Slip casting benefits and drawbacks

Advantages
- Low capital investment has to be made for the products to be produced.
- Highly homogeneous slurries can be produced.
- A wide variety of complex shapes can be produced that could not be produced using other conventional methods.

Disadvantages
- Lower dimensional precision can be achieved compared to dry pressing or powder injection molding.
- The production rate is lower than the rate of dry pressing, injection molding or extrusion.
- Differential shrinkage can be caused by a packing factor gradient that can be induced in the molds during water removal.
- The molds that are used have a low toughness so they can fracture easily therefore a large mold inventory must be maintained to insure a constant production rate.
Formulazione di uno slip ceramico

- Formulare la composizione in peso di uno slip ceramico in cui si richiede:
  - frazione volumica di zirconia in allumina pari al 10%
  - frazione di liquido (H$_2$O) in volume nello slip 55%
  - quantità totale di slip 1/2 litro
  - Disperdente 0,4% rispetto al peso delle polveri
  (densità zirconia 5,9g/cm$^3$, densità allumina 3,96g/cm$^3$)

- Attraverso la formatura per slip casting il green possiede un fattore di impacchettamento pari a 0,6. Calcolare il ritiro volumetrico e lineare atteso durante la sintetizzazione supponendo la piena densificazione
  - $V_s/V_g = (l_s/l_g)^3 = (1 - \Delta l/l_g)^3$
  - Essendo $l_g - l_s = \Delta l$, $V_s =$ volume del sinterizzato, $V_g =$ volume del green
  - $\Delta l/l = 1 - (V_s/V_g)^{1/3}$
The slip casting process

- Slip casting is the process of filling a porous mold, usually a gypsum mold, with a ceramic slurry.
- The water is removed from the slurry via capillary action through the small pores in the mold. As the water is removed the slurry the ceramic particles are collected against the surface of the mold.
- This collection of particles is the wall of the body that is to be produced. This process is allowed to continue until the correct thickness is achieved, after which the remainder of the slip is drained out of the mold.
- The green body is dried further and removed from the mold. After the green body is removed it is dried and fired so that it can go through the final machining process.
The molds used for slip casting usually have a low toughness.

They have a high porosity, which lowers the strength. If the strength is increased some porosity must be sacrificed to increase the strength.

Low strength gypsum molds wear out with time because the pores are eroded from the water that goes through them.

These molds are great for producing complex shapes because as the green body loses water and begins to dry out it shrinks away from the edges of the mold for easy removal. This is good because there is less time lost to parts that are damaged during removal.
Cast thickness as a function of casting time

\[ L = \left[ \left( 2J \Delta P t/nC \right) + \left( R_m/R_c \right)^2 \right]^{1/2} - \left( R_m/R_c \right), \]

- \( L \) = cast thickness
- \( J \) = vol. of cast/vol. of liq. Removed
- (inverse of packing factor),
- \( R_c \) = resistivity to liq. transport in the cast,
- \( \Delta P \) = apparent mold suction
- \( n \) = viscosity of liq. transported
- \( R_m \) = liquid transport resistance of the mold

Parabolic behavior of cast thickness with time and linear dependence of cast (thickness)^2 with time when slip casting a porcelain slip.
Capillary suction on the slip

\[ \Delta P = 2\gamma \cos \phi / R_c \]

- \( \Delta P \) = suction,
- \( \gamma \) = surface tension
- \( \phi \) = angle
- \( R_c \) = radius of curvature

The flow of liquid through a porous medium is:

\[ \frac{dV}{dt} = K/n \times \frac{dP}{dx} \]

- \( dP/dx \) = the pressure gradient across the filter
- \( n \) = filtrate viscosity,
- \( dV/dt \) = volumetric flow rate of the filtrate and \( K \) is the filter permeability
The goal for slip casting is to produce a body that will sinter at a low temperature to save energy and time. In order for this to happen the slip must be produced with the optimum variables determined by laboratory testing.

To achieve the maximum packing density of about 75% for a green body, a bimodal particle alumina powder with a volume fraction ratio of coarse to fine particles equal to 7:3.

The ratio of diameter sizes between the coarse and fine particles is 7:1. This ratio yields the maximum packing density after casting. A bimodal system packs better because the fine particles will fill into the interstices created by the large particles. If a larger range is used like a tri-modal or greater, the packing factor will increase according to the following equation:

$$PF_{\text{max}} = PF_c + (1-PF_c)(PF_m) + (1-PF_c)(1-PF_m)PF_f$$

This takes up the void space and decreases the size and amount of pores. The slips containing between 40% and 50% alumina produce the best green bodies with the easiest water removal.
Masters in slip casting

- Very complicated shapes that can be produced using the slip casting method

- **A trick:** As the temperature increases in the mold or surrounding area, the amount of water removed from the mold also increases. The use of microwaves to increase the temperature is a good source because they can be focused on the sample and energy can be conserved. The use of microwaves will also increase the casting rate which will increase the production rate.
# Volume loading and dispersant concentration

<table>
<thead>
<tr>
<th>Volume loading</th>
<th>Dispersant concentration (mmol)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>7.5</td>
<td>Alumina, fine; Unimodal size distribution; varied volume loading; optimized dispersant concentration</td>
</tr>
<tr>
<td>37</td>
<td>9.25</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>7.7</td>
<td>Bimodal size distribution; varied volume loading; optimized dispersant concentration</td>
</tr>
<tr>
<td>50</td>
<td>9.7</td>
<td>85% 6 μm, 15% 0.6 μm</td>
</tr>
<tr>
<td>42</td>
<td>8.0</td>
<td>Bimodal size distribution; varied volume loading; optimized dispersant concentration</td>
</tr>
<tr>
<td>50</td>
<td>9.8</td>
<td>50% 6 μm, 50% 0.6 μm</td>
</tr>
<tr>
<td>37</td>
<td>32</td>
<td>SiC; Unimodal size distribution; constant volume loading; varied dispersant concentration; cakes analyzed as a function of position</td>
</tr>
<tr>
<td>37</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

*The alumina suspensions were dispersed with tetrasodium pyrophosphate, and the SiC suspensions were dispersed with sodium silicate.*
### Slip cast oxides

<table>
<thead>
<tr>
<th></th>
<th>Alumina</th>
<th>Alumina-Mullite</th>
<th>Alumina-Titania</th>
<th>Alumina-Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>3.91</td>
<td>2.82 - 3.6</td>
<td>3.8</td>
<td>4.0 - 5.1</td>
</tr>
<tr>
<td>Permeability</td>
<td>Gas Tight</td>
<td>Gas Tight</td>
<td>Gas Tight</td>
<td>Gas Tight</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>254</td>
<td>73</td>
<td>225</td>
<td>260</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td>2468</td>
<td>550</td>
<td>2100</td>
<td>3100</td>
</tr>
<tr>
<td>Hardness (GPa)</td>
<td>19.2</td>
<td>9</td>
<td>15</td>
<td>26.4</td>
</tr>
<tr>
<td>Max. Temp. °C</td>
<td>1950</td>
<td>1700</td>
<td>1900</td>
<td>2000</td>
</tr>
<tr>
<td>Thermal Shock Resistance (cycles)</td>
<td>42</td>
<td>&gt;800</td>
<td>&gt;1000</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal cond 20-100°C (W/m-K)</td>
<td>29 - 23</td>
<td>15 - 8</td>
<td>33 - 28</td>
<td>26 - 18</td>
</tr>
<tr>
<td>Dielectric Const. @20°C</td>
<td>9.1</td>
<td>7</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Dielectric Loss @1MHz, 20°C</td>
<td>0.0002</td>
<td>0.01</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>Res. to Acids, Alkalis, Salts</td>
<td>Very Good</td>
<td>Good</td>
<td>Very Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Res/ to Molten Metals</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very Good</td>
</tr>
</tbody>
</table>
Proprietà reologiche

- Per iniziare e mantenere un flusso laminare in un liquido è necessario applicare uno shear stress
- Quando lo shear stress $\tau$ è proporzionale al gradiente di velocità il liquido viene chiamato Newtoniano
  \[ \tau = \eta (-d\nu/dr) \]
  - $\gamma' = -d\nu/dr$ viene chiamato shear rate
  - $\eta$ viene chiamata viscosità
- Nei fluidi non Newtoniani shear rate e shear stress sono legati tramite un’equazione empirica:
  \[ \tau = K(\gamma')^n \]
- La viscosità apparente può essere definita come
  \[ \eta = K(\gamma')^{n-1} \]
  - Essa rappresenta la resistenza totale allo stress
- Quando $n<1$ il fluido viene detto pseudoplastico
  - Liquidi con grandi molecole che tendono a orientarsi durante il flusso laminare riducendo la resistenza allo shear
- Quando $n>1$ il fluido viene detto dilatante
  - Sospensioni possono avere particelle che interferiscono poco a bassi shear rate e molto ad alti shear
Yield stress e tissotropia

In fluidi contenenti particelle o molecole che si attraggono mutuamente è necessario applicare uno stress iniziale $\tau_y$ non nullo per iniziare a scorrere

$$\tau - \tau_y = \eta_p \gamma'$$

$\eta_p$ È chiamata viscosità plastica ed è legata alla viscosità apparente dalla relazione:

$$\eta_p = \eta_p + \tau_y / \gamma'$$

Quando la viscosità apparente diminuisce con il tempo un fluido si dice tissotropico

- La tissotropia si osserva in fluidi pseudoplastici e di Bingham e si verifica quando i legami o l'orientazione di particelle o molecole variano con il tempo di shear ($\gamma' t$).
- Nelle sospensioni la tissotropia è generalmente un fenomeno reversibile.
Viscosità degli slip

- La viscosità di una sospensione $\eta_s$ è maggiore di quella di un liquido $\eta_l$ ed il loro rapporto si definisce viscosità relativa:
  \[
  \eta_r = \frac{\eta_s}{\eta_l}
  \]

- Le interazioni durante lo scorrimento degli slip sono complesse e vengono descritte da equazioni empiriche:
  \[
  \eta_r = 1 + K_h f^v_p
  \]
  - $f^v_p =$ frazione in volume delle particelle disperse
  - $K_h =$ fattore di forma idrodinamica apparente
    - $K_h = 2,5$ per particelle sferiche
    - $K_h > 2,5$ per particelle irregolari la cui rotazione produce un volume idrodinamico effettivo maggiore

- Una empirica relazione più generica
  \[
  \eta_r = (1-f^v_p)^{-K_f}
  \]
  - Con $K_f$ variabile tra 3 e 21 quando si passa da un particolato fine e con distribuzione continua ad un particolato di grosse dimensioni e dimensioni uniformi