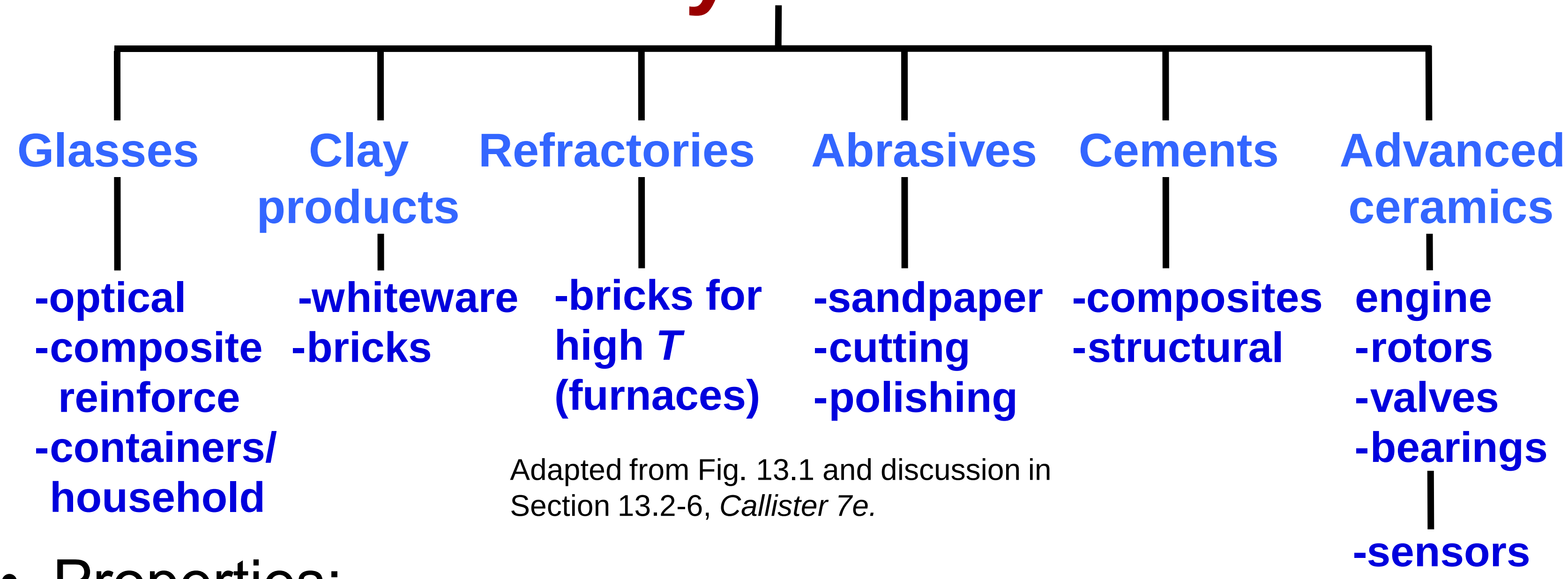
Chapter 13: Applications and Processing of Ceramics

ISSUES TO ADDRESS...

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

Taxonomy of Ceramics



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

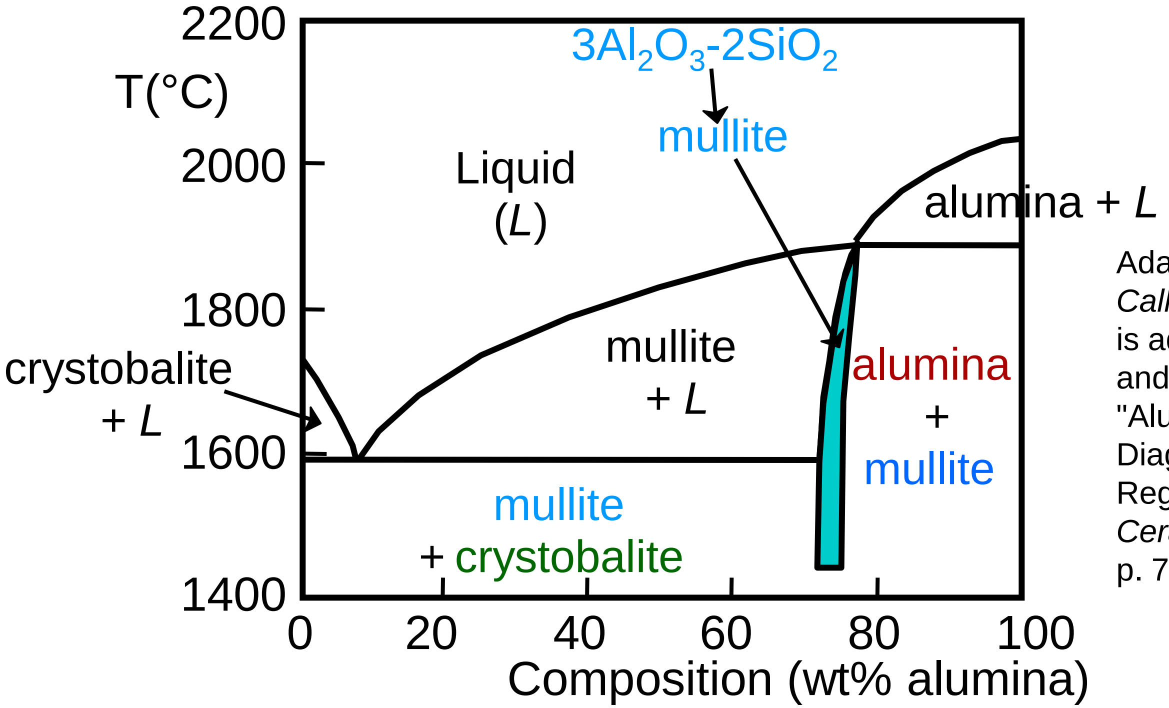
Adapted from Fig. 13.1 and discussion in Section 13.2-6, *Callister 7e.*

- Properties:
  - -- T_m for glass is moderate, but large for other ceramics.
  - -- Small toughness, ductility; large moduli & creep resist.
- Applications:
  - -- High *T*, wear resistant, novel uses from charge neutrality.
- Fabrication
  - -- some glasses can be easily formed
  - -- other ceramics can not be formed or cast.

Application: Refractories

- Need a material to use in high temperature furnaces.
- Consider the Silica (SiO_2) - Alumina (Al_2O_3) system.
- Phase diagram shows:

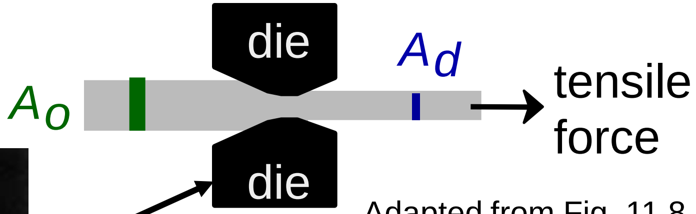
  mullite, alumina, and crystobalite as candidate refractories.



Adapted from Fig. 12.27, *Callister 7e.* (Fig. 12.27 is adapted from F.J. Klug and R.H. Doremus, "Alumina Silica Phase Diagram in the Mullite Region", *J. American Ceramic Society* **70**(10), p. 758, 1987.)

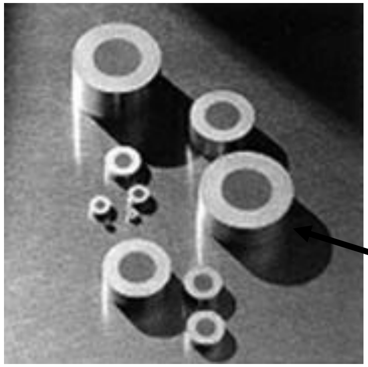
Application: Die Blanks

- Die blanks:
  -- Need wear resistant properties!

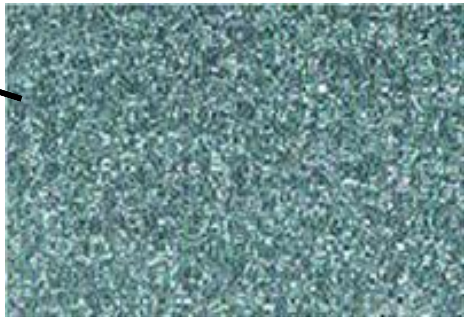


Adapted from Fig. 11.8 (d), *Callister 7e*.

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



- Die surface:
  -- 4 μm polycrystalline diamond particles that are sintered onto a cemented tungsten carbide substrate.
  -- polycrystalline diamond helps control fracture and gives uniform hardness in all directions.

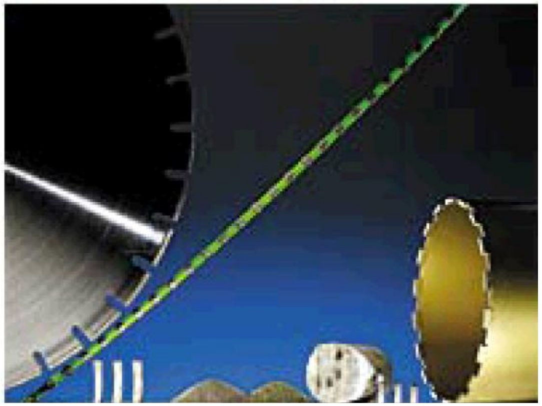


Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.

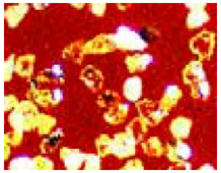
Application: Cutting Tools

- Tools:
  - -- for grinding glass, tungsten, carbide, ceramics
  - -- for cutting Si wafers
  - -- for oil drilling
- Solutions:
  - -- manufactured single crystal or polycrystalline diamonds in a metal or resin matrix.
  - -- optional coatings (e.g., Ti to help diamonds bond to a Co matrix via alloying)
  - -- polycrystalline diamonds resharpen by microfracturing along crystalline planes.


oil drill bits


blades


coated single crystal diamonds


polycrystalline diamonds in a resin matrix.

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

Application: Sensors

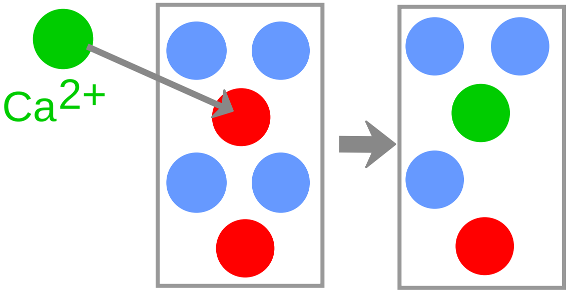
- Example: Oxygen sensor ZrO_2
- Principle: Make diffusion of ions fast for rapid response.
- Approach:

  Add Ca impurity to ZrO_2:

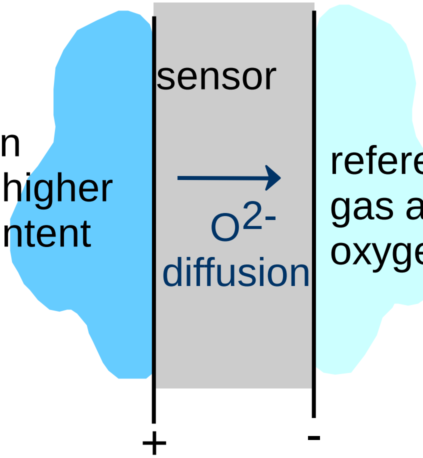
  -- increases O^{2-} vacancies

  -- increases O^{2-} diffusion rate
- Operation:

  -- voltage difference produced when O^{2-} ions diffuse from the external surface of the sensor to the reference gas.



A Ca^{2+} impurity removes a Zr^{4+} and a O^{2-} ion.



sensor

gas with an unknown, higher oxygen content

O^{2-} diffusion

reference gas at fixed oxygen content

\+ -

voltage difference produced!

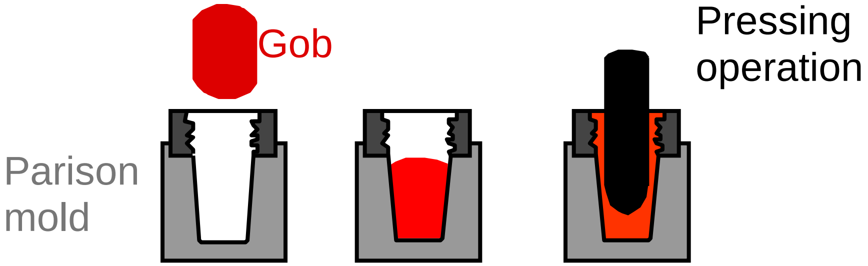
Ceramic Fabrication Methods-I

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

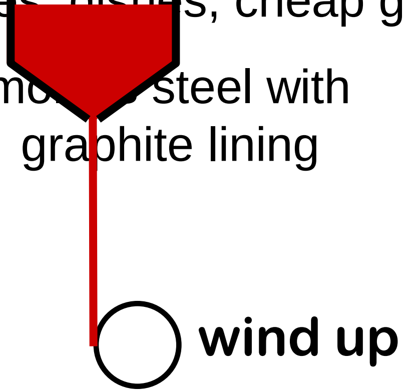
- Pressing:



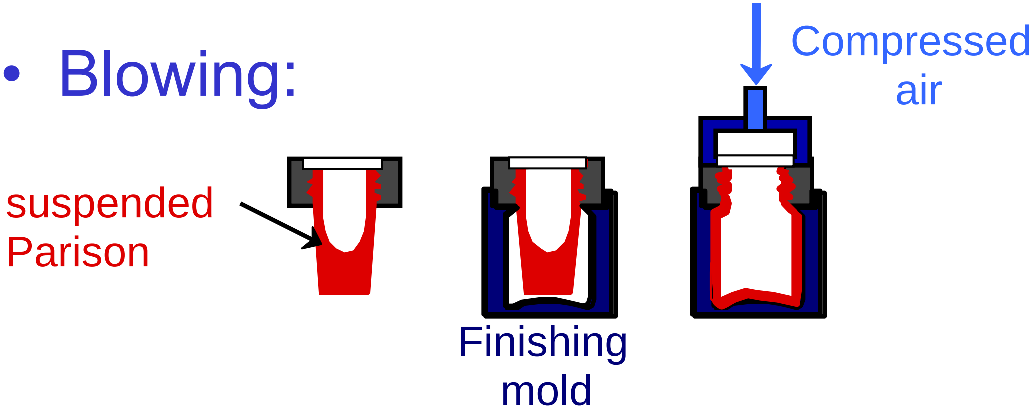
plates, dishes, cheap glasses

--mold is steel with graphite lining

- Fiber drawing:



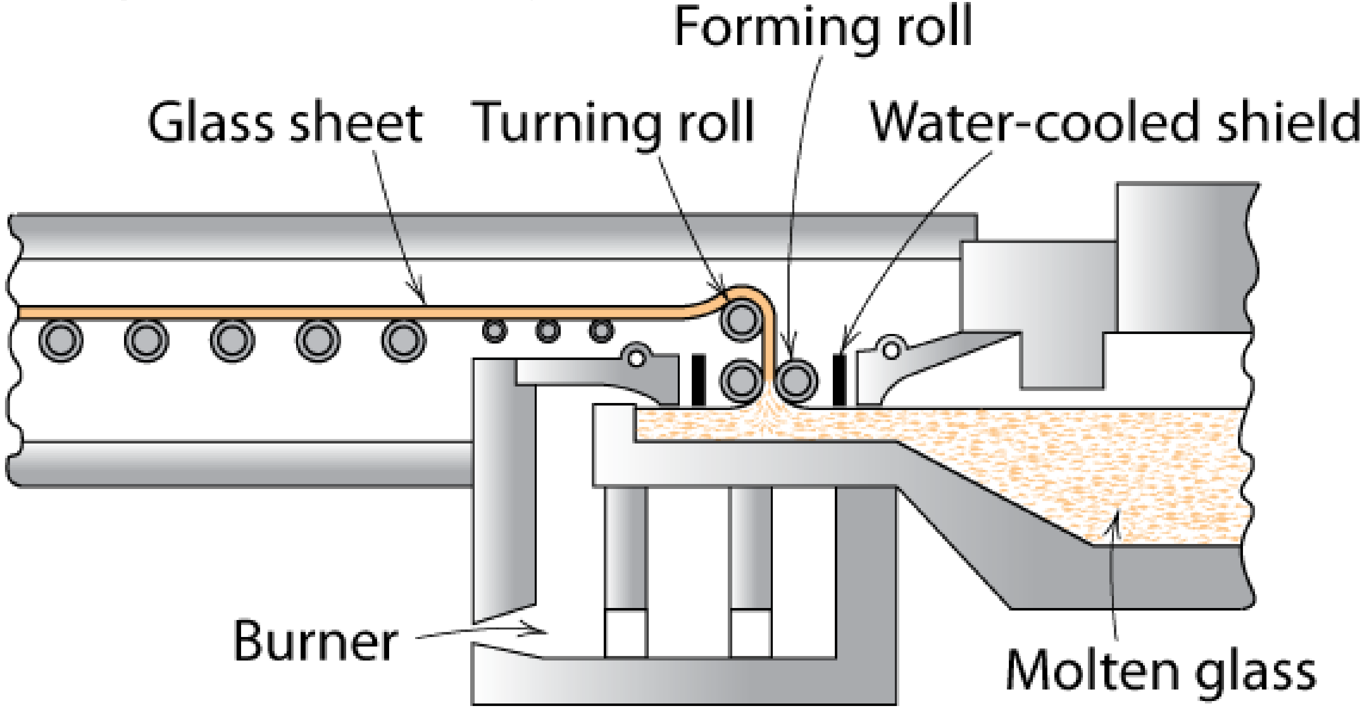
- Blowing:



Adapted from Fig. 13.8, *Callister, 7e*. (Fig. 13.8 is adapted from C.J. Phillips, *Glass: The Miracle Maker*, Pittman Publishing Ltd., London.)

Sheet Glass Forming

- Sheet forming – continuous draw
  - originally sheet glass was made by “floating” glass on a pool of mercury

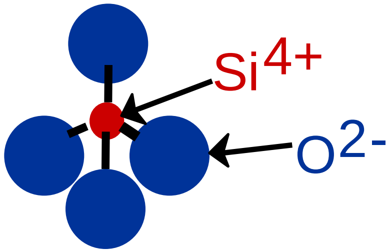


Adapted from Fig. 13.9, *Callister 7e.*

Glass Structure

- Basic Unit:

$Si0_4^{4-}$ tetrahedron



- Glass is amorphous
- Amorphous structure

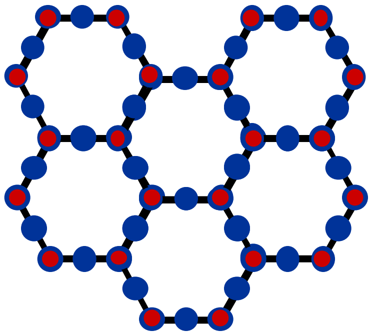
occurs by adding impurities (Na^+,Mg^{2+},Ca^{2+}, Al^{3+})

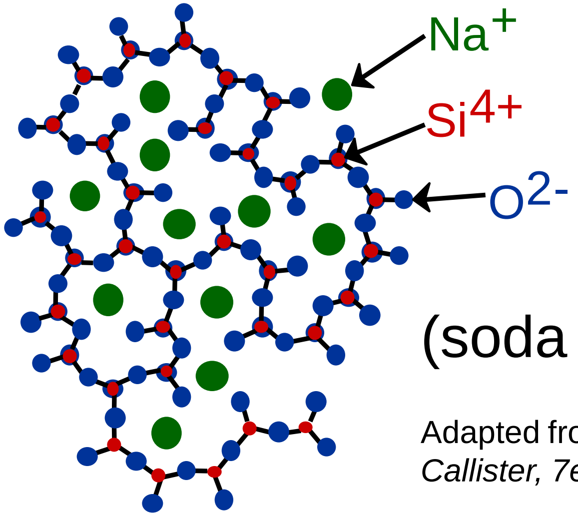
- Impurities:

interfere with formation of crystalline structure.

- Quartz is crystalline

SiO_2:



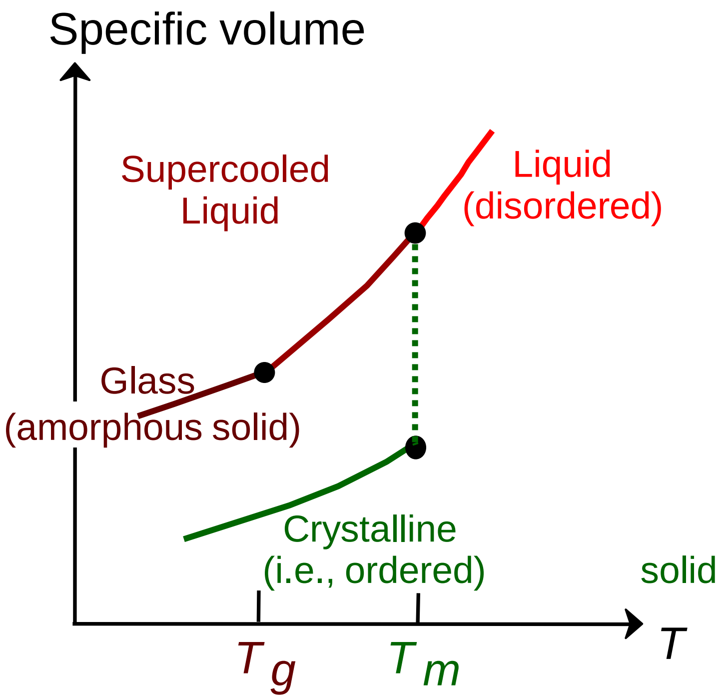


(soda glass)

Adapted from Fig. 12.11, *Callister, 7e*.

Glass Properties

- Specific volume (1/ρ) vs Temperature (*T*):



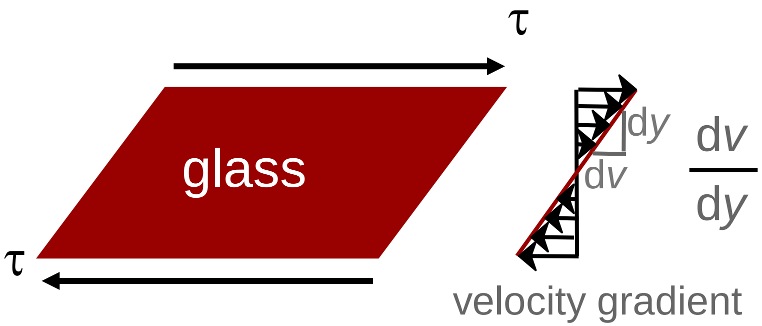
Adapted from Fig. 13.6, *Callister, 7e*.

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

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

Glass Properties: Viscosity

- Viscosity, η:
  -- relates shear stress and velocity gradient:



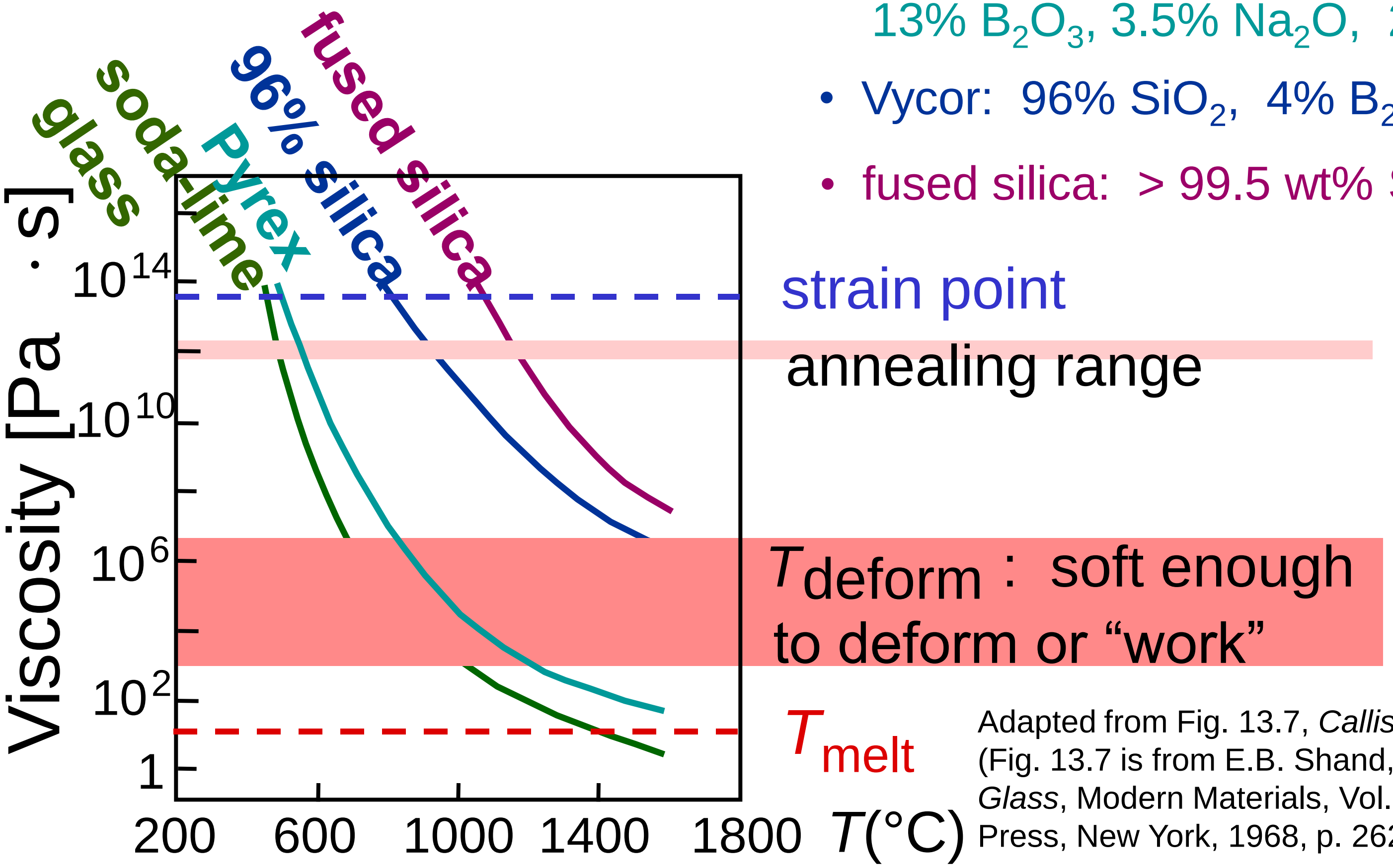
$$\tau = \eta \frac{dv}{dy}$$

η has units of (Pa-s)

Glass Viscosity vs. T and Impurities

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

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



Adapted from Fig. 13.7, *Callister, 7e*. (Fig. 13.7 is from E.B. Shand, *Engineering Glass*, Modern Materials, Vol. 6, Academic Press, New York, 1968, p. 262.)

Heat Treating Glass

- Annealing:

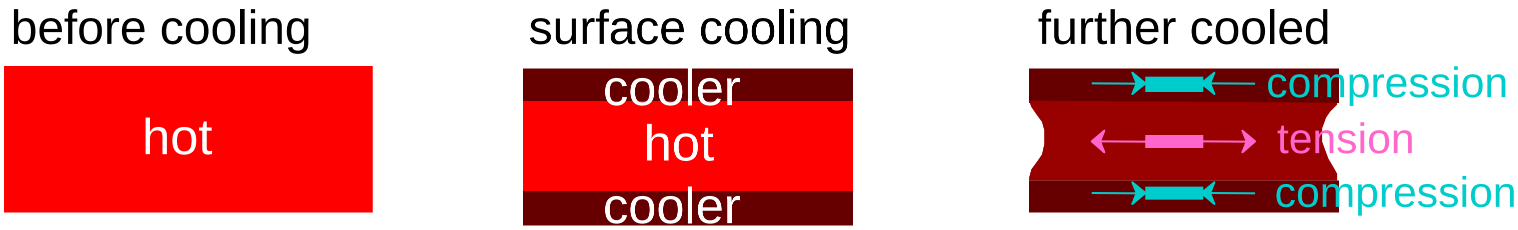
  --removes internal stress caused by uneven cooling.

- Tempering:

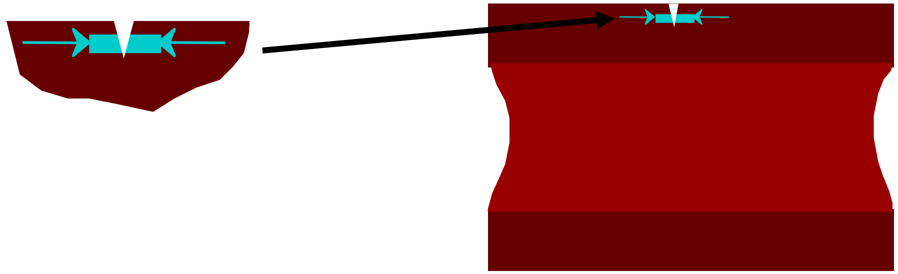
  --puts surface of glass part into compression

  --suppresses growth of cracks from surface scratches.

  --sequence:



--Result: surface crack growth is suppressed.



Ceramic Fabrication Methods-IIA

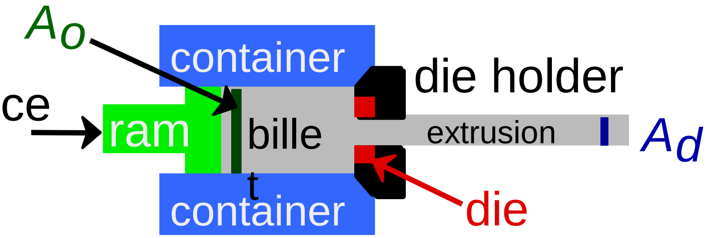
GLASS FORMING

PARTICULATE FORMING

CEMENTATION

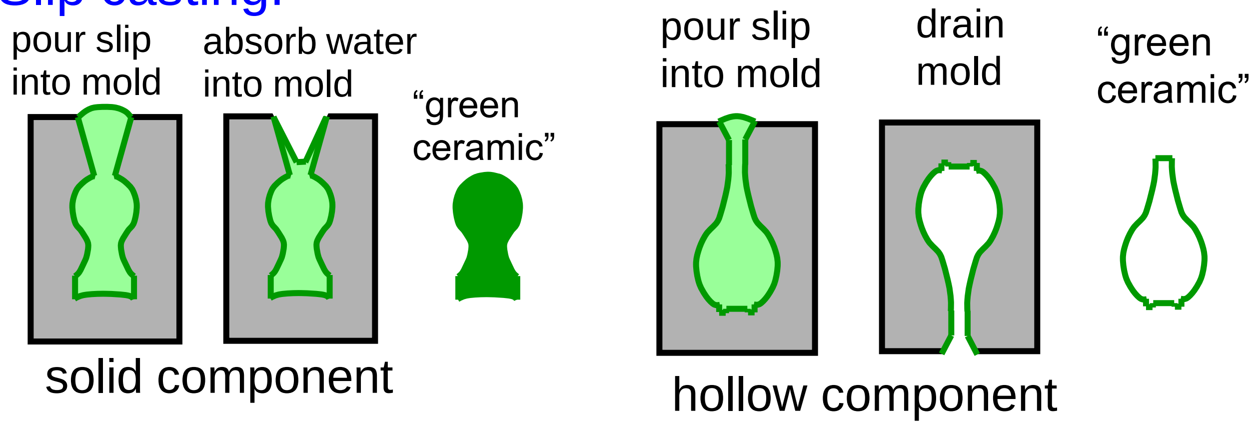
- Milling and screening: desired particle size
- Mixing particles & water: produces a "slip"
- Form a "green" component

  --Hydroplastic forming:
  extrude the slip (e.g., into a pipe)



Adapted from Fig. 11.8 (c), *Callister 7e*.

  --Slip casting:



Adapted from Fig. 13.12, *Callister 7e*. (Fig. 13.12 is from W.D. Kingery, *Introduction to Ceramics*, John Wiley and Sons, Inc., 1960.)

- Dry and fire the component

Clay Composition

A mixture of components used

(50%) 1. Clay

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

(25%) 3. Fluxing agent (Feldspar)

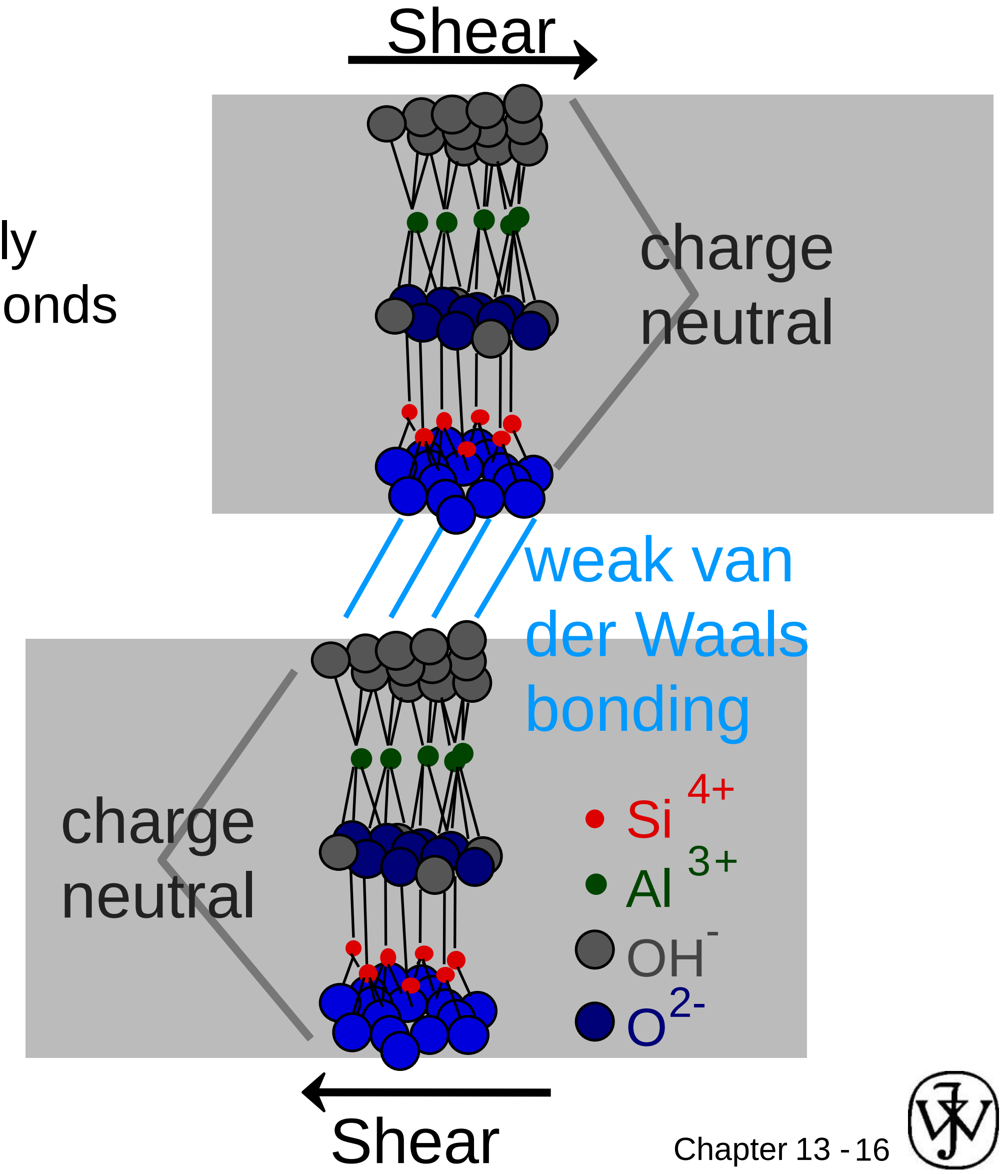
binds it together

aluminosilicates + K^+, Na^+, Ca^+

Features of a Slip

- Clay is inexpensive
- Adding water to clay
  - -- allows material to shear easily along weak van der Waals bonds
  - -- enables extrusion
  - -- enables slip casting

- Structure of Kaolinite Clay:



Shear

charge neutral

weak van der Waals bonding

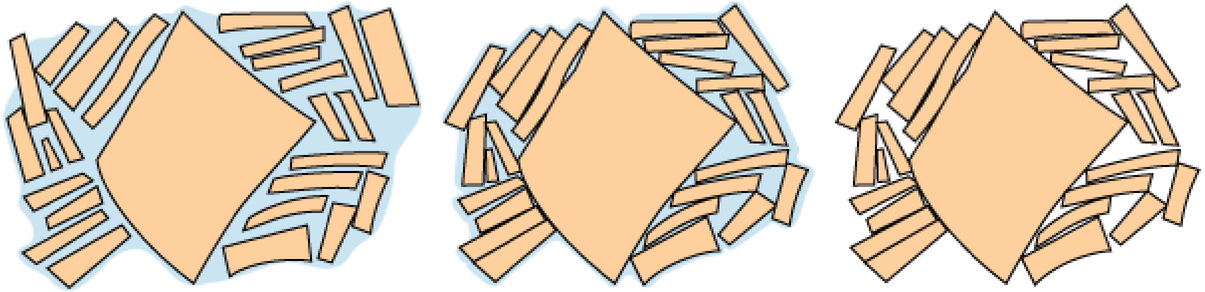
charge neutral

Shear

Adapted from Fig. 12.14, *Callister 7e*. (Fig. 12.14 is adapted from W.E. Hauth, "Crystal Chemistry of Ceramics", *American Ceramic Society Bulletin*, Vol. 30 (4), 1951, p. 140.)

Drying and Firing

- **Drying**: layer size and spacing decrease.



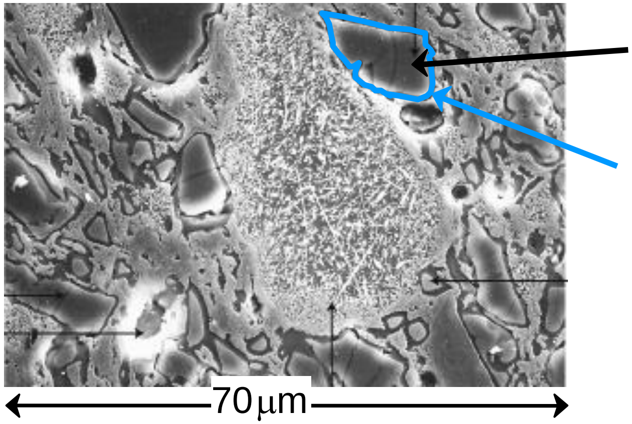
wet slip   partially dry   "green" ceramic

Adapted from Fig. 13.13, *Callister 7e*. (Fig. 13.13 is from W.D. Kingery, *Introduction to Ceramics*, John Wiley and Sons, Inc., 1960.)

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

- **Firing**:
  --*T* raised to (900-1400°C)
  --vitrification: liquid glass forms from clay and flows between SiO_2 particles. Flux melts at lower *T*.

micrograph of porcelain



SiO_2 particle (quartz)

glass formed around the particle

Adapted from Fig. 13.14, *Callister 7e*. (Fig. 13.14 is courtesy H.G. Brinkies, Swinburne University of Technology, Hawthorn Campus, Hawthorn, Victoria, Australia.)

Ceramic Fabrication Methods-IIB

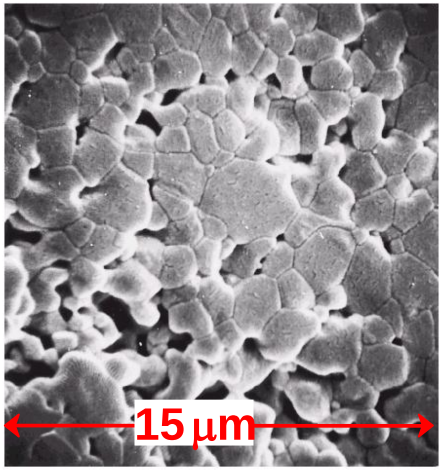
GLASS FORMING

PARTICULATE FORMING

CEMENTATION

Sintering: useful for both clay and non-clay compositions.

- Procedure:
  - -- produce ceramic and/or glass particles by grinding
  - -- place particles in mold
  - -- press at elevated *T* to reduce pore size.
- Aluminum oxide powder:
  - -- sintered at 1700°C for 6 minutes.



Adapted from Fig. 13.17, *Callister 7e*. (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.)

Powder Pressing

Sintering - powder touches - forms neck & gradually neck thickens

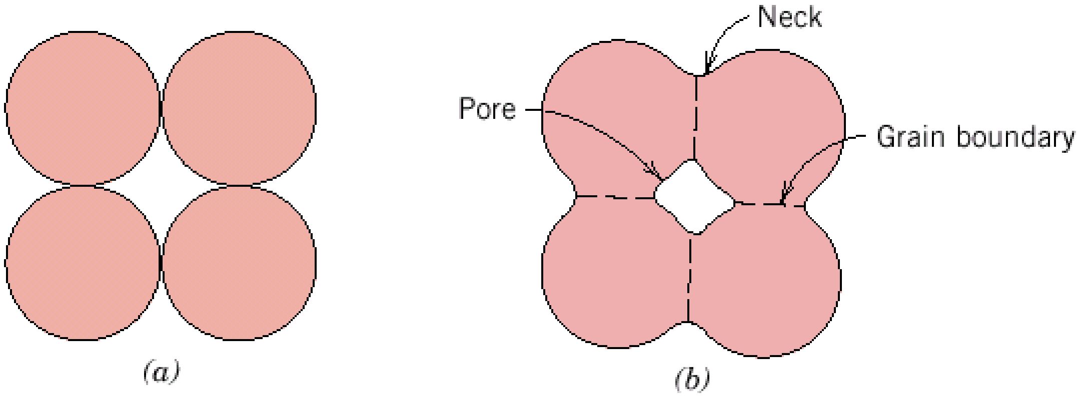
- add processing aids to help form neck
- little or no plastic deformation

Uniaxial compression - compacted in single direction

Isostatic (hydrostatic) compression - pressure applied by fluid - powder in rubber envelope

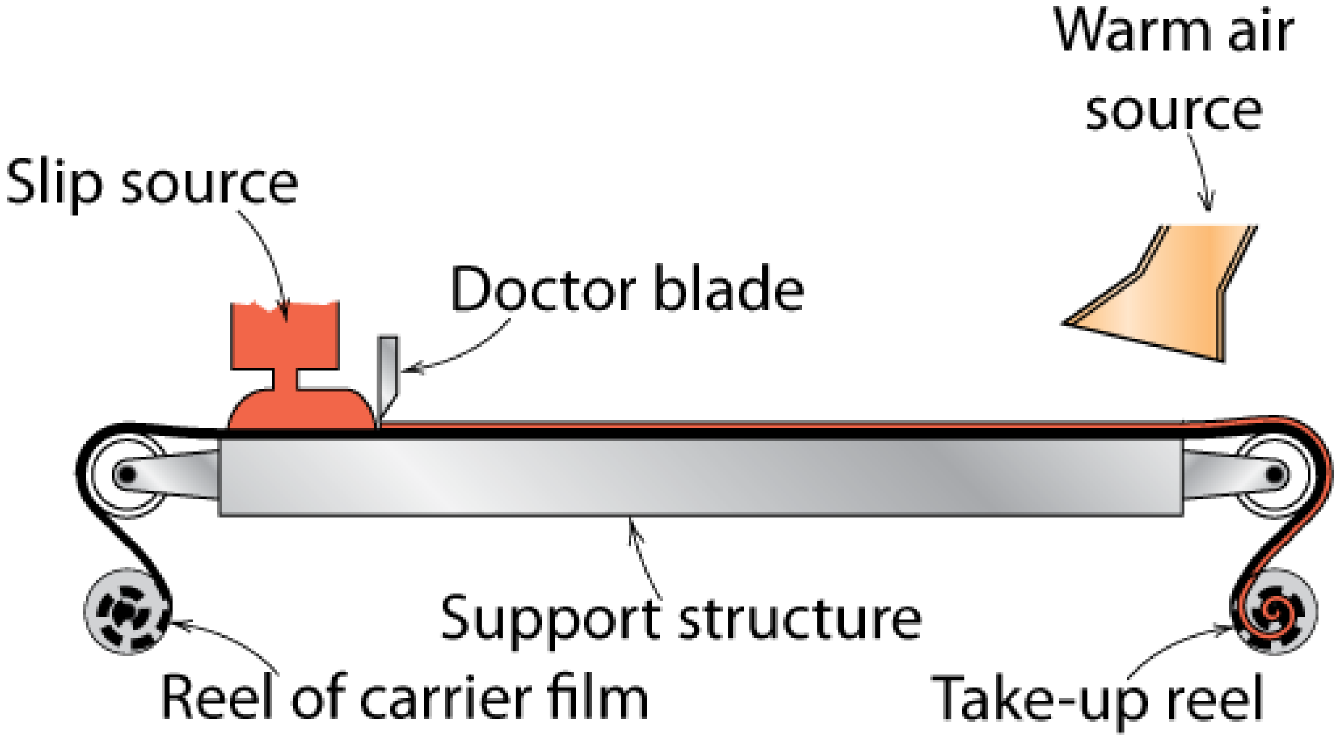
Hot pressing - pressure + heat

Adapted from Fig. 13.16, *Callister 7e*.



Tape Casting

- thin sheets of green ceramic cast as flexible tape
- used for integrated circuits and capacitors
- cast from liquid slip (ceramic + organic solvent)



Adapted from Fig. 13.18, *Callister 7e*.

Ceramic Fabrication Methods-III

GLASS FORMING

PARTICULATE FORMING

CEMENTATION

- Produced in extremely large quantities.
- Portland cement:
  - -- mix clay and lime bearing materials
  - -- calcinate (heat to 1400°C)
  - -- primary constituents:
    - tri-calcium silicate
    - di-calcium silicate
- Adding water
  - -- produces a paste which hardens
  - -- hardening occurs due to hydration (chemical reactions with the water).
- Forming: done usually minutes after hydration begins.

Applications: Advanced Ceramics

Heat Engines

- Advantages:
  - Run at higher temperature
  - Excellent wear & corrosion resistance
  - Low frictional losses
  - Ability to operate without a cooling system
  - Low density

- Disadvantages:
  - Brittle
  - Too easy to have voids- weaken the engine
  - Difficult to machine

- Possible parts – engine block, piston coatings, jet engines

Ex: Si_3N_4, SiC, & ZrO_2

Applications: Advanced Ceramics

- Ceramic Armor
  - – Al_2O_3, B_4C, SiC & TiB_2
  - – Extremely hard materials
    - shatter the incoming projectile
    - energy absorbent material underneath

Applications: Advanced Ceramics

Electronic Packaging

- Chosen to securely hold microelectronics & provide heat transfer
- Must match the thermal expansion coefficient of the microelectronic chip & the electronic packaging material. Additional requirements include:
  - – good heat transfer coefficient
  - – poor electrical conductivity
- Materials currently used include:
    - Boron nitride (BN)
    - Silicon Carbide (SiC)
    - Aluminum nitride (AlN)
      - – thermal conductivity 10x that for Alumina
      - – good expansion match with Si

Summary

- Basic categories of ceramics:
  - -- glasses
  - -- clay products
  - -- refractories
  - -- cements
  - -- advanced ceramics
- Fabrication Techniques:
  - -- glass forming (impurities affect forming temp).
  - -- particulate forming (needed if ductility is limited)
  - -- cementation (large volume, room *T* process)
- Heat treating: Used to
  - -- alleviate residual stress from cooling,
  - -- produce fracture resistant components by putting surface into compression.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: