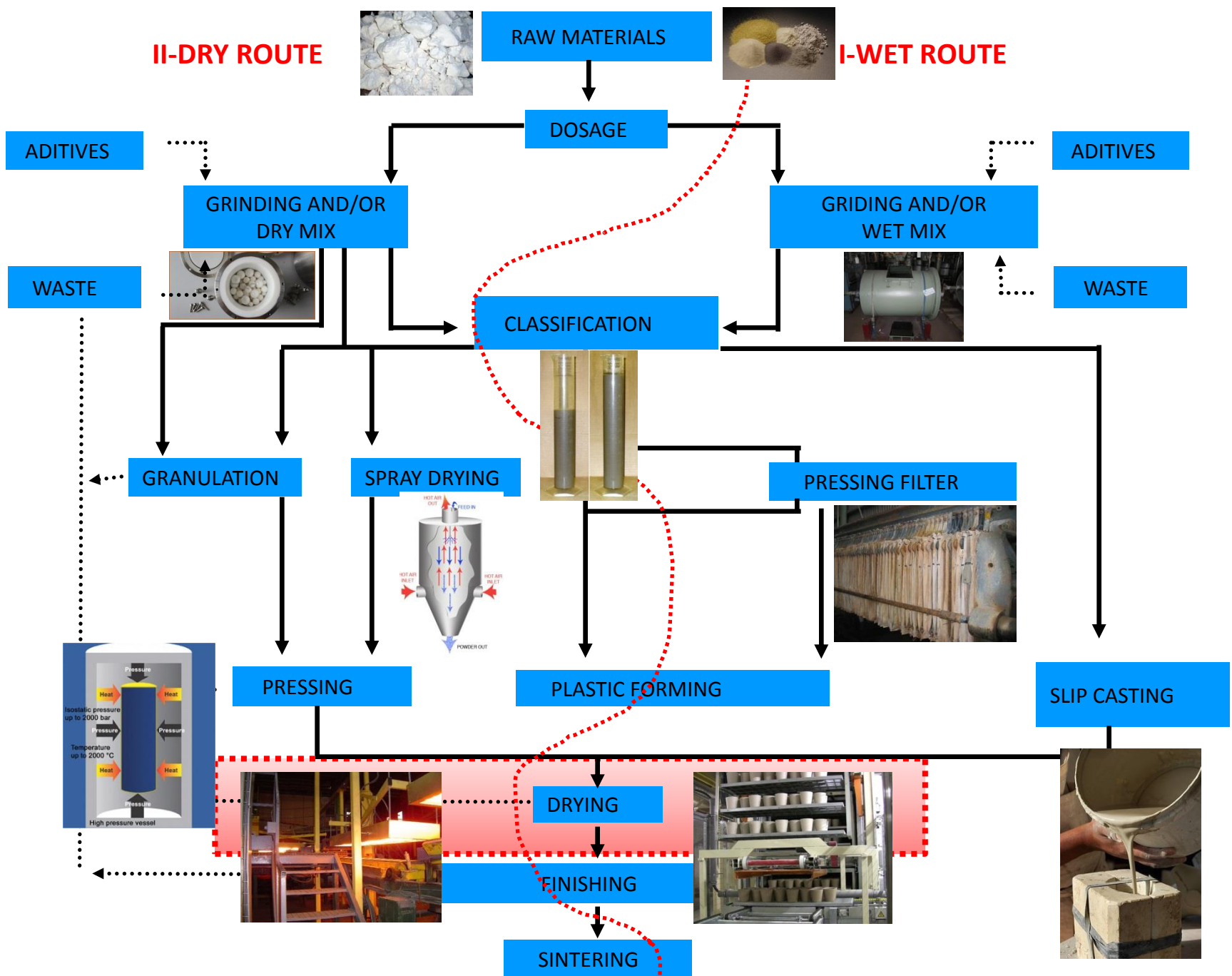
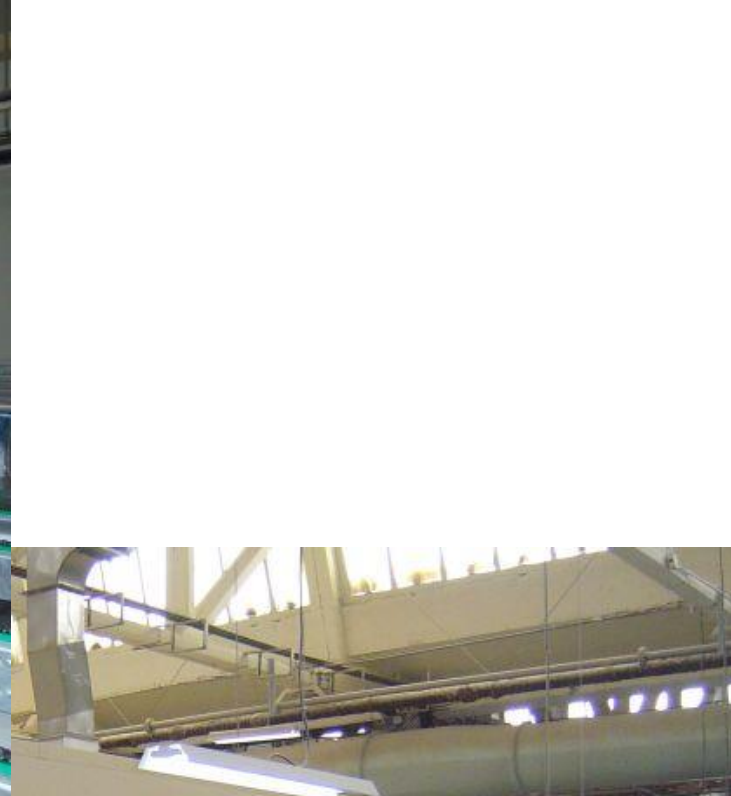


TECNOLOGIA DOS MATERIAIS CERÂMICOS

VI – DRYING



Drying



<http://www.lippert.de>

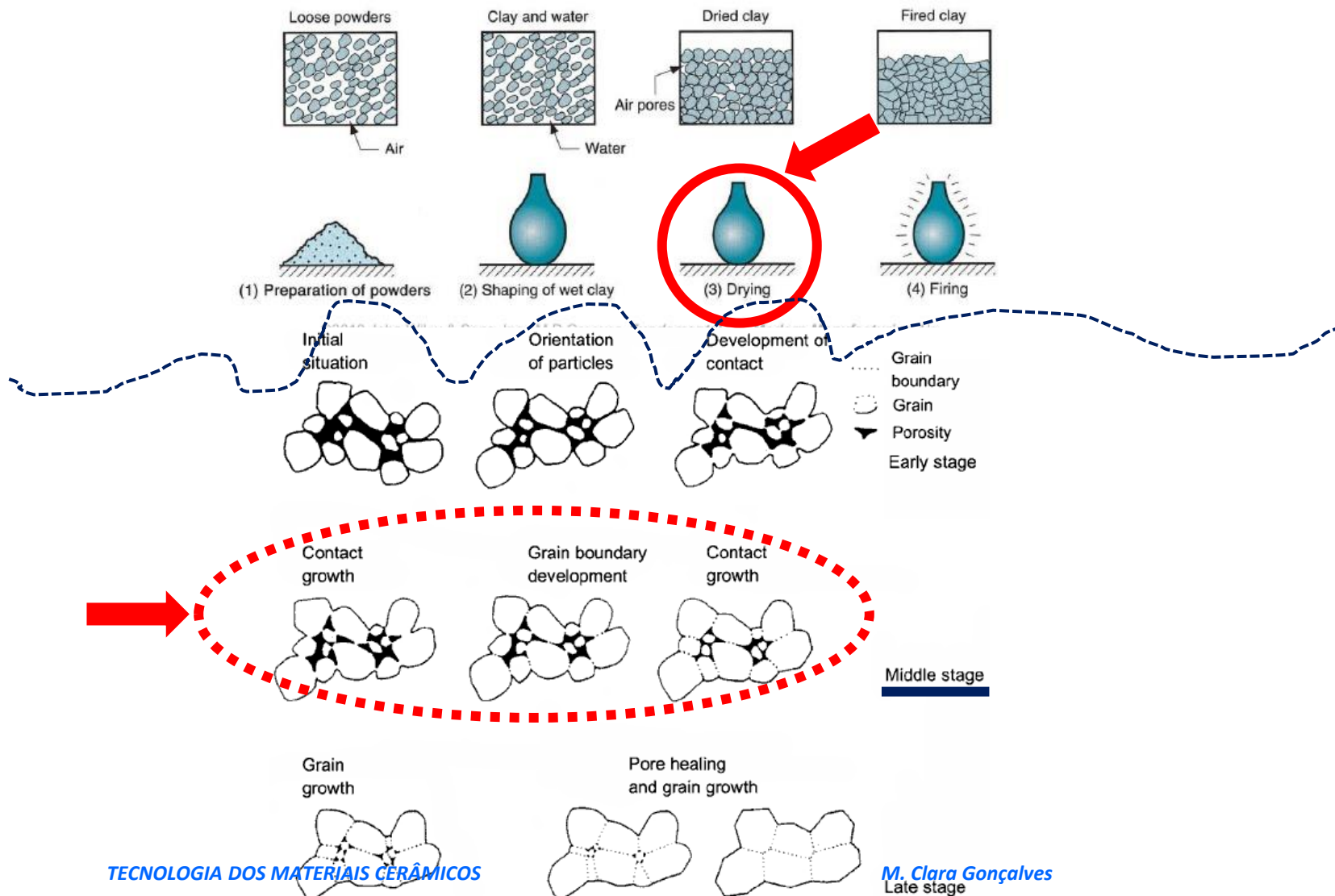
Drying





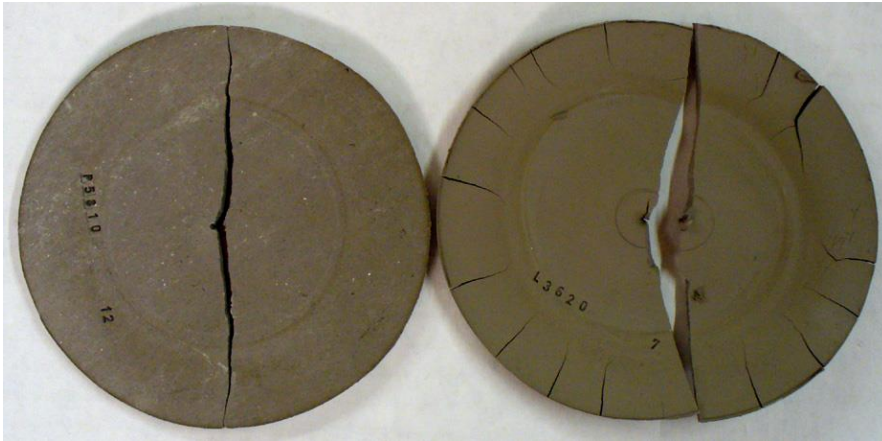
Processing Overview for Traditional Ceramics

- Condition of powders and part during (1) preparation of raw materials, (2) shaping, (3) drying, and (4) firing

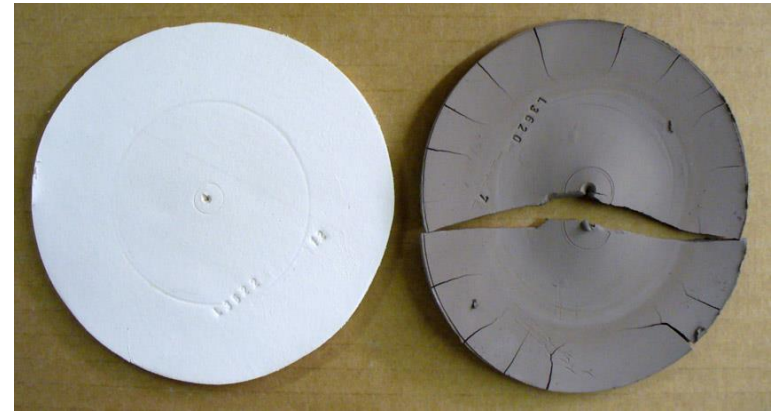


Drying: what could go wrong?

Cracks !



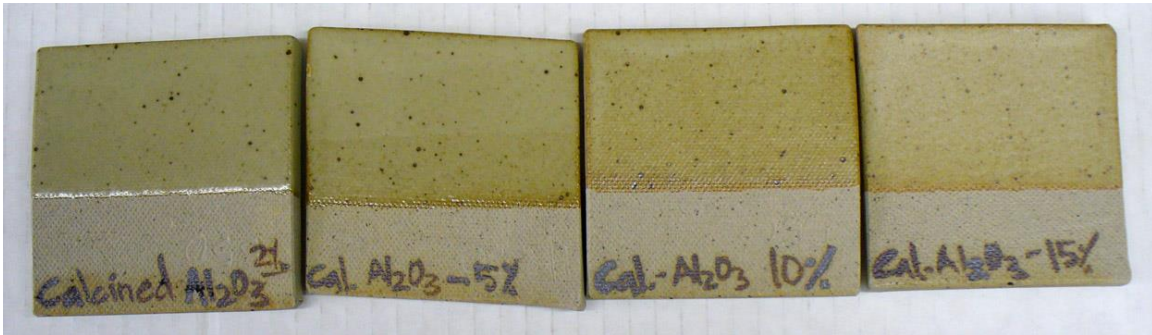
http://digitalfire.com/4sight/glossary/glossary_firing_shrinkage.html



http://earthwork7.blogspot.pt/2011_09_01_archive.html

Drying: what could go wrong?

Linear/volumic deformation !



Examples of materials mixed with 25% vol clay bentonite and fired to cone 9



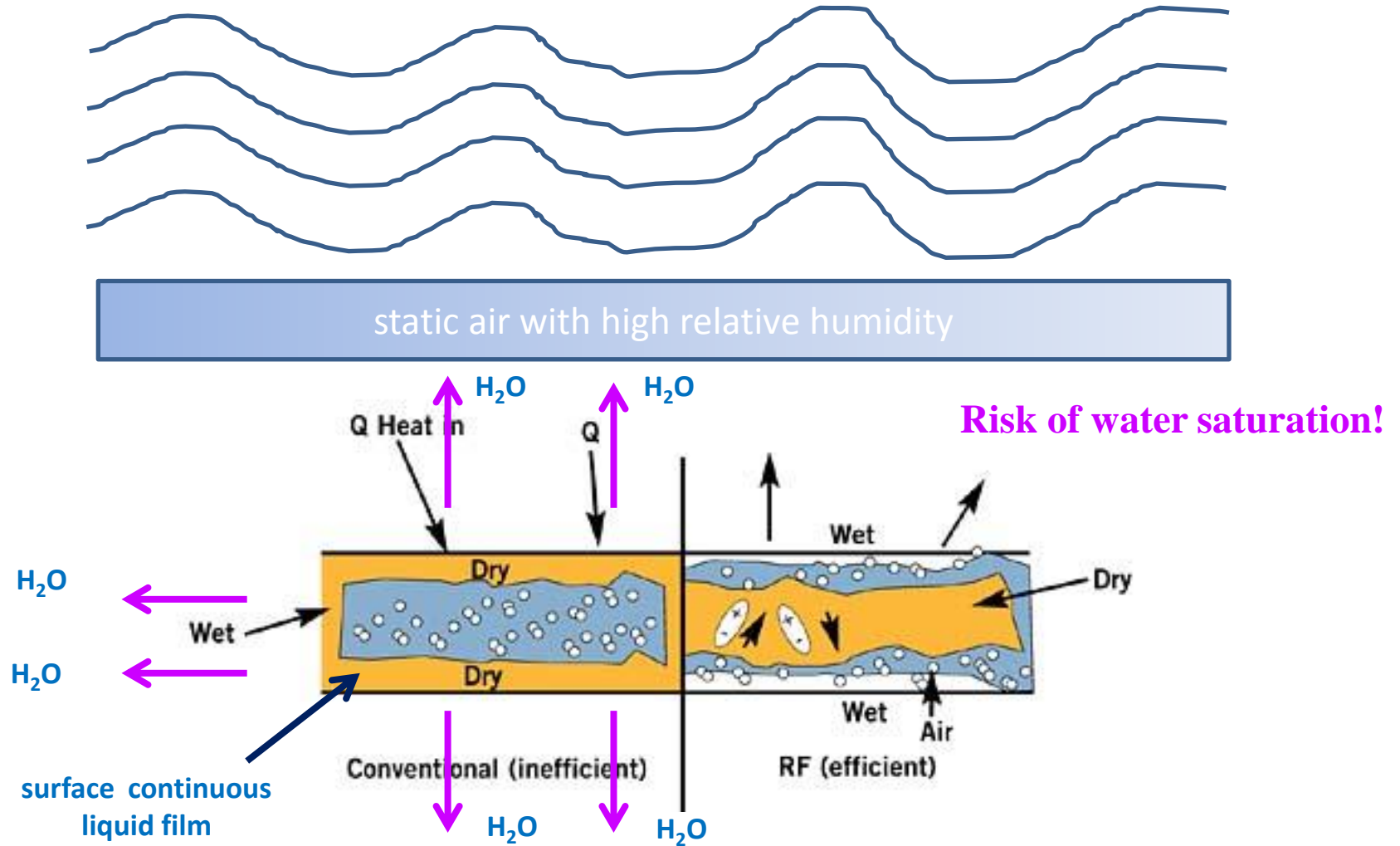
Drying: what could go wrong?

Warping !



Drying: inside the drying chamber

air in movement →



<http://www.ceramicindustry.com/articles/82979-lean-drying>

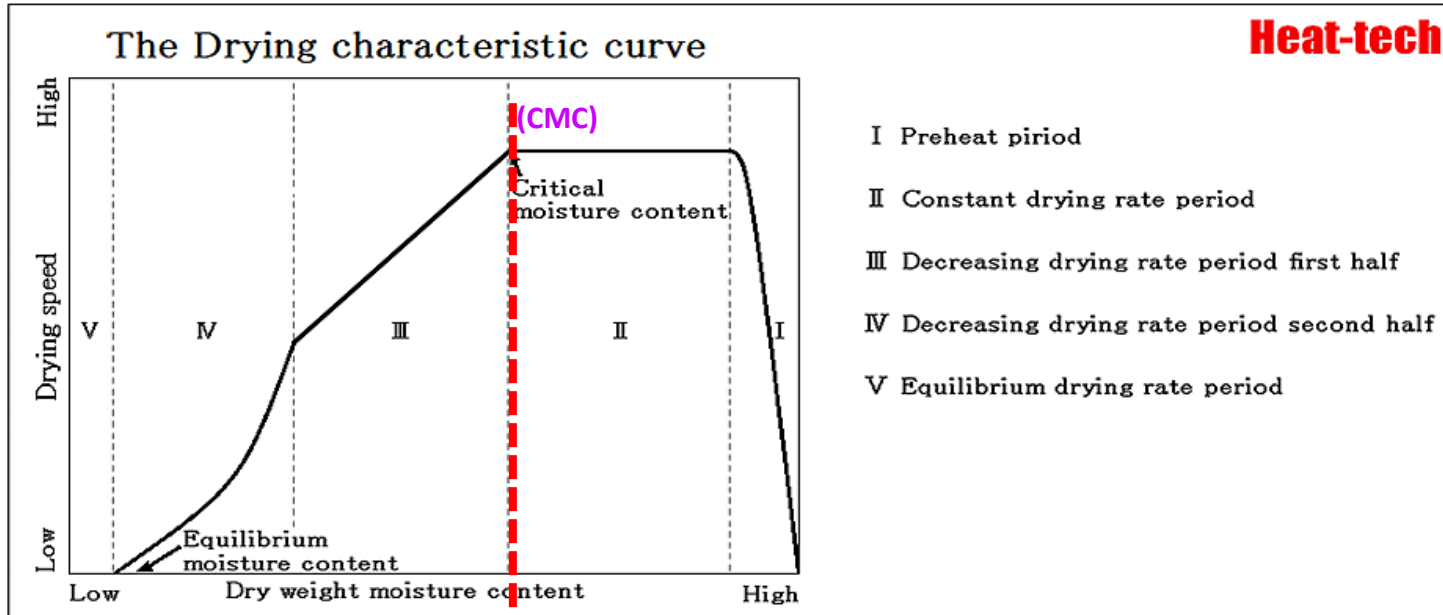
Drying

$$T < T_{\text{boiling}}$$

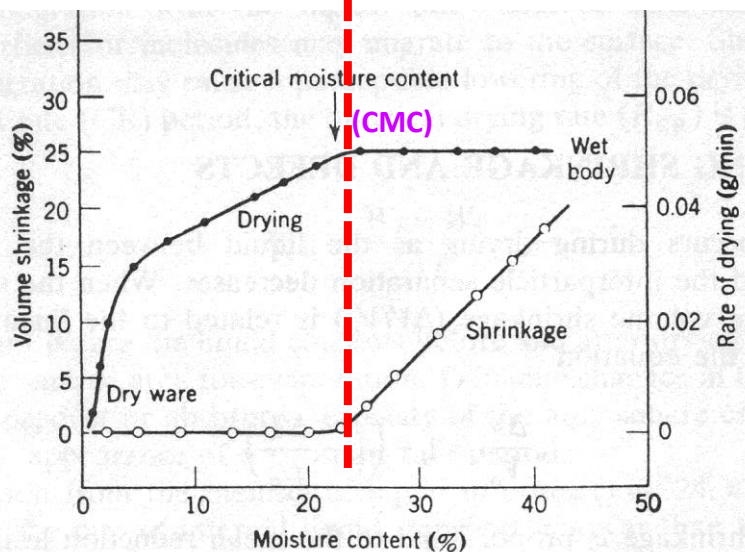
Liquid evaporation rate = $f(T, \text{liquid surface area})$
= $f(\text{liquid concentration in air})$

$$T > T_{\text{boiling}}$$

Liquid evaporation rate = $f(\text{velocity of } Q \text{ transfer into the system})$
 $\neq f(\text{liquid concentration in air})$



- I Preheat period
- II Constant drying rate period
- III Decreasing drying rate period first half
- IV Decreasing drying rate period second half
- V Equilibrium drying rate period



Critical moisture content (CMC) corresponds to the termination of shrinkage. Until CMC a superficial liquid film is distributed uniformly throughout the volume.

What really happens at this point?

At CMC the superficial liquid film is interrupted! Liquid evaporation is no more controlled by T (and liquid film surface area) but by liquid diffusion from interior towards exterior of ceramic piece.

Fig. 24.4 Change in bulk volume on drying a ceramic body. (From W. D. Kingery, *Introduction to Ceramics*, Wiley-Interscience, 1960).

Drying

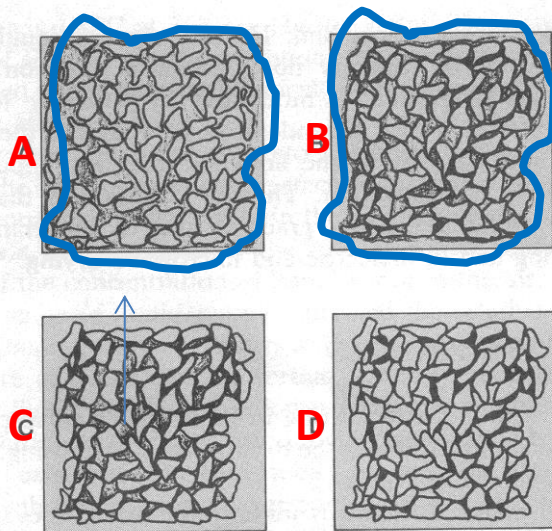


Fig. 24.3 Apparent volume and distribution of liquid among particles during slow drying: (A) as cast with interparticle contacts, (B) just preceding the end of the constant rate period, (C) on entering the falling rate, and (D) near the end of the falling rate period (liquid in capillaries with a sharp meniscus and liquid physically adsorbed on surfaces remains).

surface continuous liquid film

FIG. 4 STEPS IN DRYING A CLAY MASS

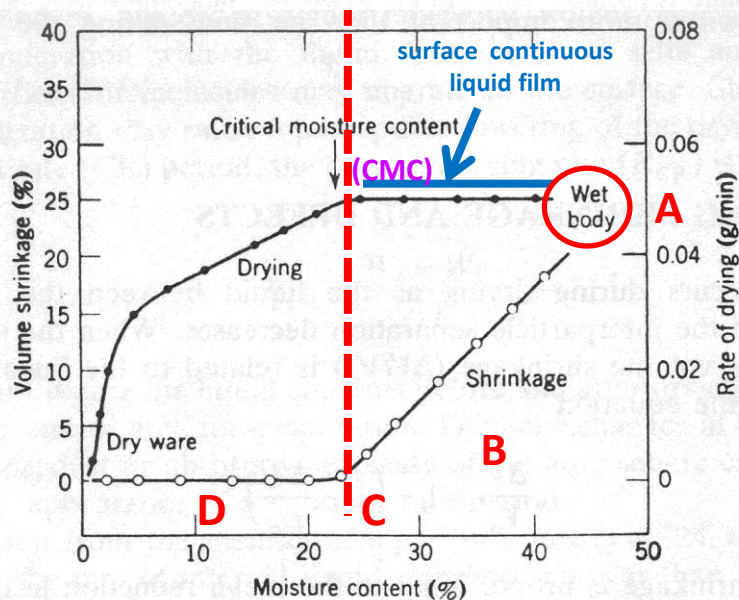
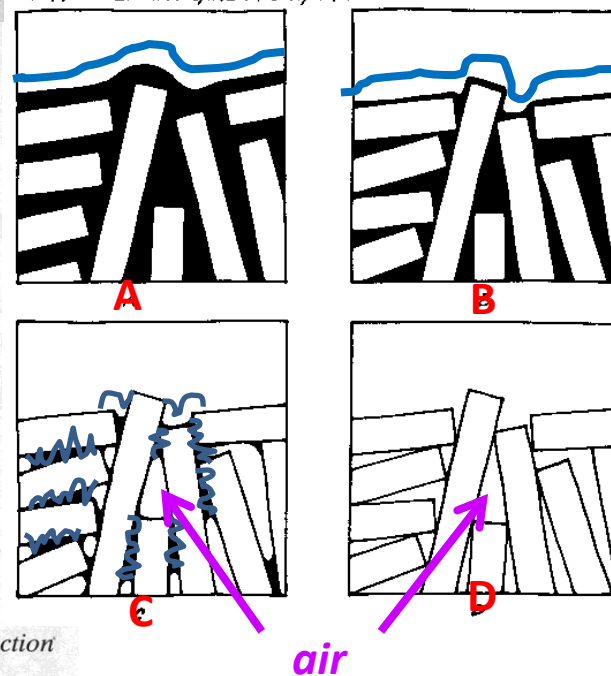


Fig. 24.4 Change in bulk volume on drying a ceramic body. (From W. D. Kingery, *Introduction to Ceramics*, Wiley-Interscience, 1960).

Drying

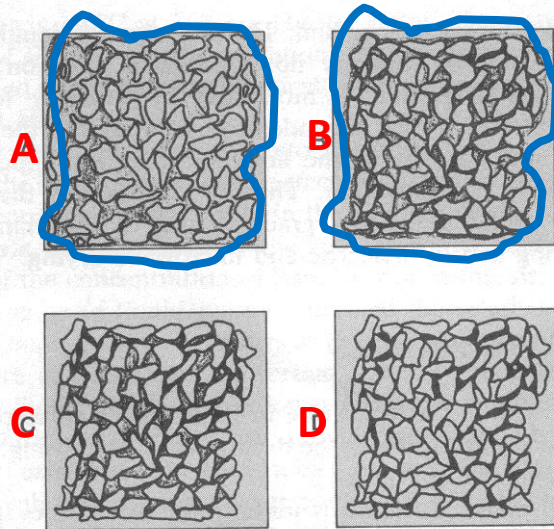


Fig. 24.3 Apparent volume and distribution of liquid among particles during slow drying: as cast with interparticle contacts, (B) just preceding the end of the constant rate period, on entering the falling rate, and (D) near the end of the falling rate period (liquid in capilla with a sharp meniscus and liquid physically adsorbed on surfaces remains).

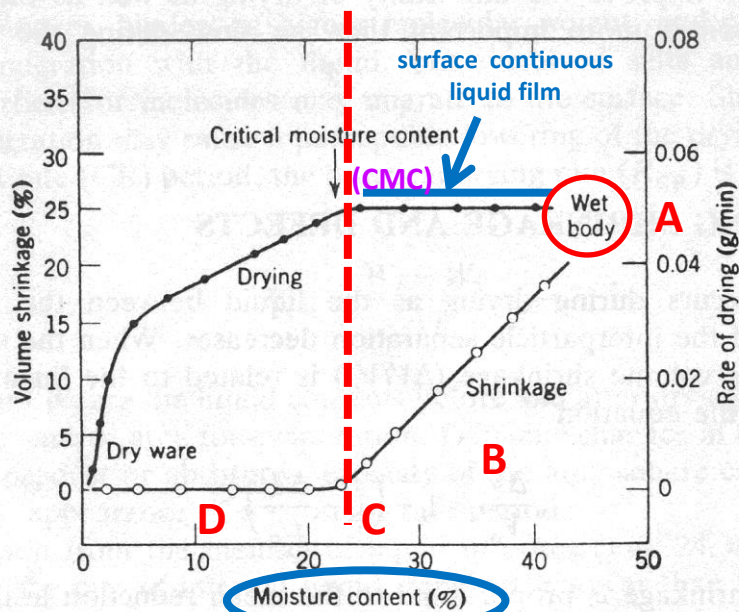
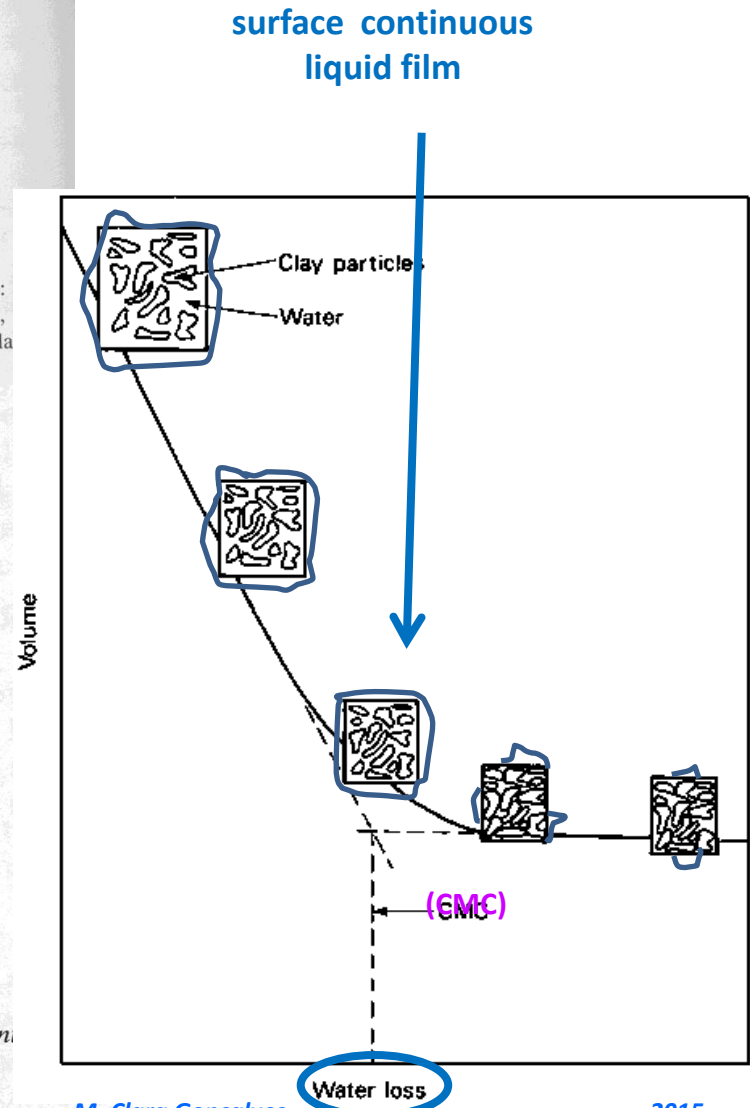


Fig. 24.4 Change in bulk volume on drying a ceramic body. (From W. D. Kingery, *Intro to Ceramics*, Wiley-Interscience, 1960).



Drying

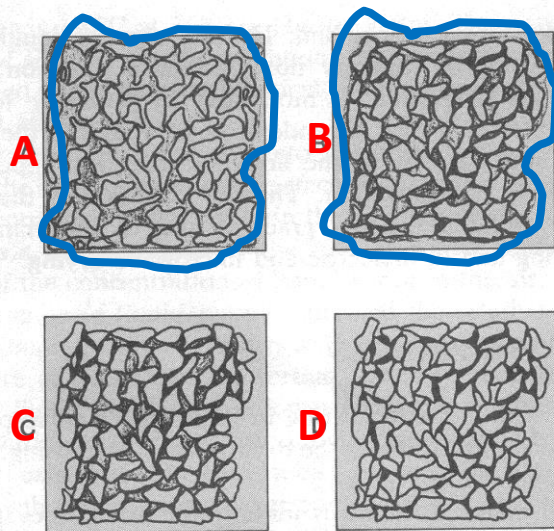


Fig. 24.3 Apparent volume and distribution of liquid among particles during slow drying: as cast with interparticle contacts, (B) just preceding the end of the constant rate period, on entering the falling rate, and (D) near the end of the falling rate period (liquid in capilla with a sharp meniscus and liquid physically adsorbed on surfaces remains).

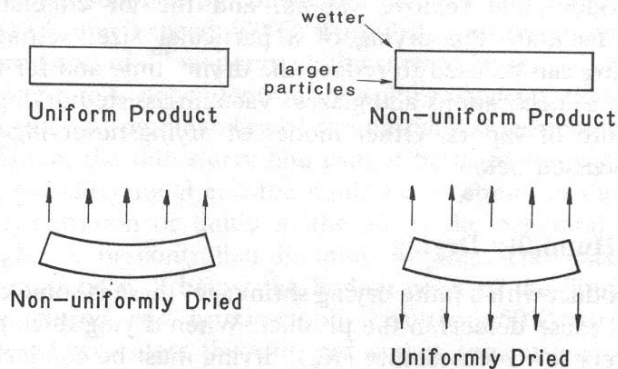
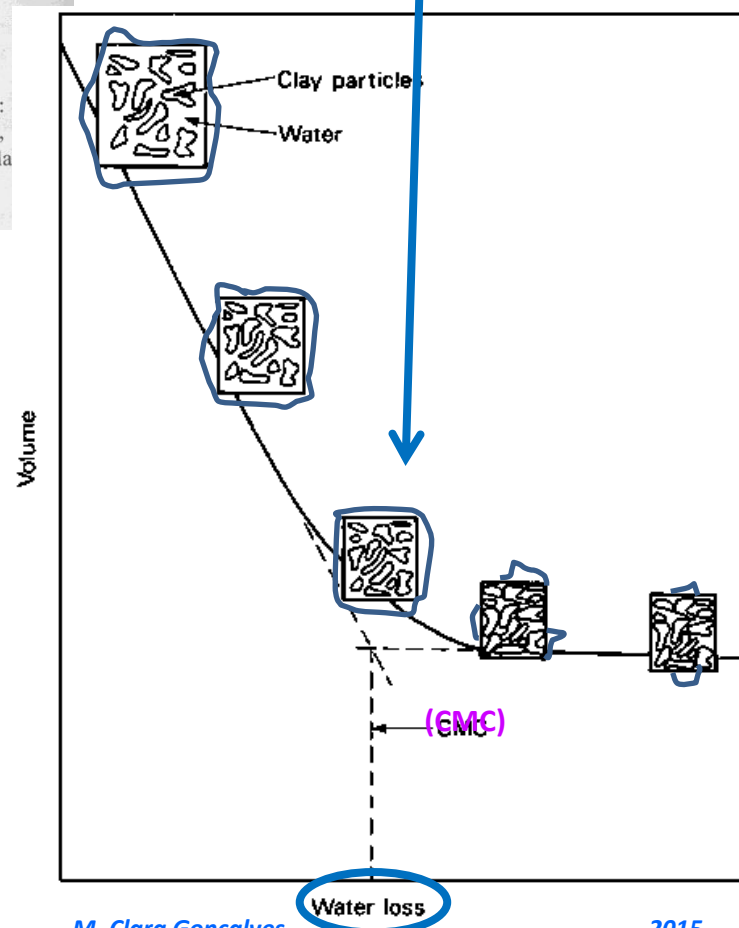


Fig. 24.6 Distortion produced by nonuniform drying shrinkage.



Drying: inside the drying chamber

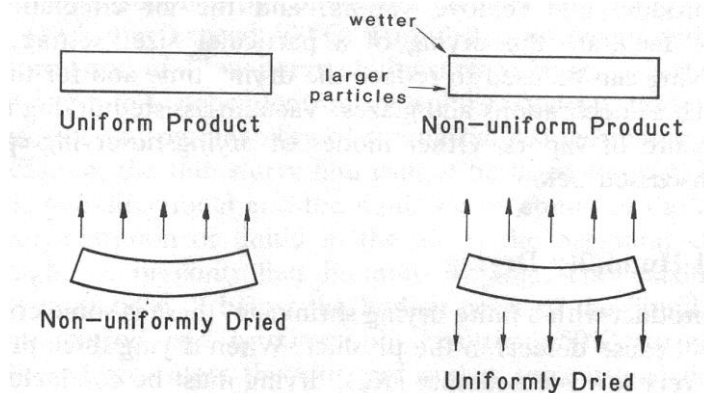
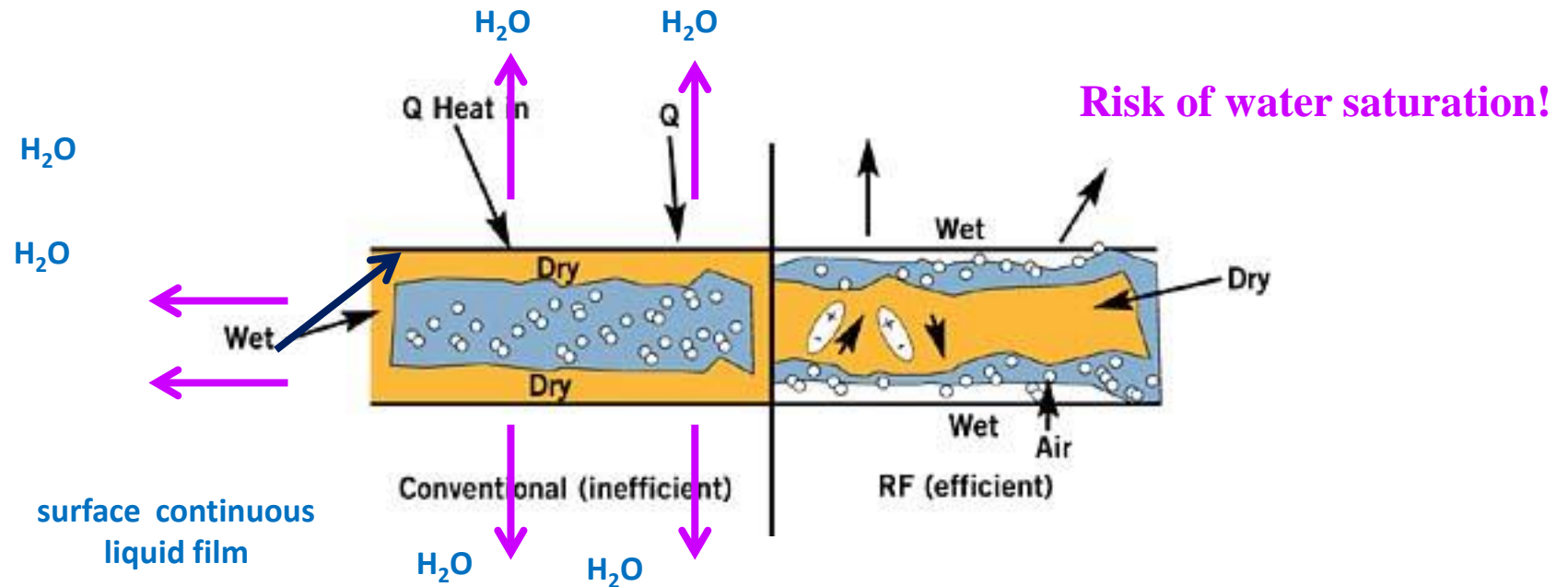


Fig. 24.6 Distortion produced by nonuniform drying shrinkage.



static air with high relative humidity



<http://www.ceramicindustry.com/articles/82979-lean-drying>

Drying

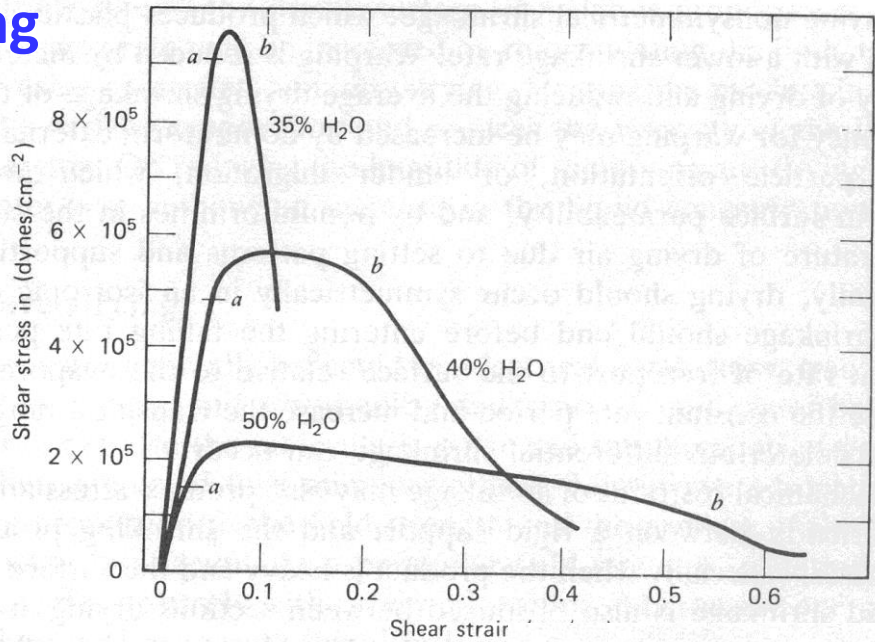


Fig. 24.5 Stress-strain diagram for an uncompressed (liquid concentration in wt.%). (After F. H. Norton Press, Cambridge, MA, 1952.)

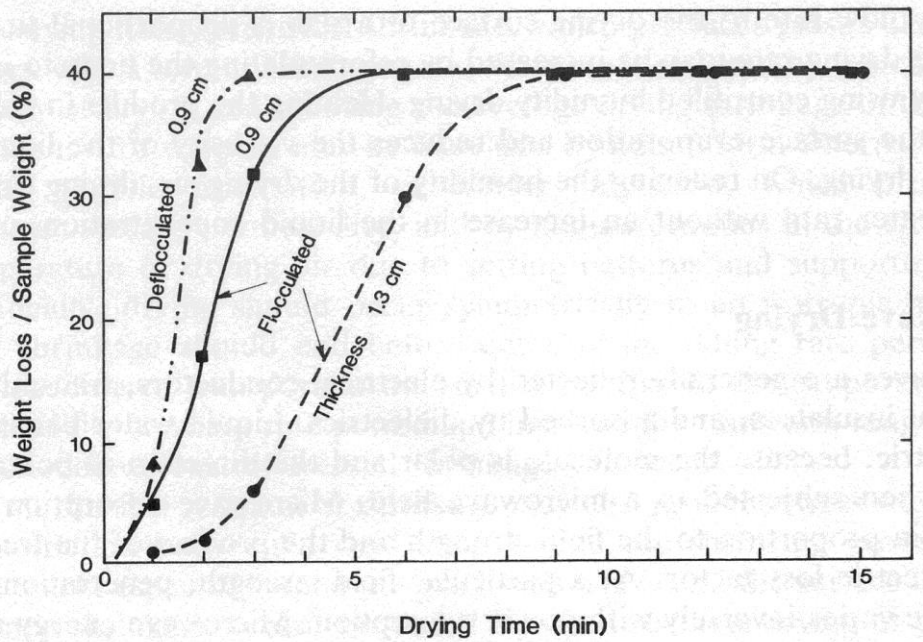


Fig. 24.7 Drying behavior on rapidly heating to 500°C for a slurry that develops a low-permeability skin.

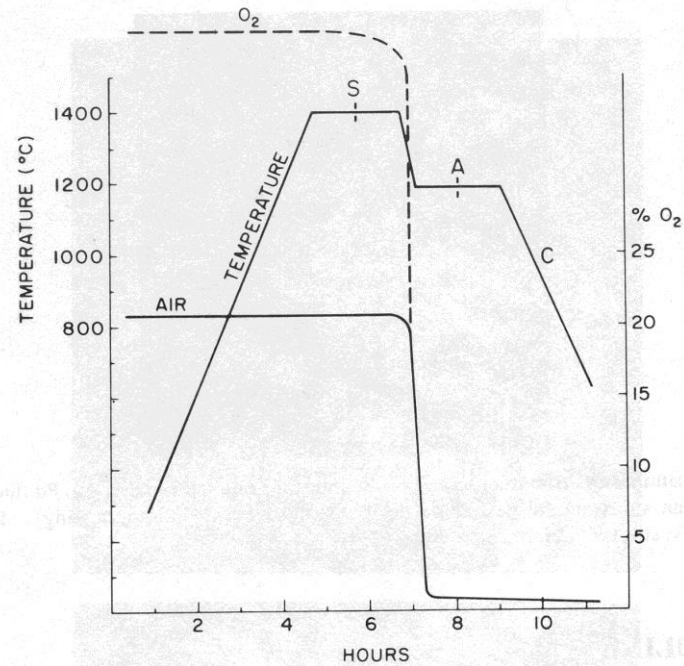
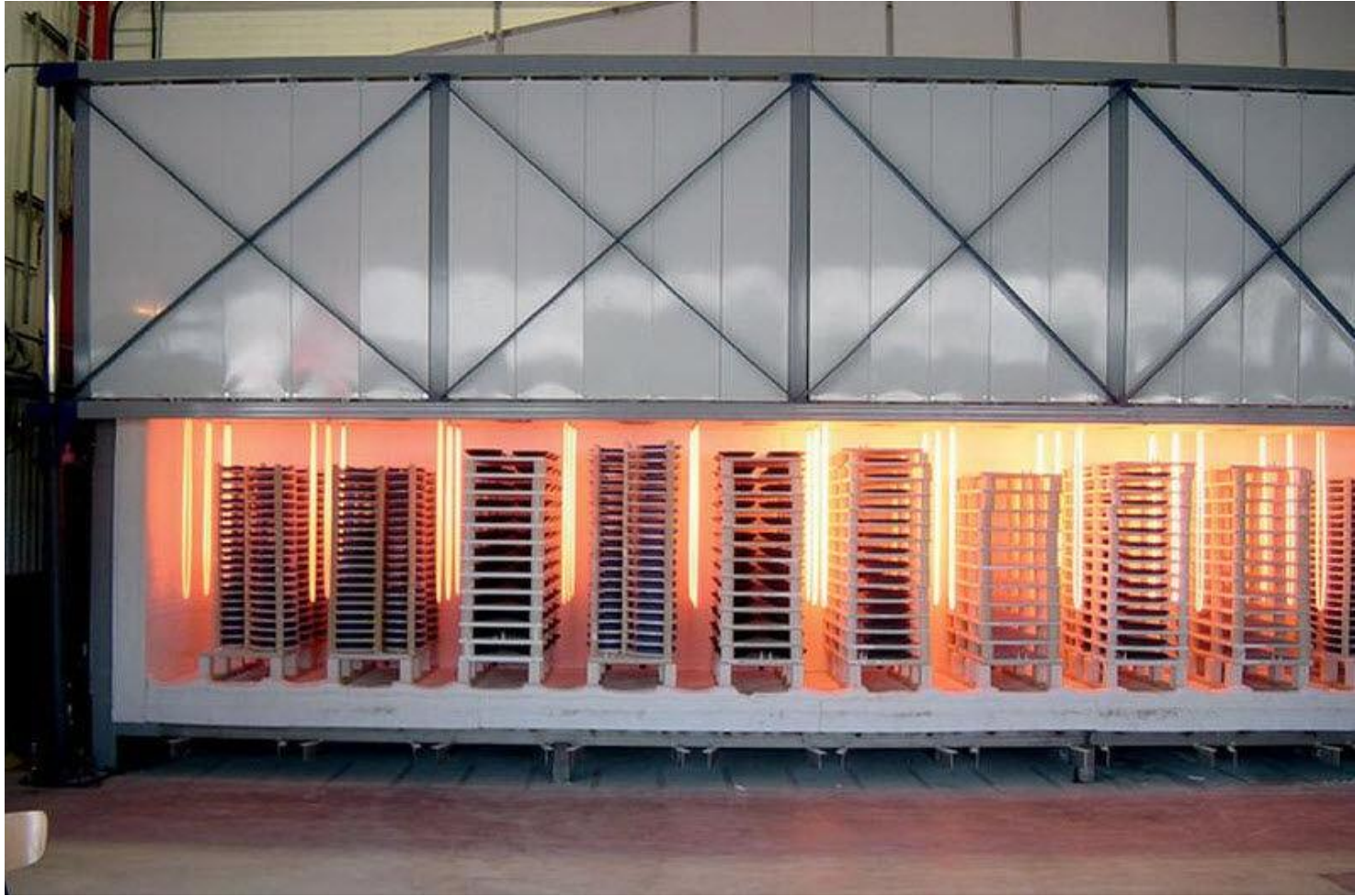


Fig. 26.21 Schematic of firing cycle for manganese zinc ferrites showing controlled atmospheres during sintering, annealing, and cooling cycles. (Courtesy T. Reynolds, p. 211 in *Treatise on Materials Science and Technology Vol. 9: Ceramic Fabrication Processes*, F. F. Y. Wang (ed), Academic Press, New York, 1976.)

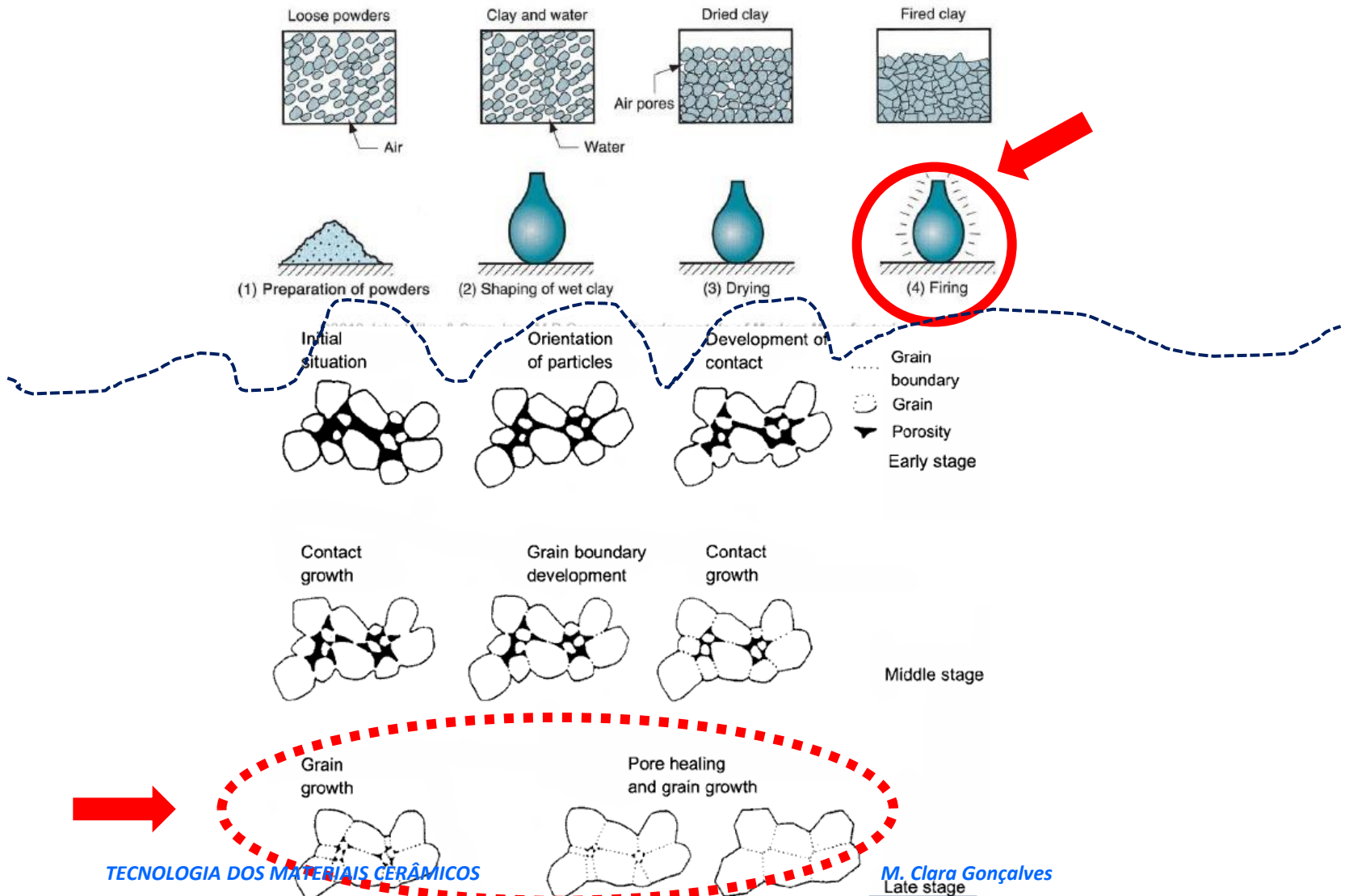






Processing Overview for Traditional Ceramics

- Condition of powders and part during (1) preparation of raw materials, (2) shaping, (3) drying, and (4) firing





Types of Sintering

1. **Solid state sintering**

Only solid phases are present at the sinter temperature

2. **Liquid phase sintering**

Small amounts of liquid phase are present during sintering

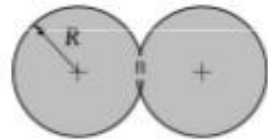
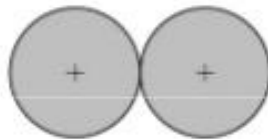
3. **Reactive sintering**

Particles react with each other to new product phases

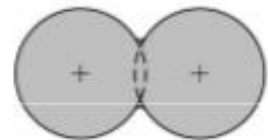
Sintering

Schematic illustration of two mechanisms for sintering metal powders: (a) solid-state material transport; (b) liquid-phase material transport. R = particle radius, r = neck radius, and ρ = neck profile radius.

(a)

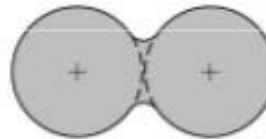


Neck formation
by diffusion

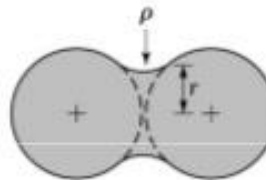


Distance between
particle centers
decreased, particles
bonded

(b)



Neck formation
by vapor phase
material transport

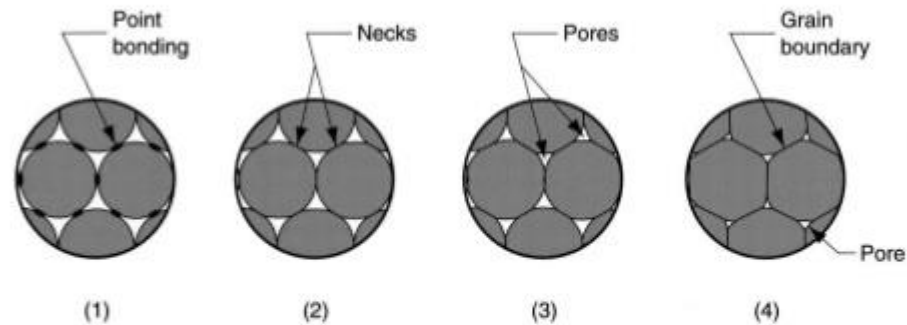


Particles bonded,
no shrinkage (center
distances constant)

Sintering Stages

- Initial Stage
 - Interparticle contact increases by neck growth
 - Relative density increases from ~60 to ~65%
- Intermediate Stage
 - Continuous pore channels coincident with three grain edges
 - Increase from ~65 to ~90% density

Sintering Sequence



Sintering on a microscopic scale: (1) particle bonding is initiated at contact points; (2) contact points grow into "necks"; (3) the pores between particles are reduced in size; and (4) grain boundaries develop between particles in place of the necked regions.

Sintering

Sintering Mechanisms

3 Particle Model

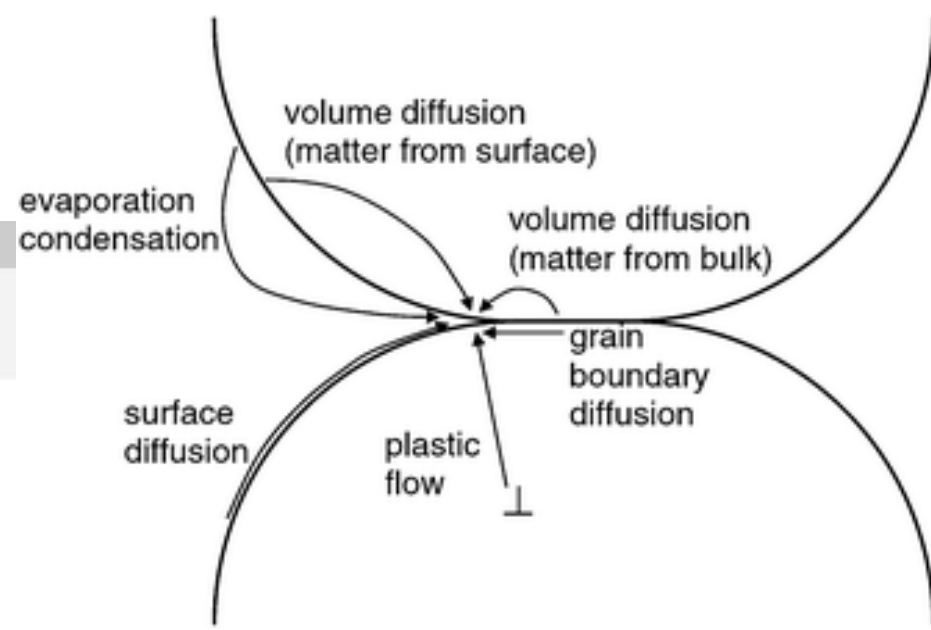
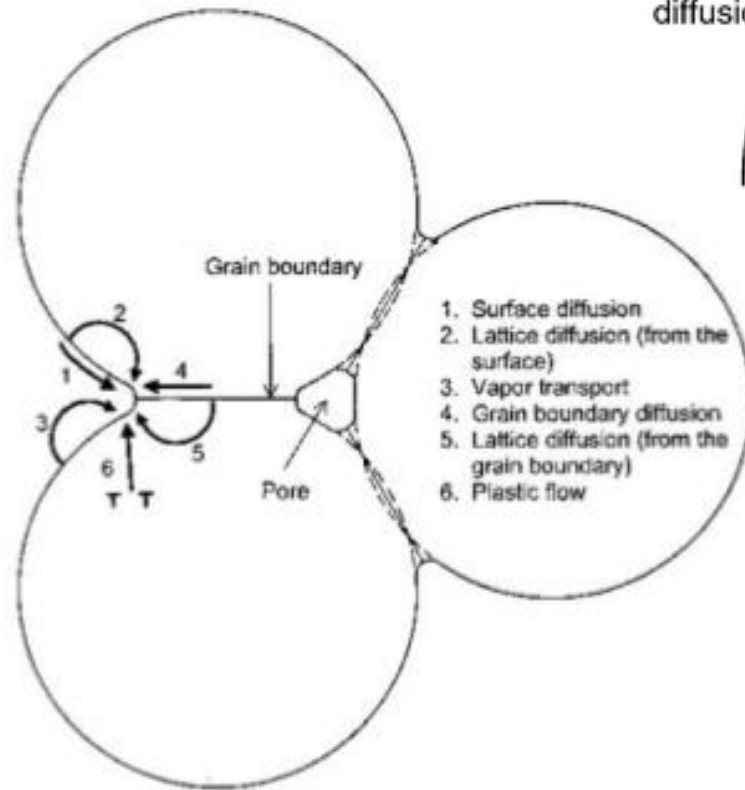


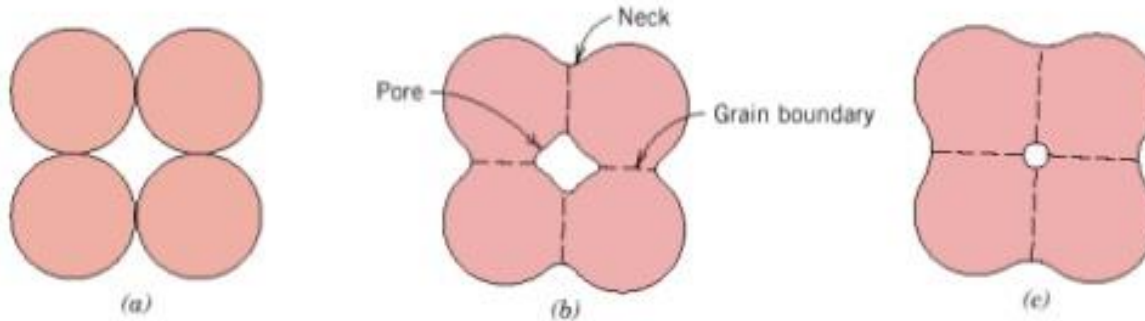
Figure : Fig 2.1, Sintering of Ceramics, Rahaman, pg. 46

Sintering

Sintering

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

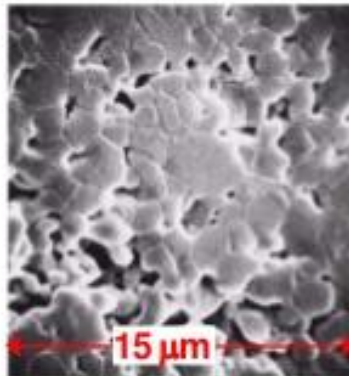
-- powder particles coalesce and reduction of pore size



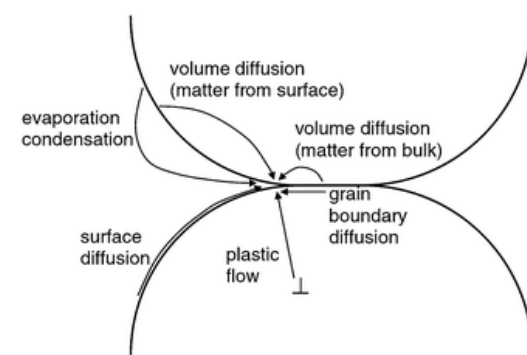
Adapted from Fig. 13.16, Callister & Rethwisch Be.

Aluminum oxide powder:

-- sintered at 1700°C for 6 minutes.



Adapted from Fig. 13.17, Callister & Rethwisch Be. (Fig. 13.17 is from W.D. Kingery, H.K. Bowen, and D.R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley and Sons, Inc., 1976, p. 483.)



Sintering

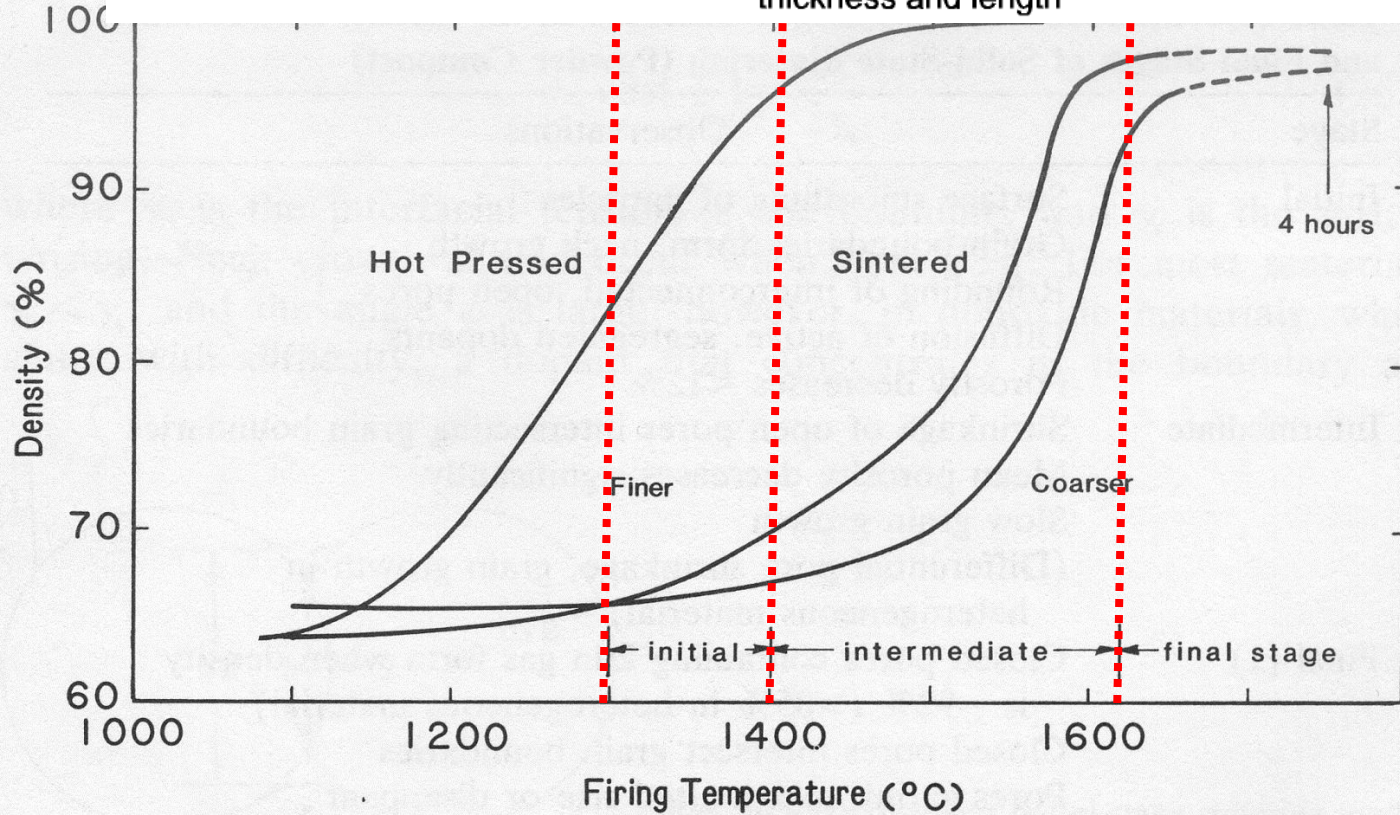
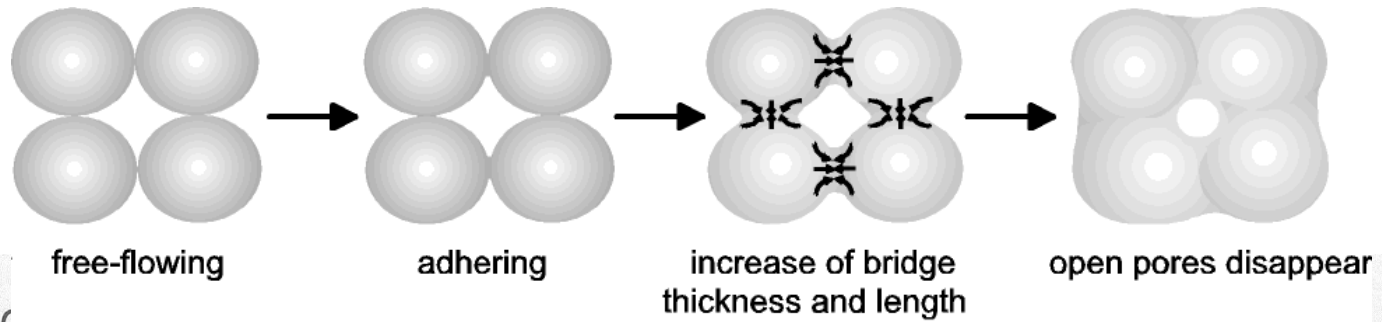


Fig. 26.5 Densification behavior of compacts of two log-normal reactive alumina powders ($\bar{a}_{GM} = 1.3$ and $0.8 \mu\text{m}$) and the initial, intermediate, and final stages of sintering for the coarser powder.

Sintering

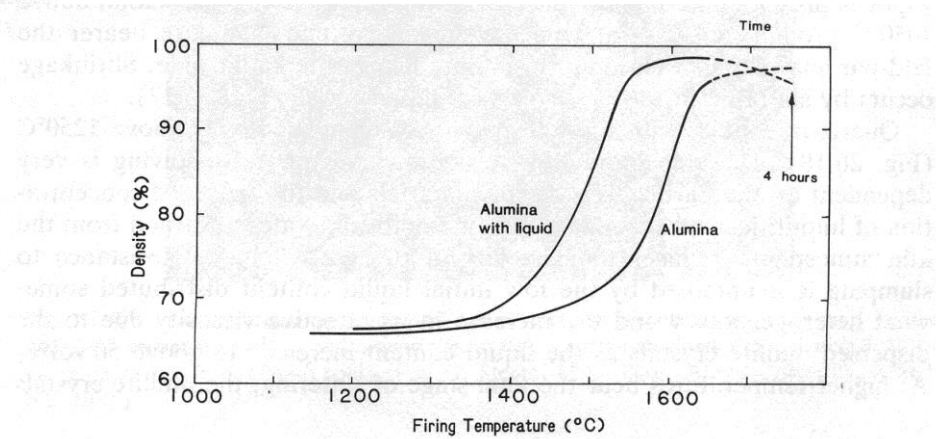
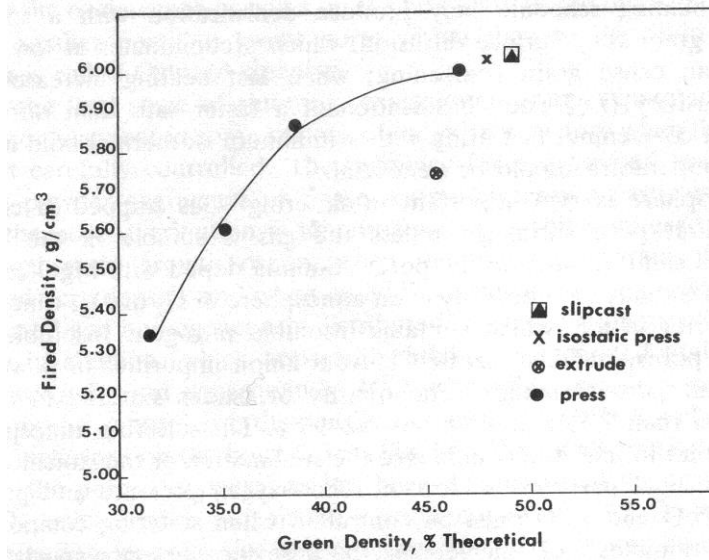
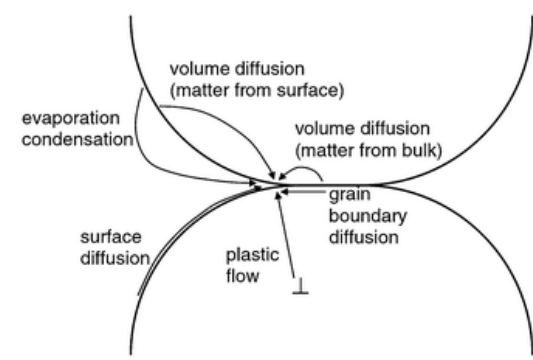


Fig. 26.16 Comparative densification behavior of a nominally 1- μm alumina powder and the alumina powder containing 5 wt% of an alkaline earth aluminosilicate glass phase.

Sintering

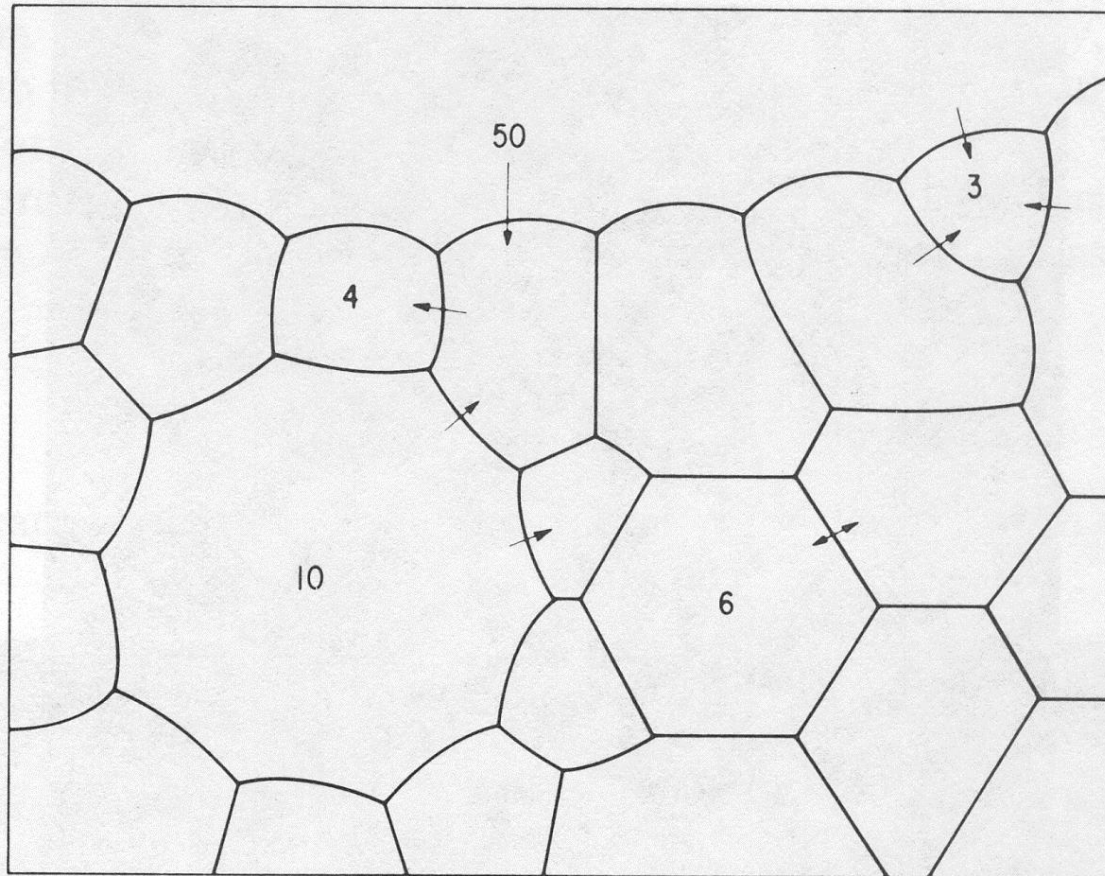
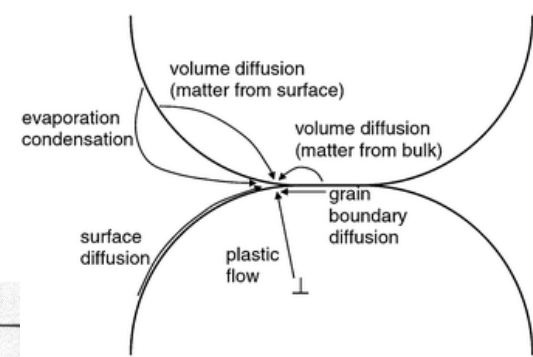


Fig. 26.9 Section through a polycrystalline solid showing grains with a different number of sides; arrows indicate direction of boundary displacement. (Reprinted with permission from J. E. Burke and J. H. Rosolowski, in *Treatise on Solid State Chemistry Vol. 4: Reactivity of Solids*, Plenum, New York, 1976.)

Further reading

- **Ceramic Processing and Sintering.** M. N. Rahaman CRC Press (2003)
- **Sintering of Ceramics – New Emerging Techniques.** Arunachalam Lakshmanan (Ed.) INTECWEB.ORG (2012)