MIT 3.071
Amorphous Materials

6: Glass Shaping

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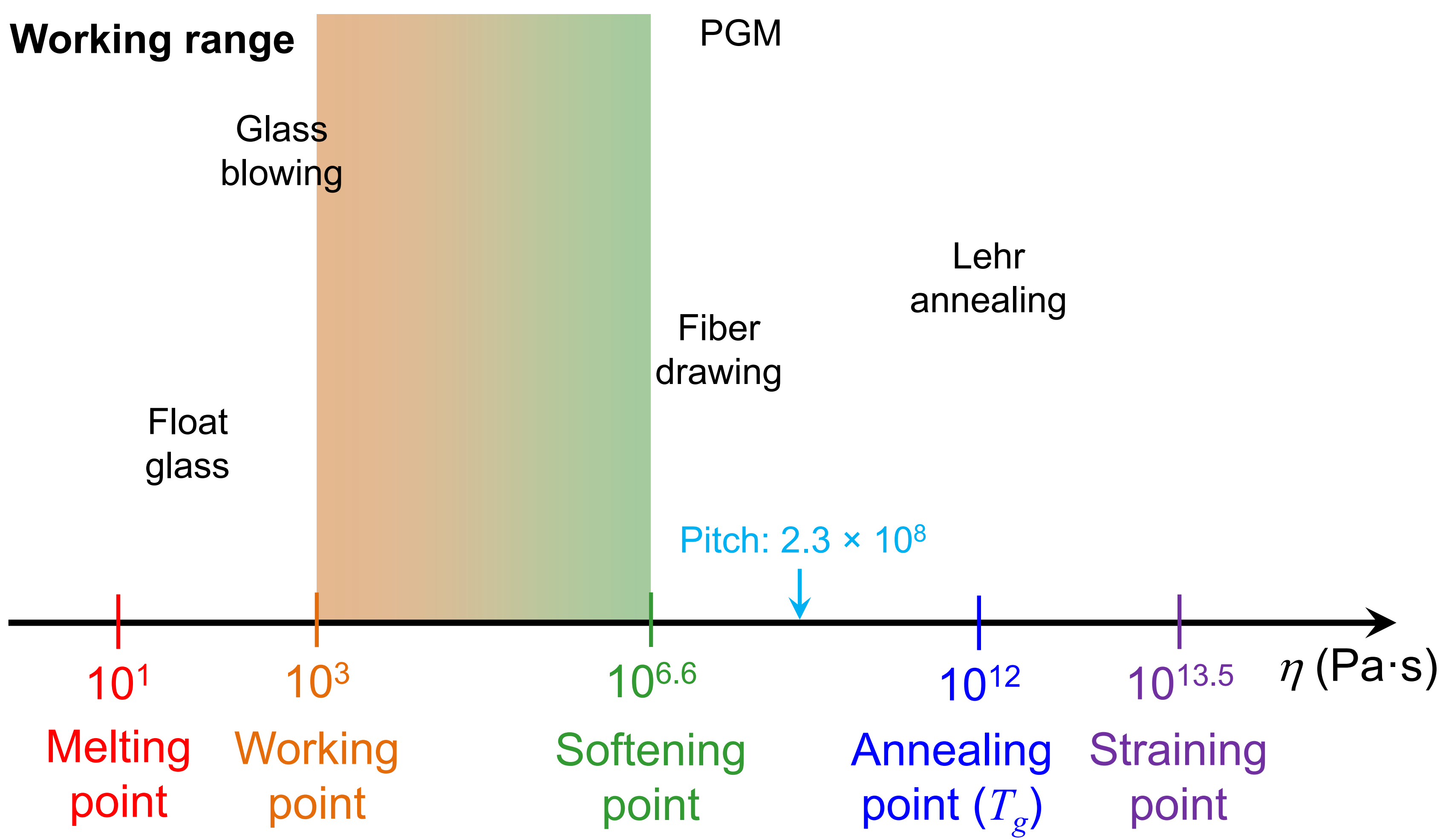
After-class reading list

- Fundamentals of Inorganic Glasses
  - Ch. 20
- Introduction to Glass Science and Technology
  - Ch. 13

"Viscosity makes things happen essentially in slow motion. If you are trying to melt a crystalline solid (like ice or an aluminum oxide ceramic), as soon as you reach the melting point, a drop of liquid forms and falls away from the melting surface. Glass, on the other hand, … gradually transforms from a hard solid to a slowly softening liquid. This soft liquid gradually stiffens as it cools (because of its increasing viscosity), allowing glass blower time to shape and manipulate the glass."

http://madsci.org/posts/archives/2007-09/1188944613.Ph.r.html

Viscosity reference points

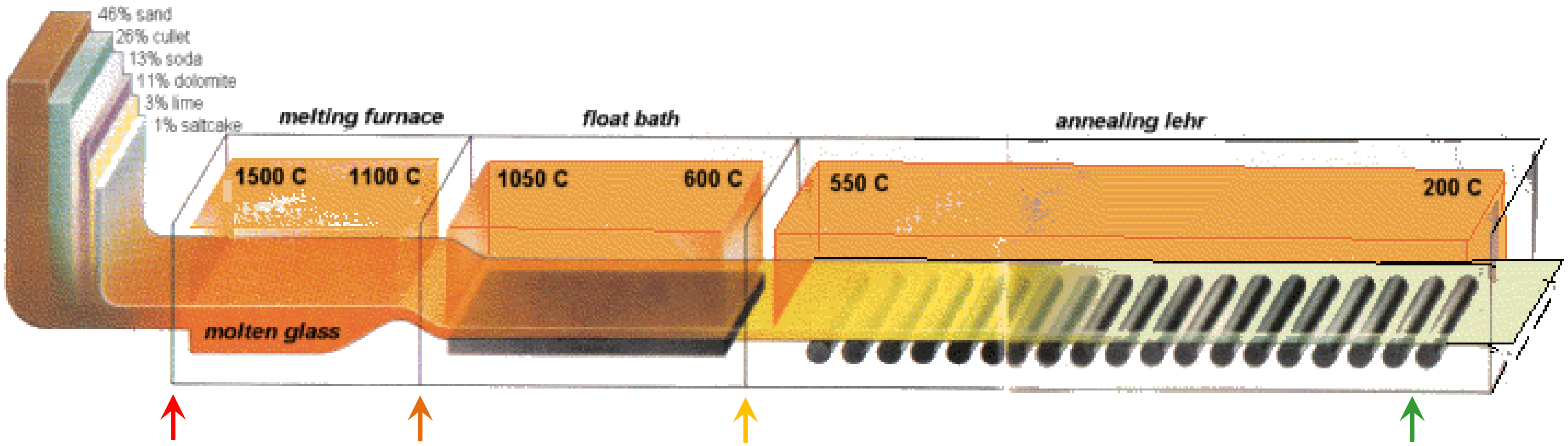


Basic properties of common silicate glasses

	Soda-lime	Borosilicate	Fused silica
CTE (ppm/°C)	9.2	3.2	0.5
Working point (°C)	1005	1252	N/A
Softening point (°C)	696	821	1650
Annealing point (°C)	510	560	1140
Strain point (°C)	475	510	1070

Flat glass manufacturing: float glass process

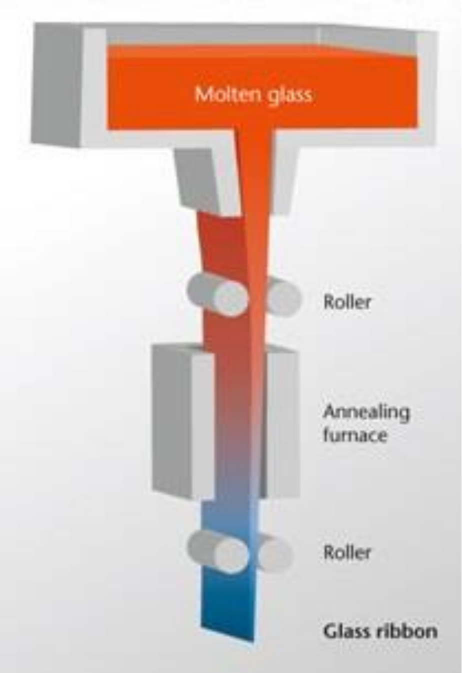
- Forming of a continuous ribbon of glass using a molten tin bath
  - Melting and refining (homogenization and bubble removal)
  - Float bath: glass thickness controlled by flow speed
  - Annealing: stress release
  - Inspection, cutting and shipping

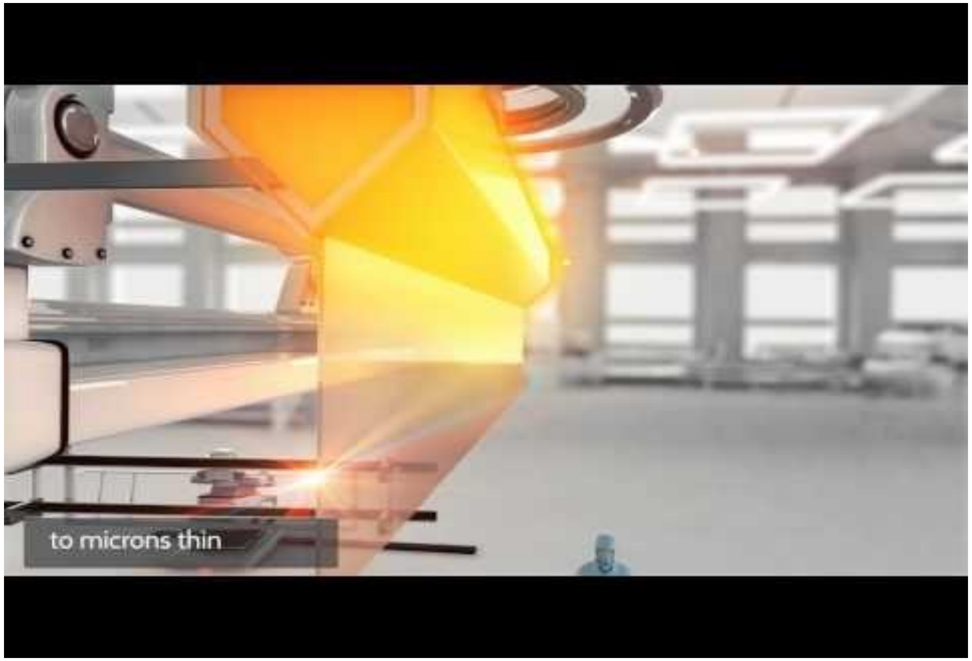


10^1 Pa·s $10^{2.5}$ Pa·s 10^{12} Pa·s   > 10^{15} Pa·s

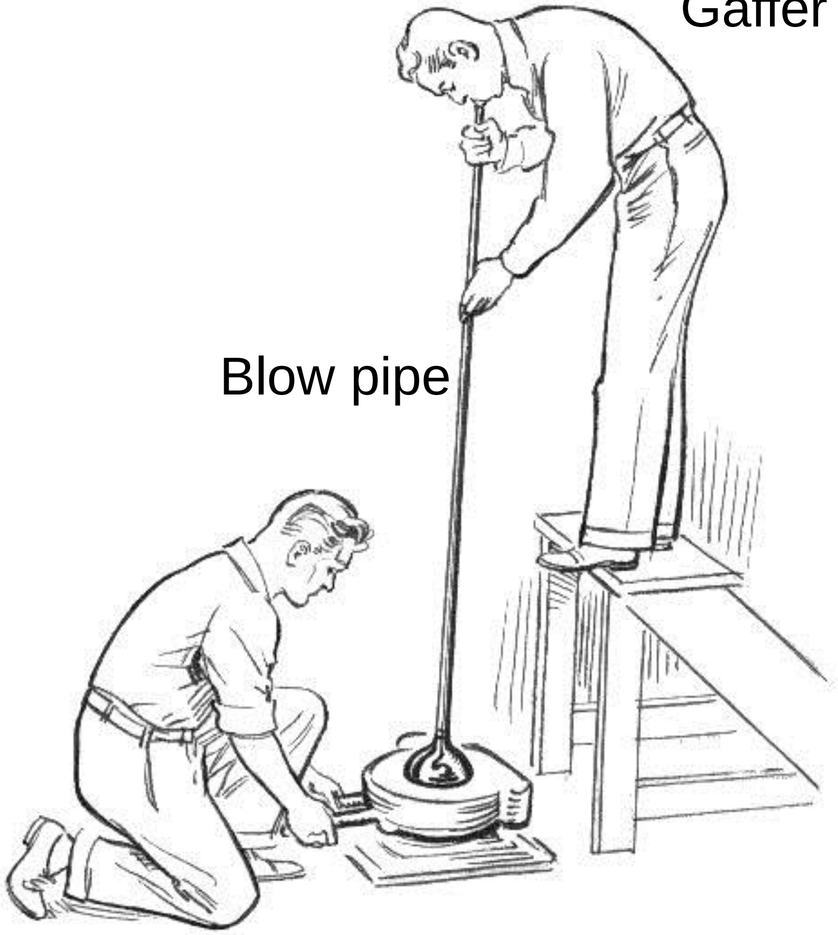
Flat glass manufacturing: down-draw methods

- Preserves pristine surfaces: no subsequent polishing required
- Broad range of thicknesses from millimeter to tens of microns
- Mostly used for flat panel display glasses



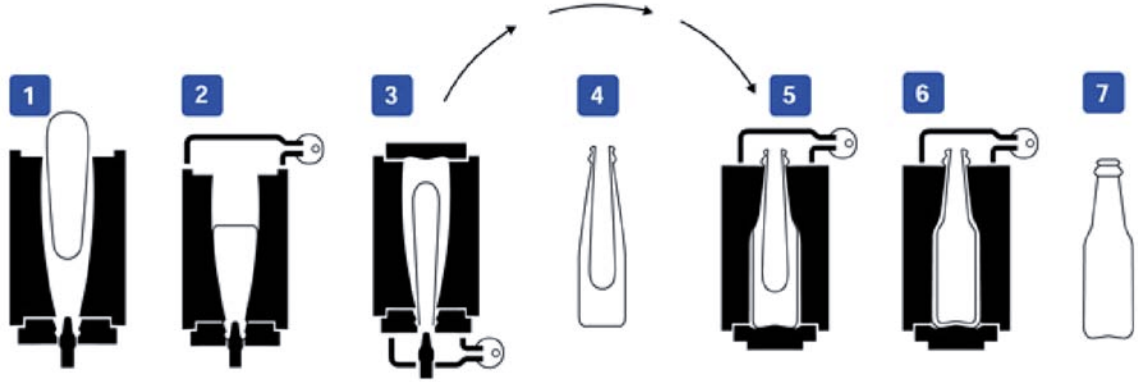


Glass blowing

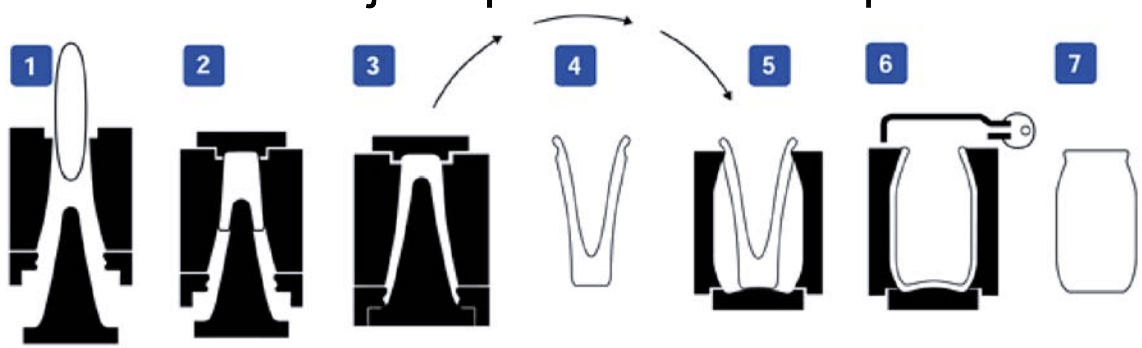


Glass container production

- Narrow-neck containers (e.g., bottles): blow-and-blow process



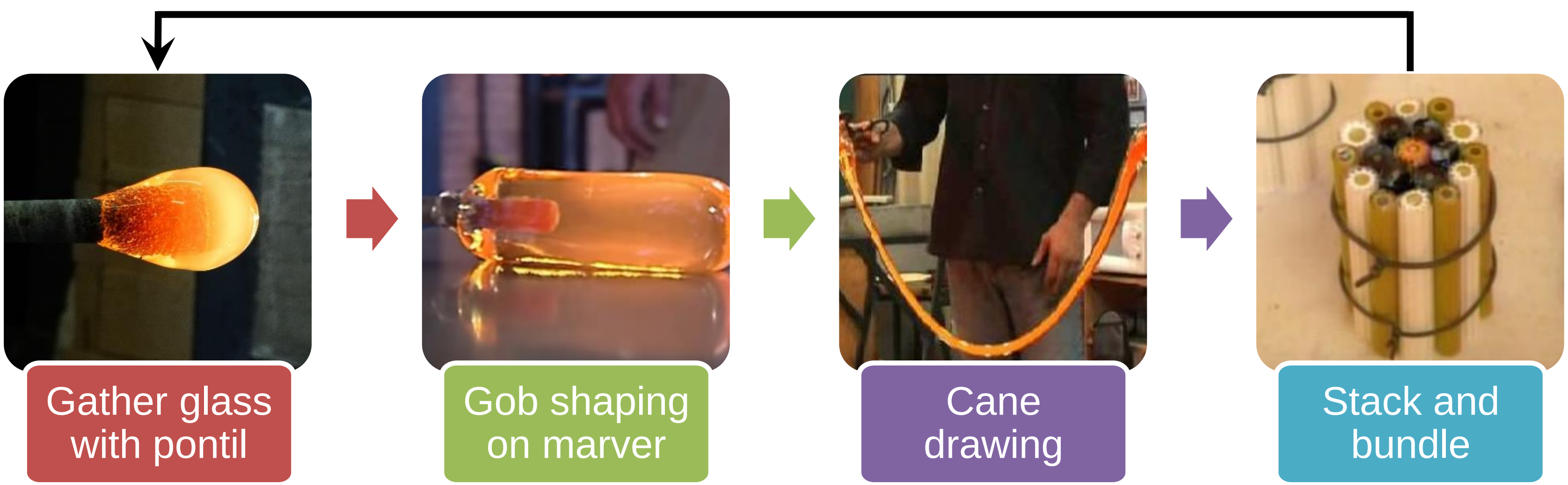
- Wide-mouthed jars: press-and-blow process



http://www.beatsonclark.co.uk/

Glass caneworking

- Canes: thin glass rods (often with color); can be of a single color, or contain multiple strands arrayed in a pattern (murrine)
- Basic glass work technique for adding intricate stripe patterns to glassware or blown glass



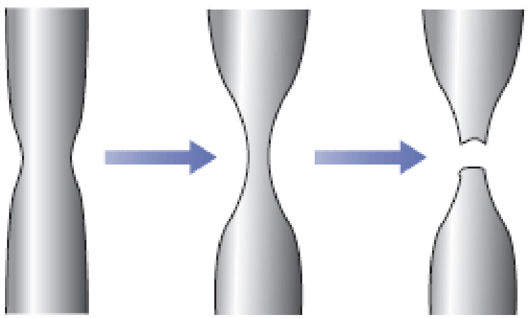
Glass caneworking

Reticello

Millefiori

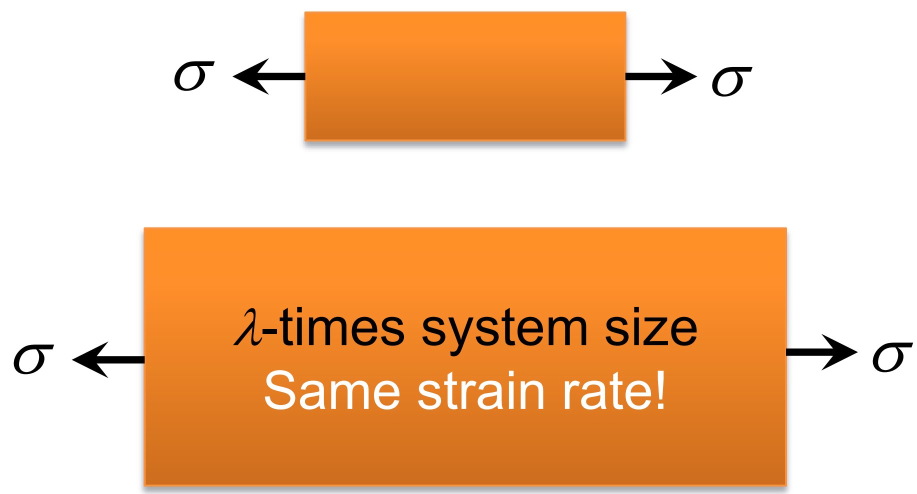
Zanfirico

Stability of drawn cane structures

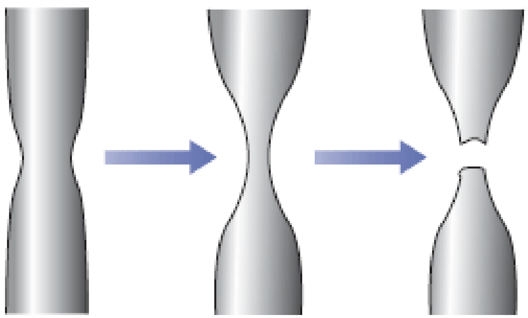


Scaling analysis

- Scale-invariance of viscous flow: strain rate $\dot{\varepsilon}$ remains invariant if the externally applied stresses are kept constant regardless of system size



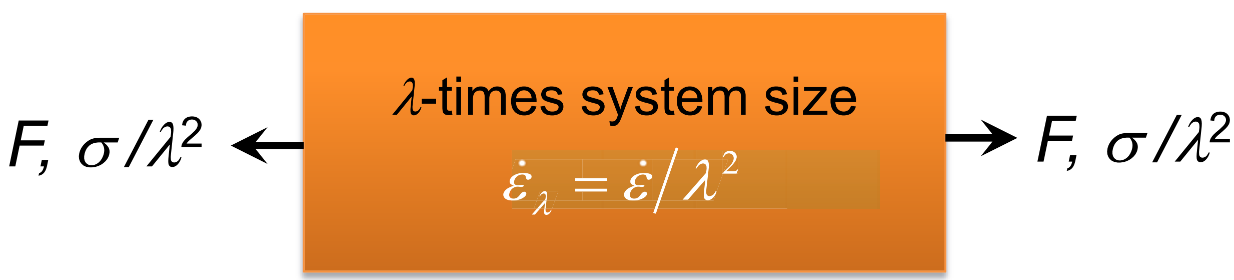
Stability of drawn cane structures



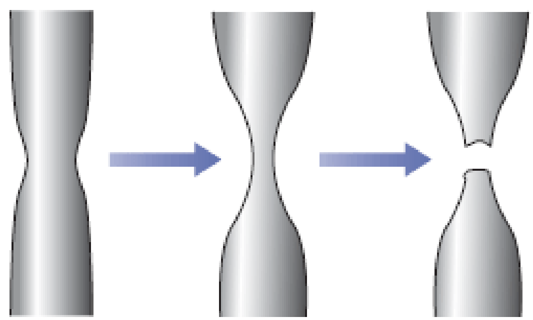
Cane diameter D change:

$$\frac{\partial D}{\partial t} \propto \frac{1}{\eta D}$$

Necking develops if viscosity is independent of diameter D

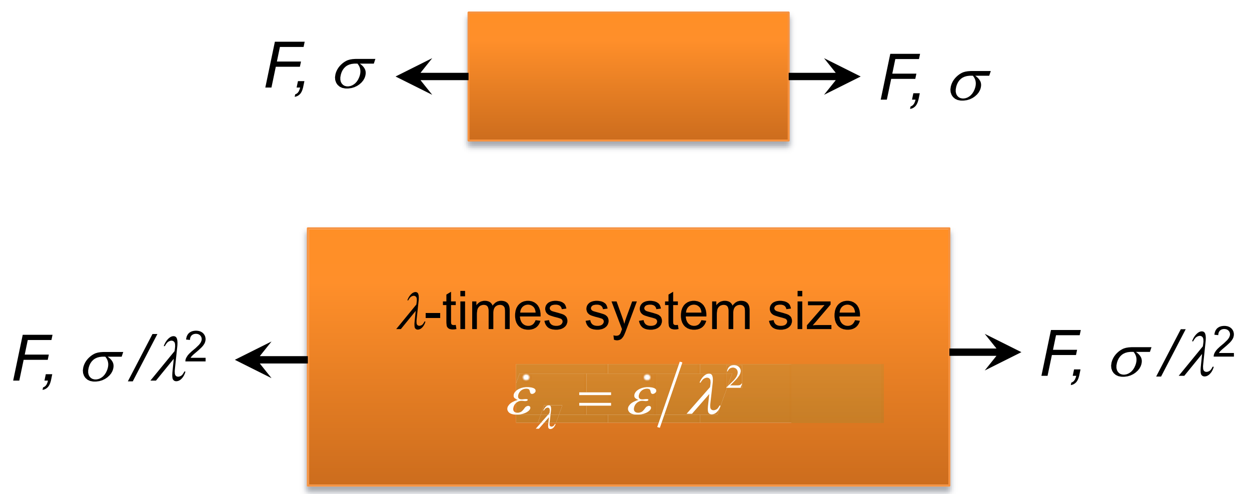


Stability of drawn cane structures

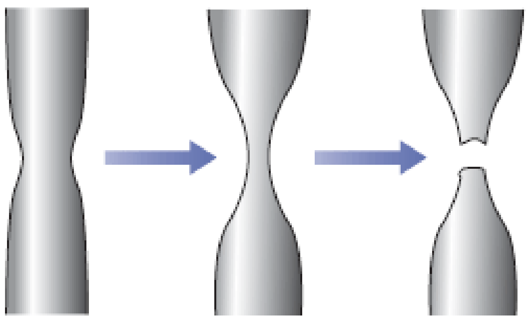


Stability threshold:

$$\dot{\varepsilon} = \frac{1}{D}\frac{\partial D}{\partial t} \propto \frac{1}{\eta D^2} = \text{constant}$$



Stability of drawn cane structures



Now consider heat dissipation:

- Radiative heat transfer dominates
- Stefan-Boltzmann law

  Heat flux: $q = e\sigma T^4$ e : emissivity

  σ = 5.67 × 10^{-8} W/m^{2}K^4
- Temperature change rate

$$\frac{\partial T}{\partial t} = -\frac{qS}{c_P V} = -\frac{4e\sigma T^4}{c_P D}$$

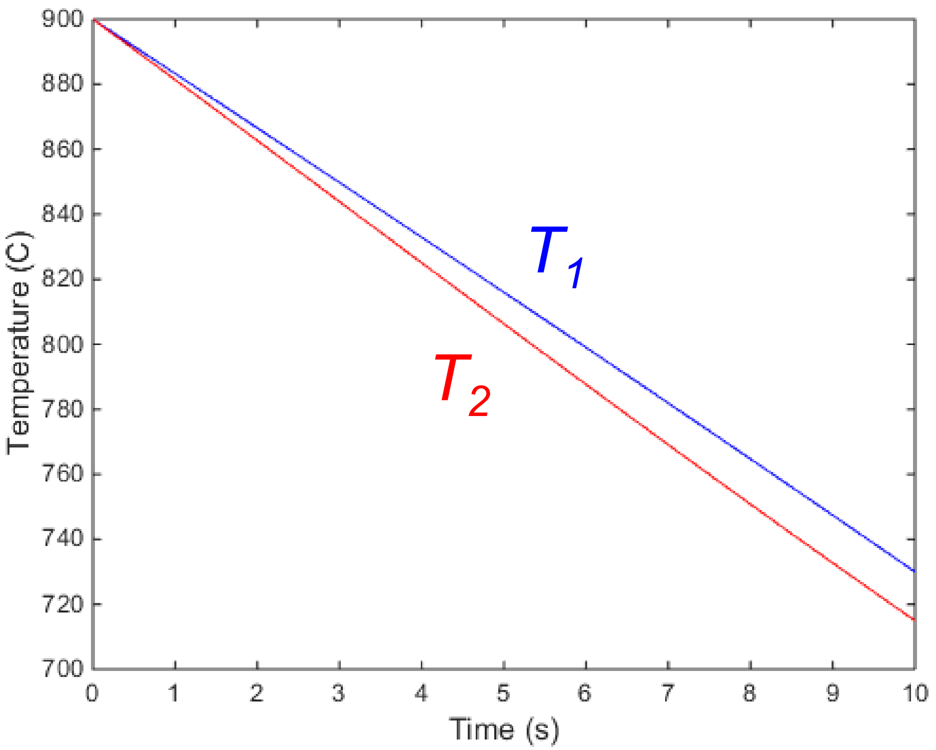
- Viscosity dependence on temperature

$$\eta = \eta_0 \exp\left[\frac{\Delta E_a(T)}{k_B T}\right]$$ High T range

Modeling outcome

Assumptions:

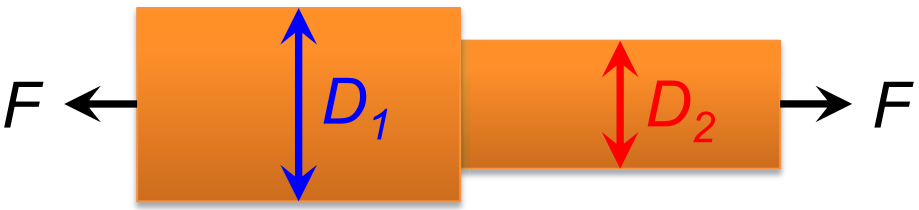
- Uniform temperature distribution along the cane cross-section
- No heat or mass exchange between cane sections
- Only considers radiative heat transfer from glass cane to the surroundings
- Constant drawing speed

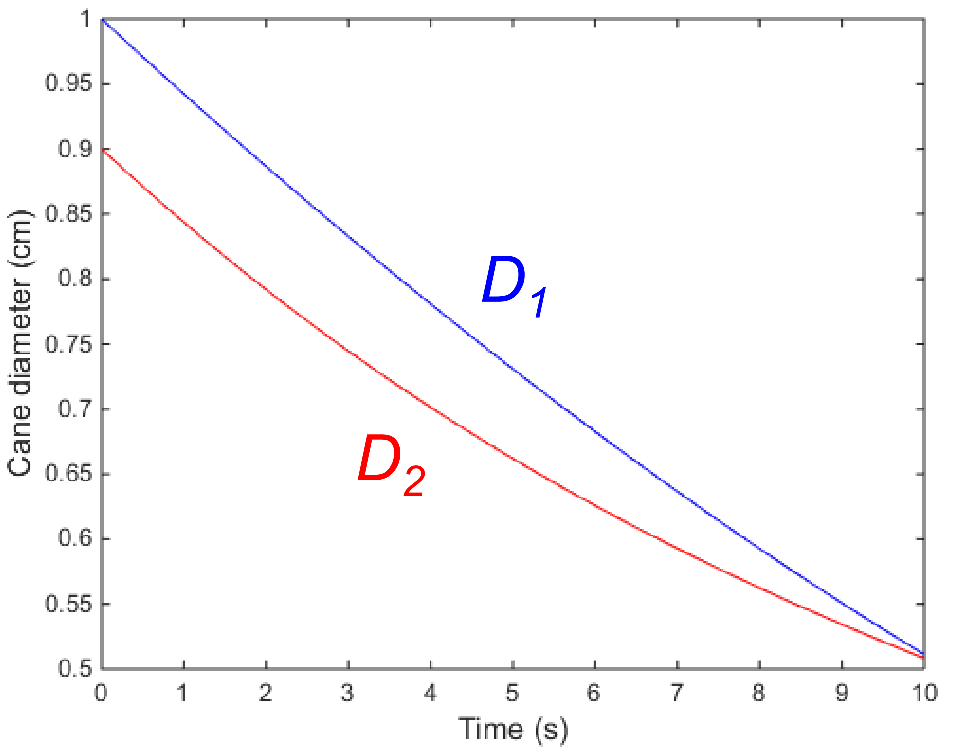


Modeling outcome

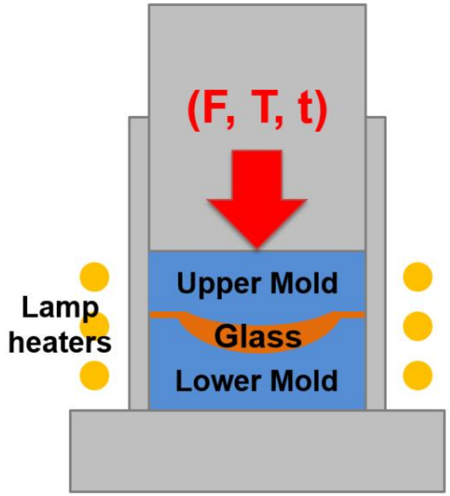
Conclusions:

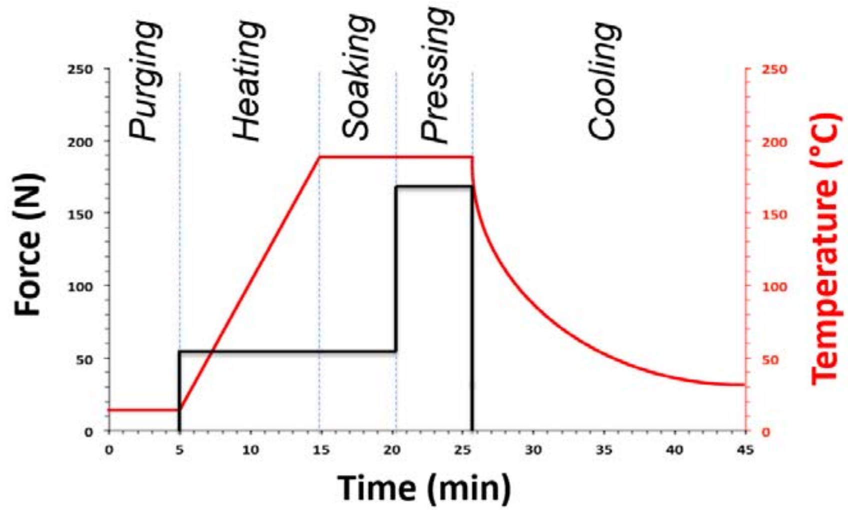
- Thinner section cools faster
- Viscosity increase in thinner section prevents necking
- Cane diameter non-uniformity damps out





Precision glass molding (compression molding)

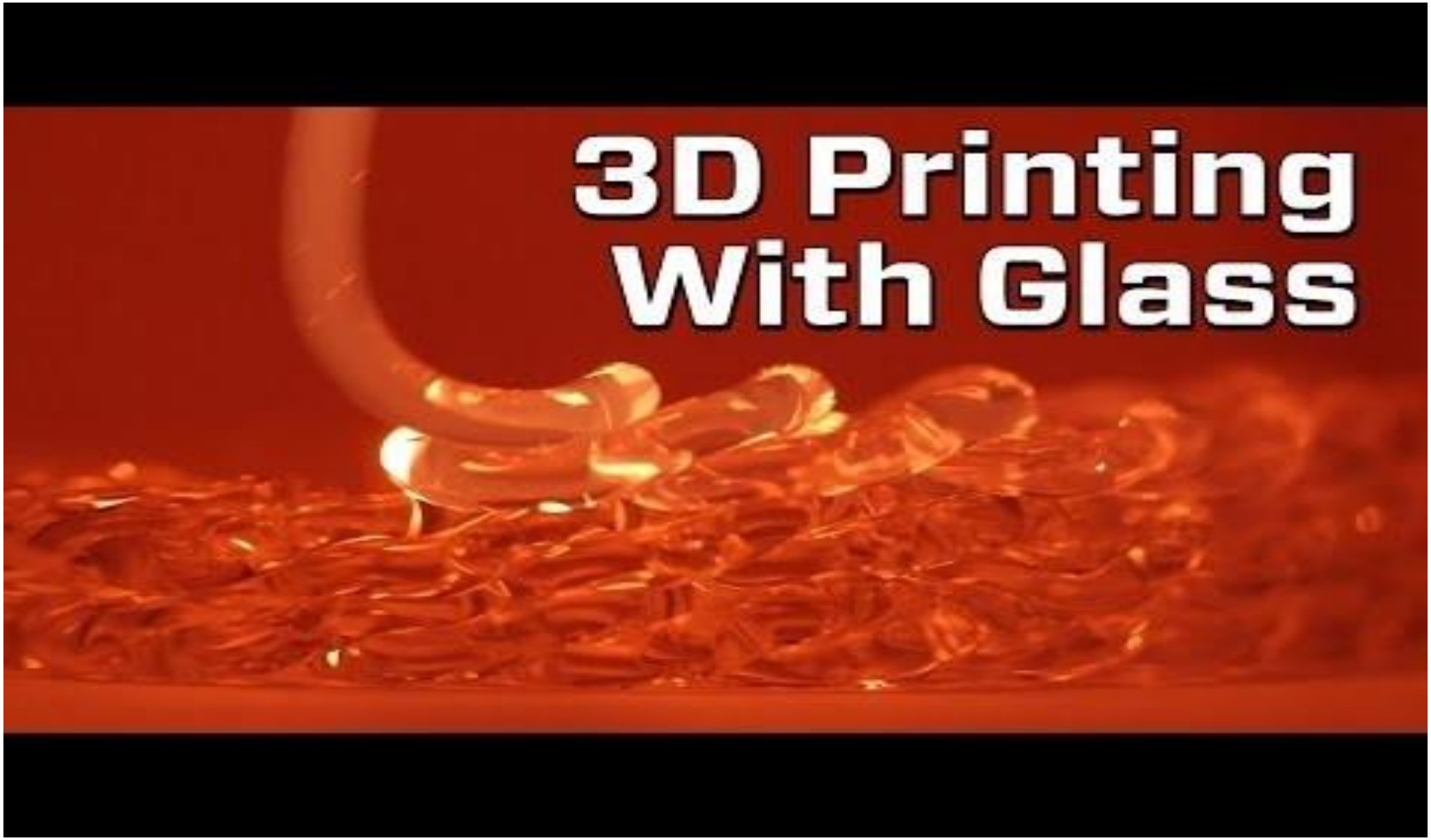




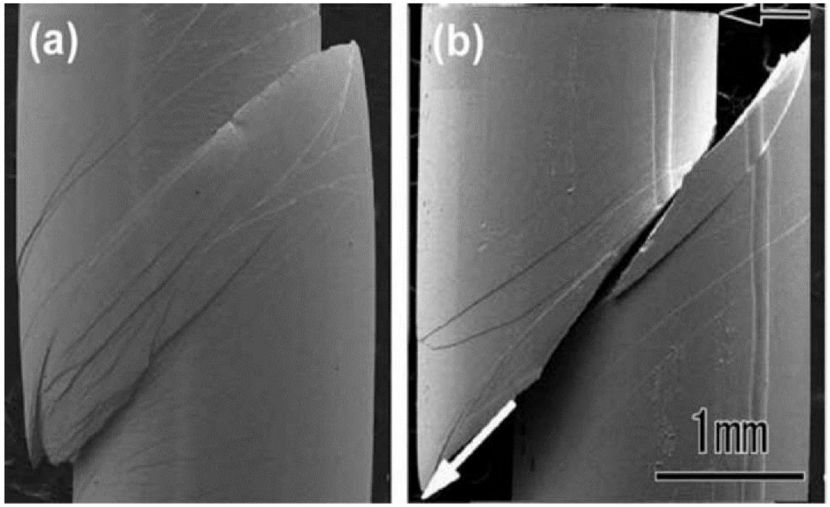
- Viscosity: $10^{6.6} - 10^{8}$ Pa·s; pressure: ~ MPa
- Mold sticking and damage: TiN or SiC low friction coatings
- Non-uniform temperature distribution
- Post-molding deformation: thermal shrinkage, viscoelasticity

http://www.rpoptics.com/wp-content/uploads/2015/01/Precision-Glass-Molding-Technical-Brief_21.pdf

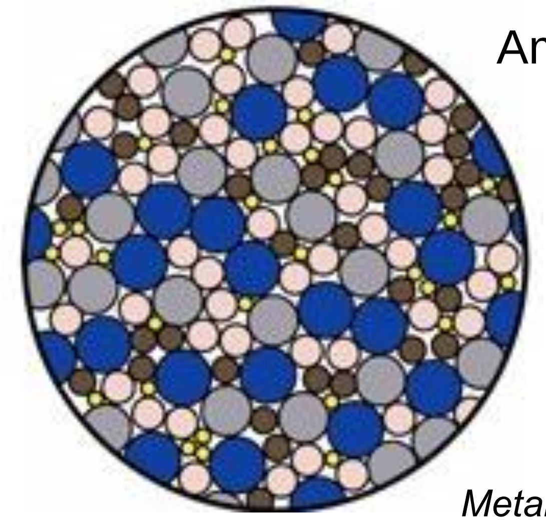
3-D glass printing



Mechanical properties of bulk metallic glass (BMG)



Source: Louzguine-Luzgin, D.V., et al."Mechanical Properties and Deformation Behavior of Bulk Metallic Glasses." *Metals* 3 (2013) 1-22.

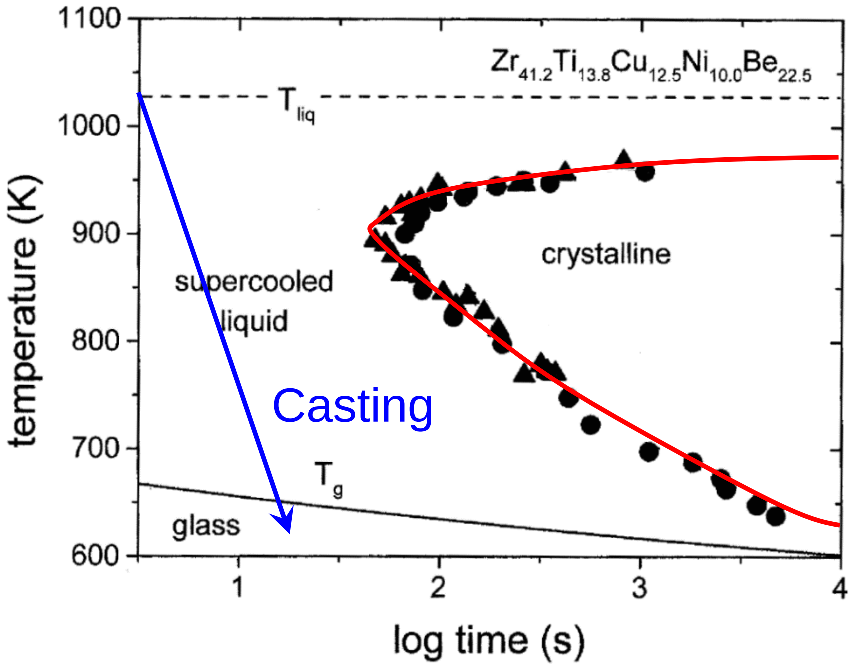


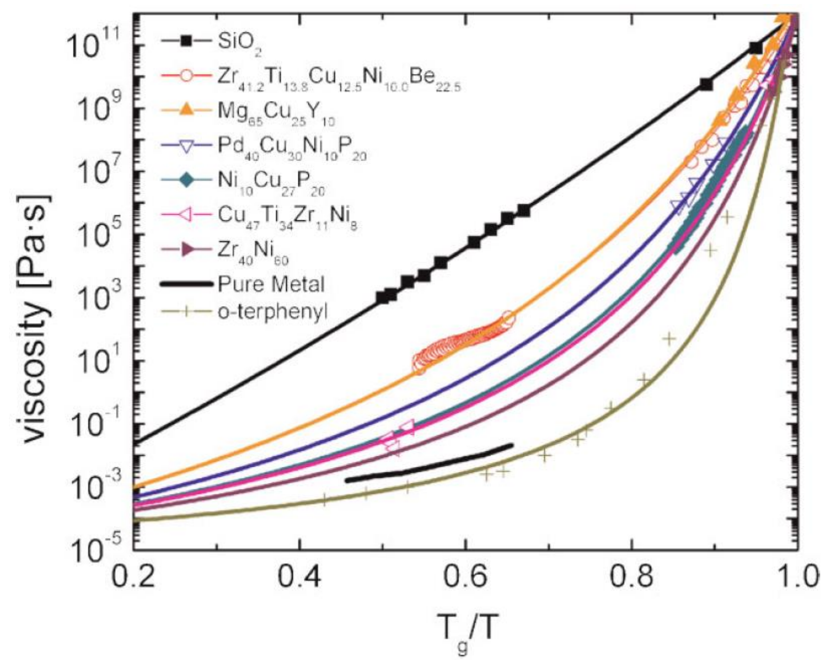
Amorphous metal

Metals **3**, 1 (2013).

- Absence of dislocations and slip planes in BMG
  - Large elastic limit and high yield strength (2% and 2 GPa in Zr-based BMGs)
  - Poor global plasticity: absence of strain hardening, strong tendency towards shear localization
- Cold working is not a viable processing solution

BMG processing design

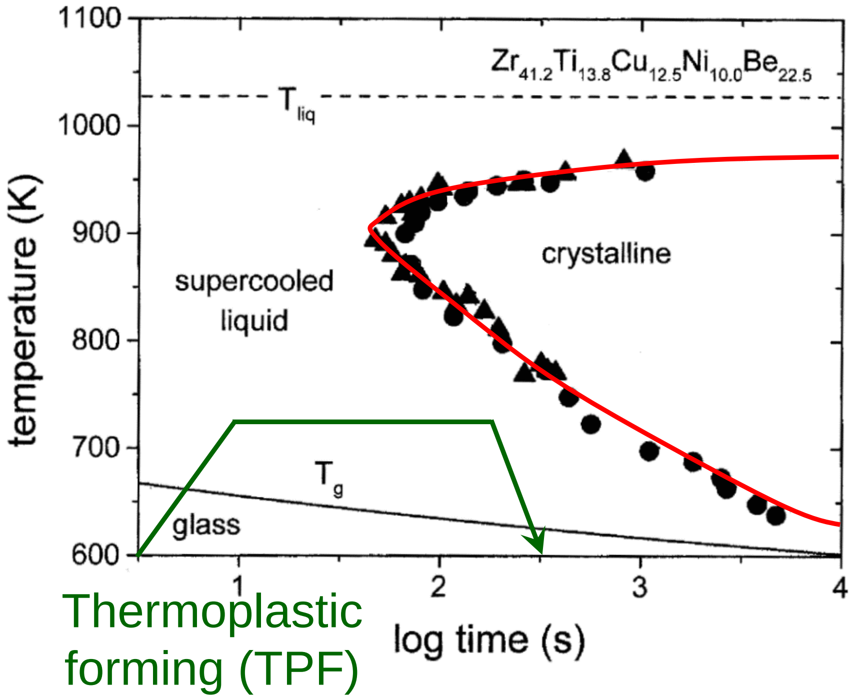


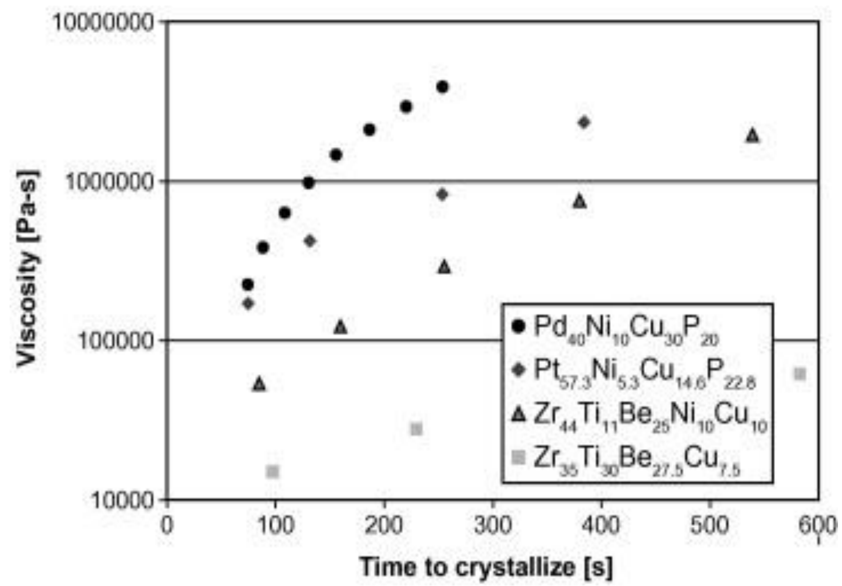


Adv. Mater. **22**, 1566 (2010).

- Casting: suction casting, die casting
  - Reduced volume shrinkage (< 1%)
  - Cooling rate control: mold filling and crystallization mitigation

BMG processing design





Scripta Mater. **60**, 160 (2009).

- Thermoplastic forming: compression & injection molding, extrusion, rolling, blow molding, 3-D printing
  - Thermal embrittlement: free volume decrease