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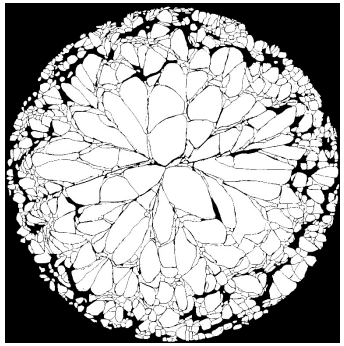

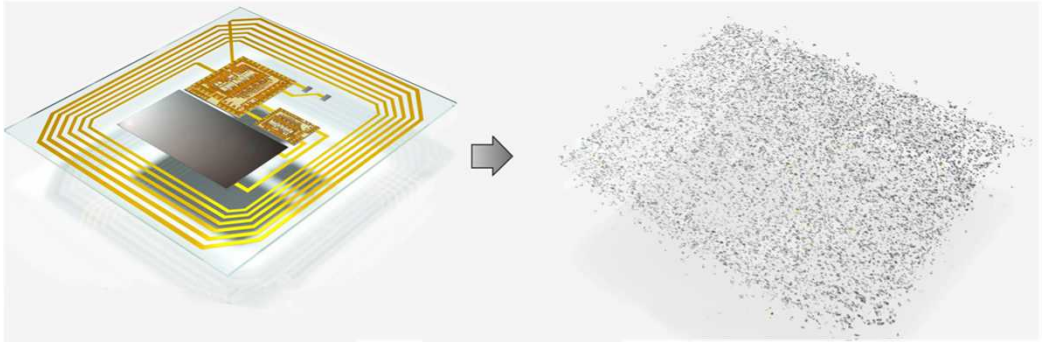

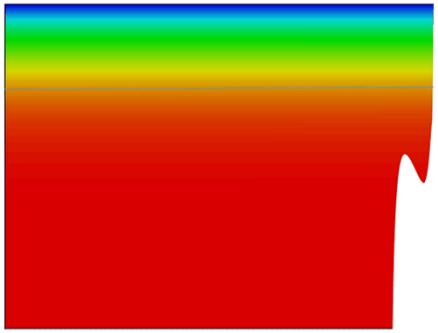

Predicting Fragmentation of Ion-Exchanged Glass

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1. Sandia National Laboratories
2. Palo Alto Research Center – A Xerox Company

Materials Science & Technology 2016

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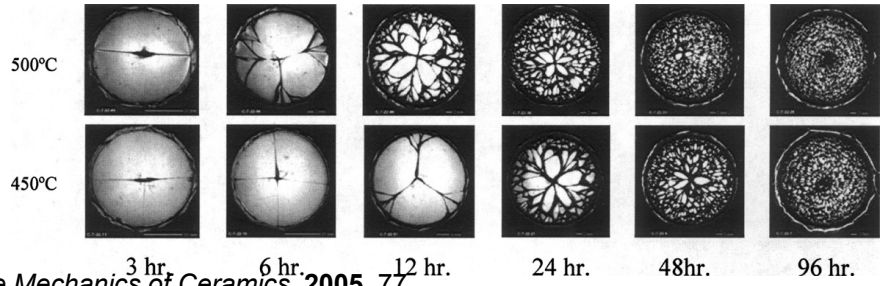
Outline

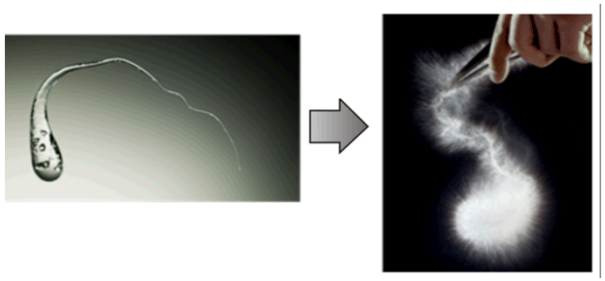
- Motivation / Approach
- Background
- Method: Model Formulation
- Model Results
- Method: Experiments
- Experimental results combined with Simulation
- Conclusions
- Acknowledgements

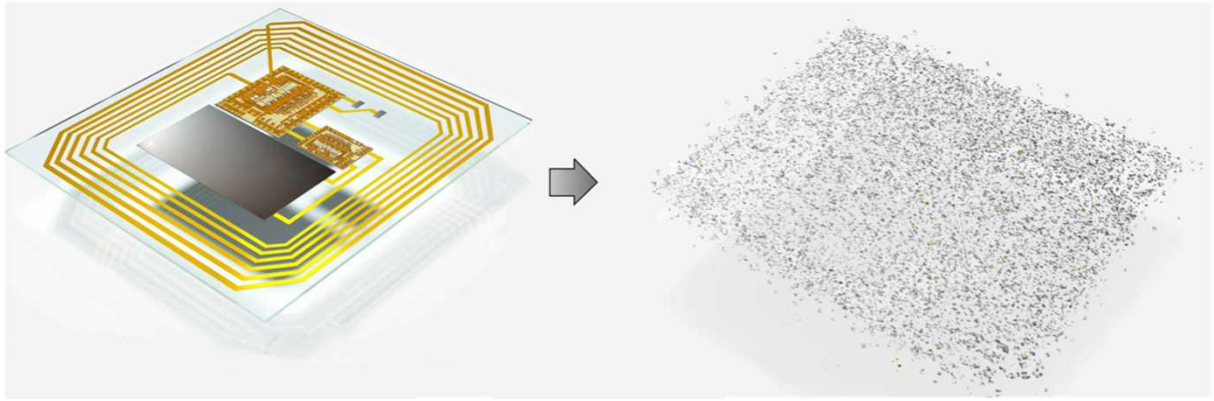
Transient Electronics

- Design disintegrating circuits from highly stressed substrates that fragment upon stress release
- Ion Exchanged glass is a well known material process whose stress profile can be engineered to control fragmentation



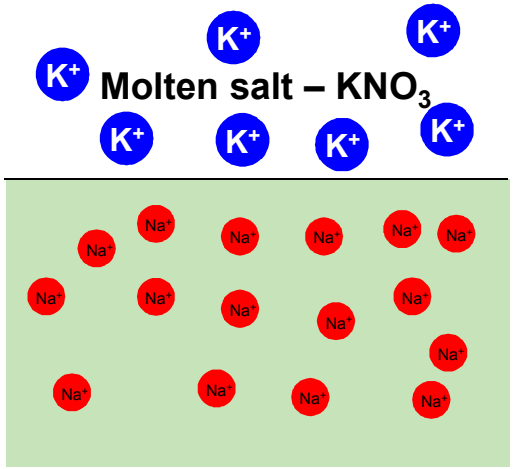
Fracture Mechanics of Ceramics, **2005**, 77



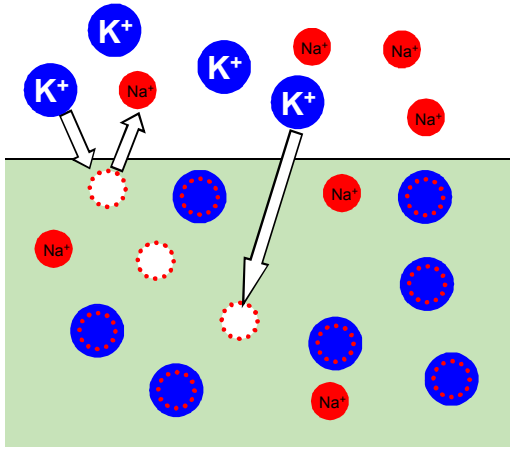


Need predictive model to optimize / minimize particle size after fragmentation.

Ion Exchange Glass Process



Glass in molten salt bath

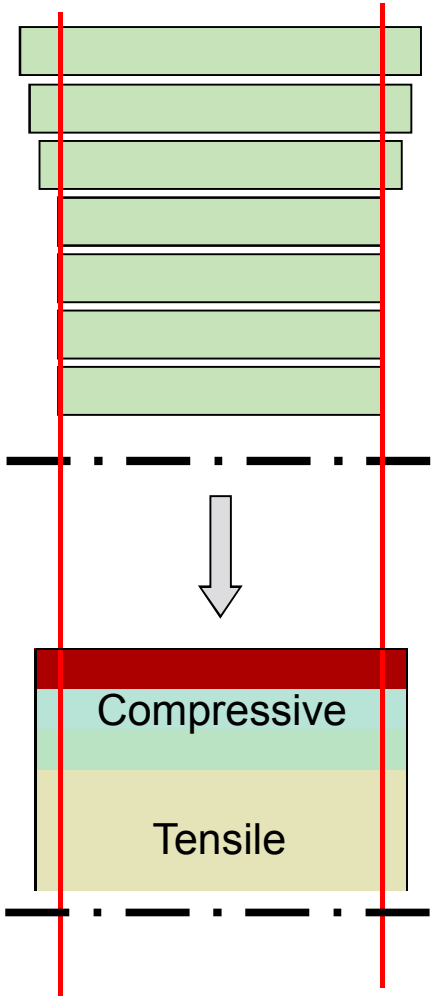


K^+ (in salt) → K^+ (in glass)

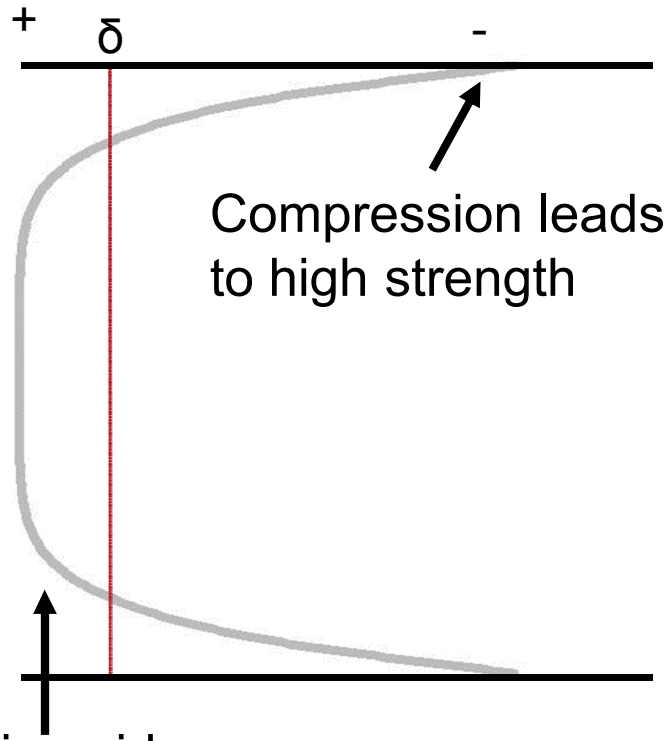
Sodium (Na) containing glass is heated in a molten Potassium Nitrate (KNO_3)
Na^+ ions exchange with K^+ ions

Process Parameters:
Exchange Temperature 400 – 500 °C
Exchange Time 3 – 100 hrs
Glass Thickness

Induced Stress Profile



Stress free condition



Compression leads to high strength

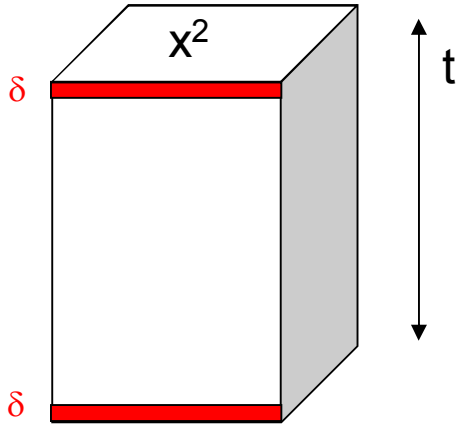
Tension aids fragmentation

Exchange process causes a surface compression layer with a resulting central tension region.

Previous Fragmentation Model

Sandia National Laboratories

Analytical Model



$$\Delta U_E = \left(\frac{1-\nu}{E}\right)\sigma_t^2 dV$$

Energy Stored in Central Tension Region

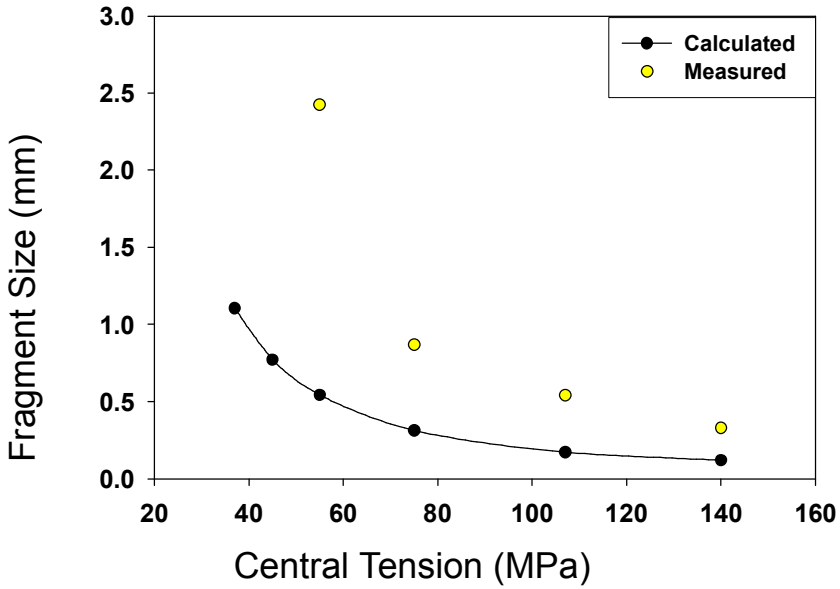
$$U_E = \frac{(1-\nu)}{E}x^2\sigma_t^2(t-2\delta)$$

Energy Required to create the free surface

$$U_S = 4xt\gamma$$

Fragment size, $x = \frac{K_{1c}^2}{\sigma_t^2}(1+\nu)\frac{t}{(0.5t-\delta)}$

Experimental Comparison

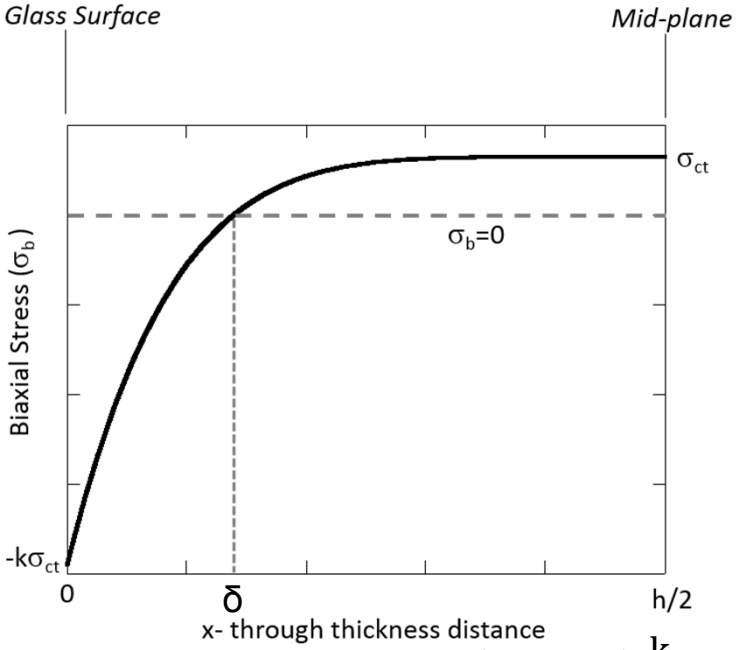


Assumptions in the Analytical model
Not all energy is released.
All of the released energy is not used to create free surfaces.
(e.g. kinetics, heat, sound, etc.)

Fracture Mechanics of Ceramics, **2005**, 77

Model Formulation

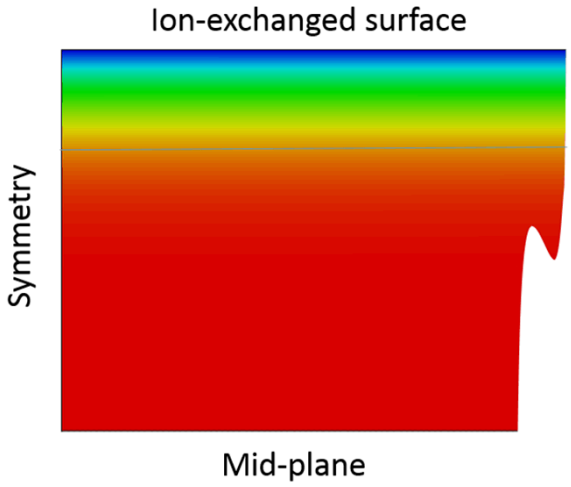
Analytically Imposed Strain Field



$$\frac{\sigma_b}{\sigma_{ct}} = (1-(k+1)\left(\frac{2x}{t}-1\right)^k$$

Simulated Stress Field

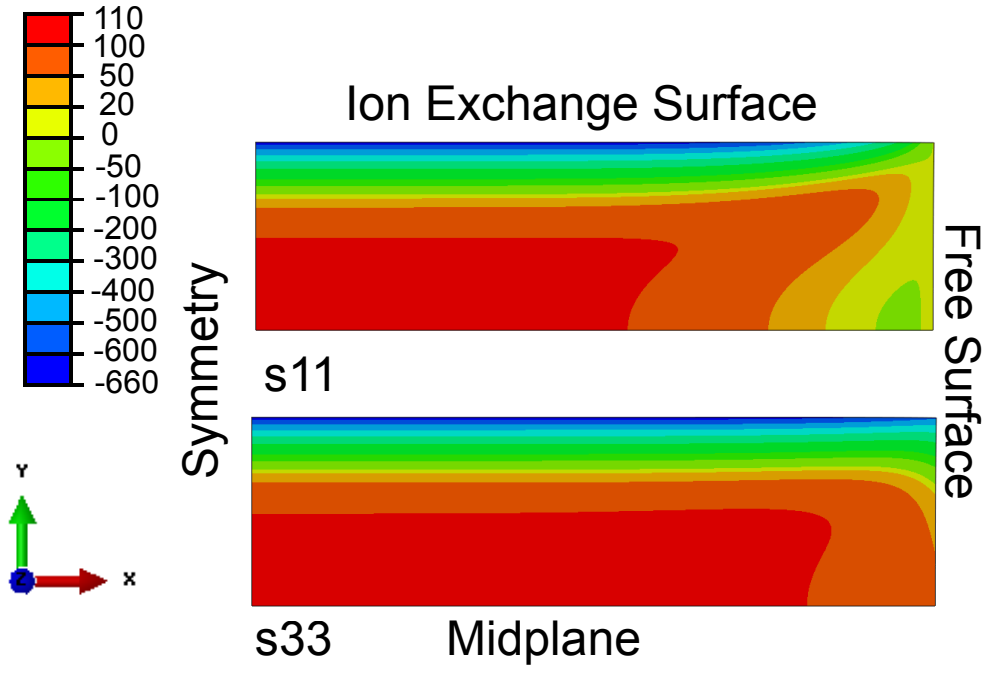
SIMULIA
ABAQUS



Biaxial Stress State

Imposing a strain field with FEA simulations allows for a representation of the stress profile in ion exchanged glass.

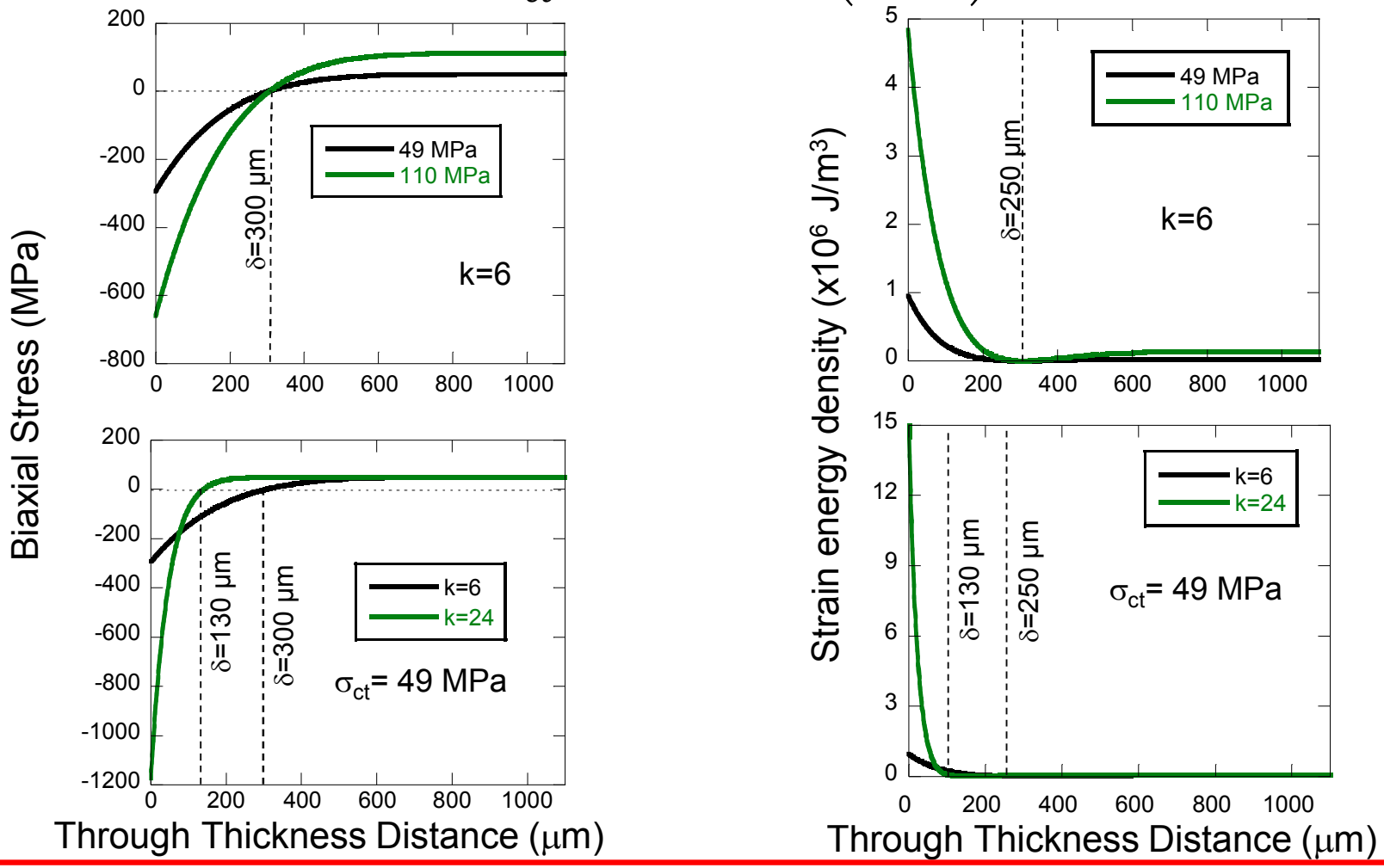
Biaxial Stress State



Simulation represents the stress relieved during the creation of a free surface (i.e. fragmentation).

Model Stress Profile

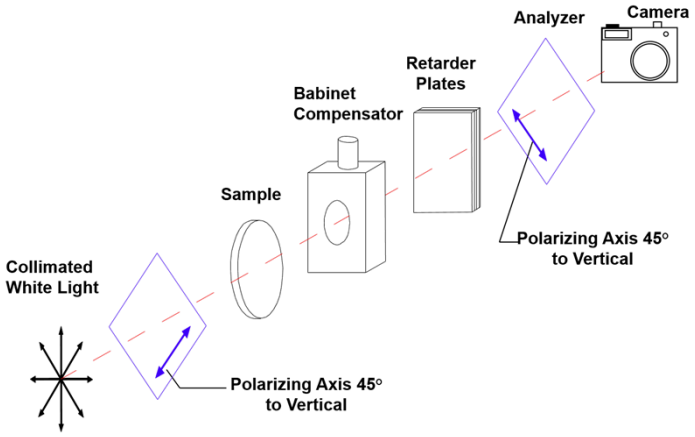
$$\frac{\sigma_b}{\sigma_{ct}} = (1-(k+1)\left(\frac{2x}{t}-1\right)^k$$

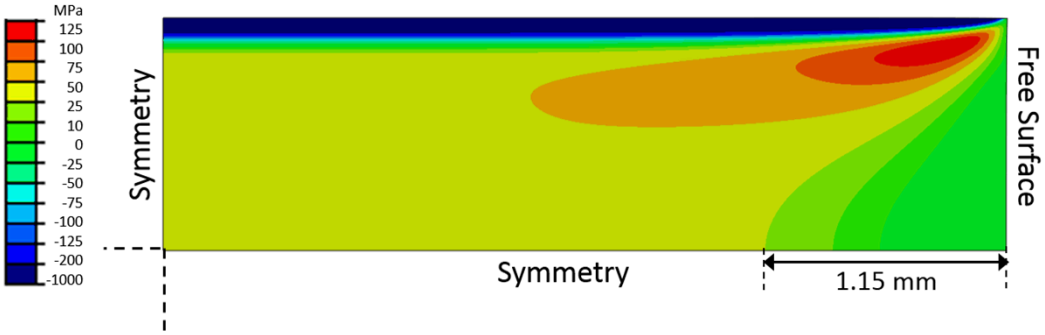


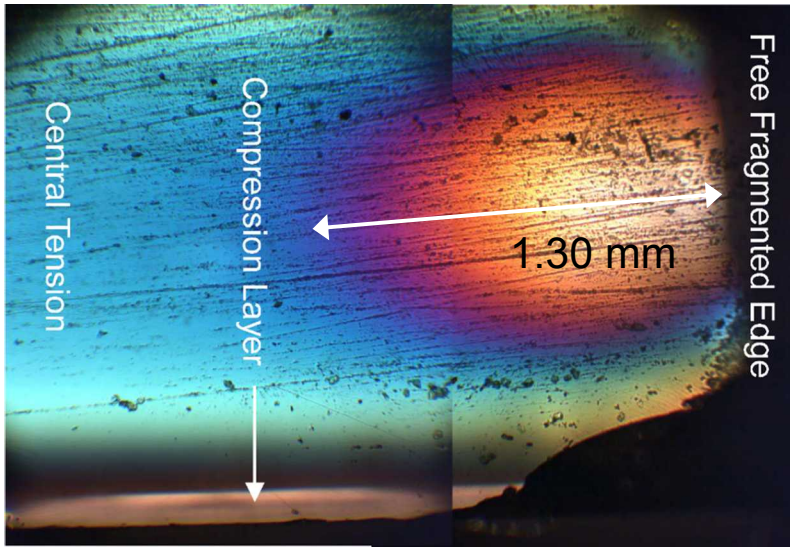
Shape parameter (k) can be used to adjust case depth (δ).

Experimental Comparison

Glass Thickness: 2.2 mm
Exchange Temperature: 450 °C
ExchangeTime: 24 hours
Central Tension: 49 MPa
Case Depth: 138 µm

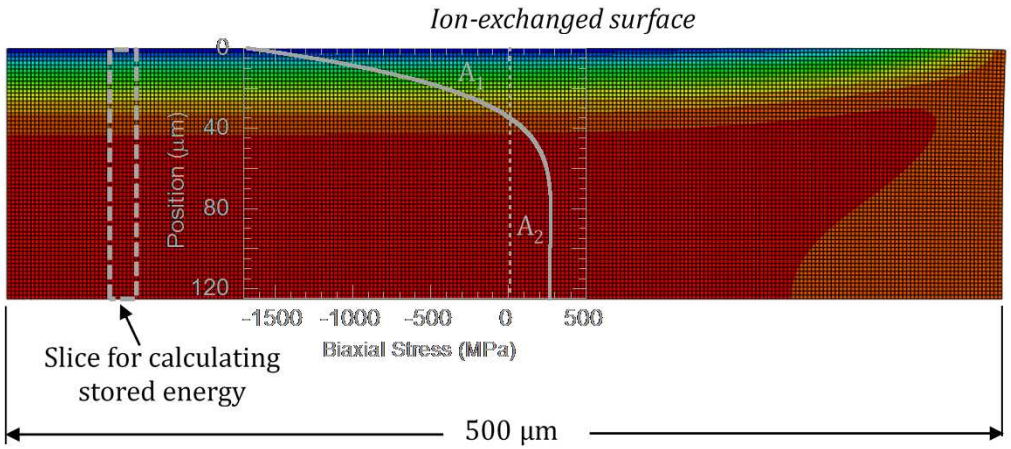


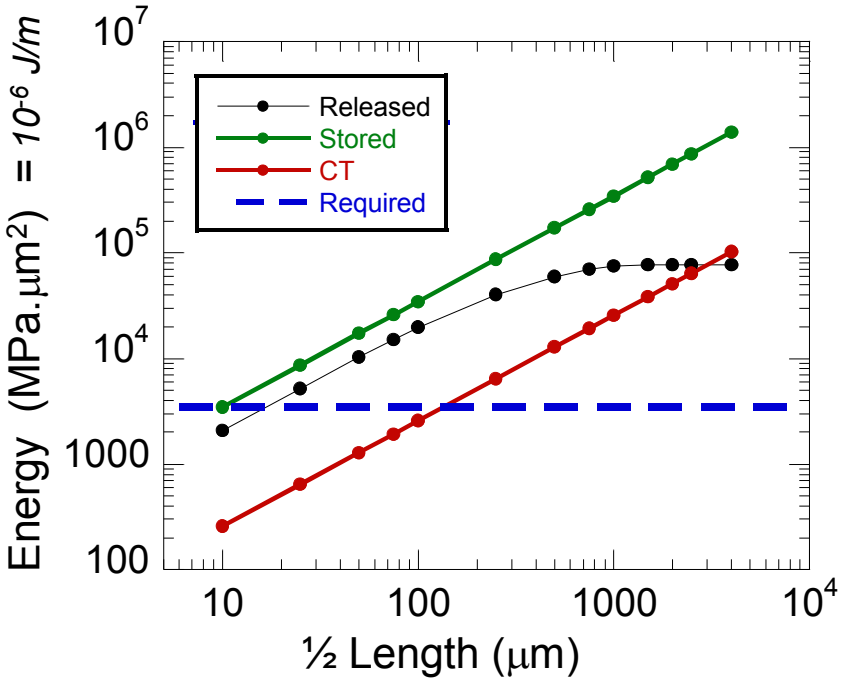




Simulations represents real fragment.

Energy Release Analysis



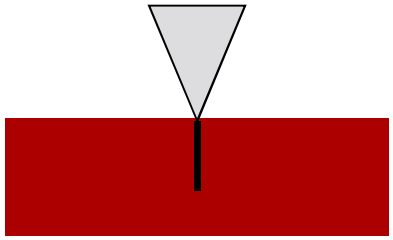


FEA simulations can determine how much energy is released for various fragment sizes.

Image Analysis

Process Protocols:
Glass Thickness: 2.2 mm
Exchange Temperature: 450 °C
ExchangeTime: 24 hours
Central Tension: 49 MPa
Case Depth: 138 μm

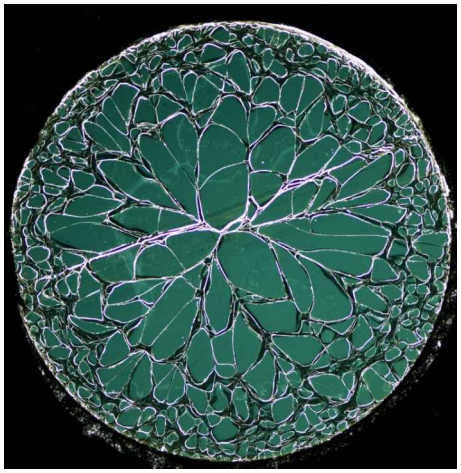
Procedure:
- Gold coated exchanged glass
- Vicker's Punch Loaded to failure
- Image Processing



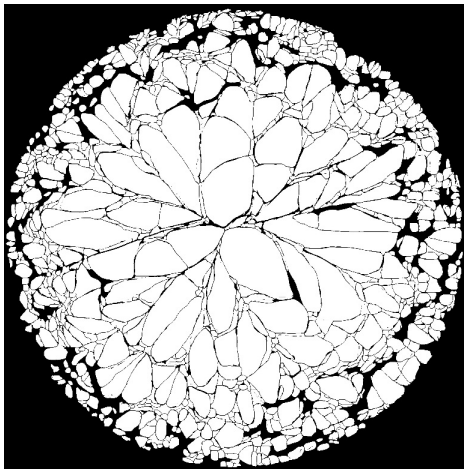
Punch

Reflected light

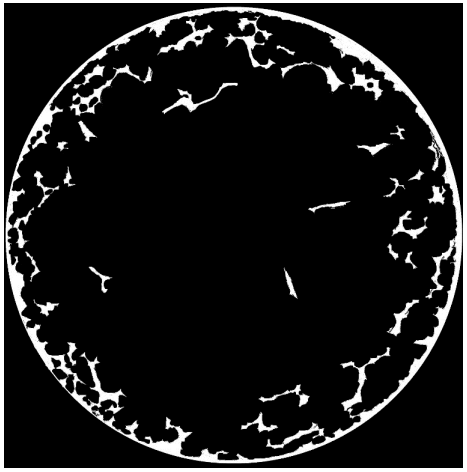
Transmitted light



Binary Image Processed



Unaccounted Area



Experiments Combined with Simulations

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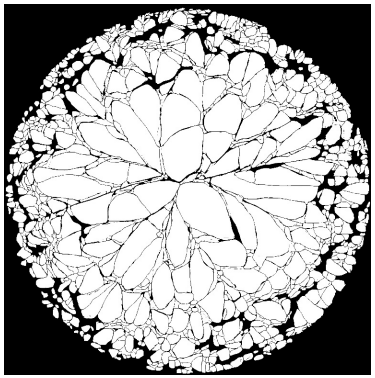
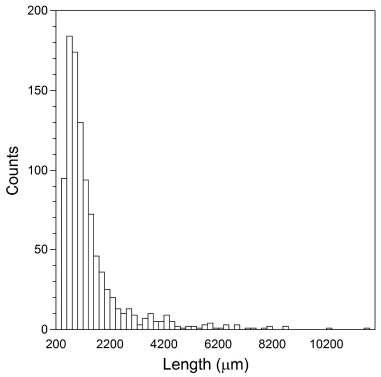
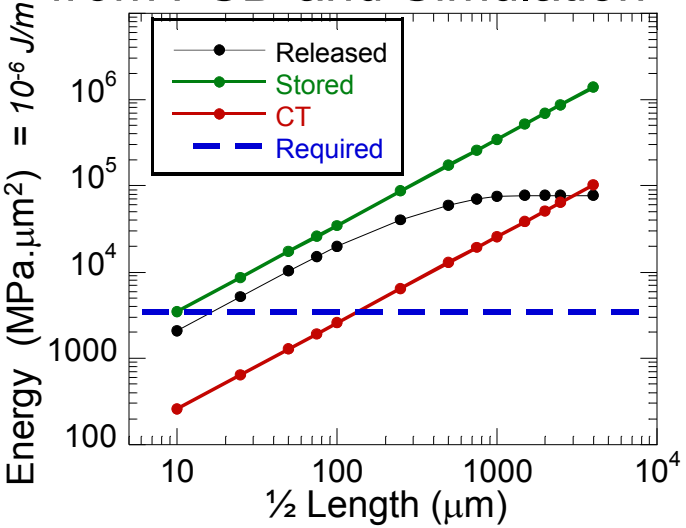
Fragmented Glass



Particle Size Distribution



Calculate Energy Released from PSD and Simulation



Glass	Thickness (mm)	Temp. (C)	Time (hr)	Central Tension (MPa)	Case Depth (μm)	Avg. Particle Size (mm)	Stored Energy Density x10⁶ J/m³	Energy Release / Energy Stored (%)	Energy required / Energy Released (%)
Corning 0317	2.2	450	24	49	130	1.464	0.31 x 10^6	~35%	~5 – 16%
Corning 2319	0.25	400	14	280	54	0.196	2.41 x 10^6	~44%	~3 – 10%

Conclusions

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- FEA can simulate a real ion-exchange glass fragment.
- Simulations can determine:
  - Energy stored in an ion-exchanged glass.
  - Energy released in specific sized fragments.
- Estimate the amount of energy released in fragmented glass.
- Estimate the amount of released energy that goes into creating new surfaces.

Acknowledgements

- Scott Grutzik (SNL)
- DARPA MTO Contract No. HR0011-14-C-0013