Crack Stability and Fracture Initiation in Chemically Tempered Glass:

SAND2014-18866C

Robert Cook's Contributions

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Outline

Engineered Stress Profile (ESP) Glass and its development

- R-curves and crack stability
- Crack stability using compressive stresses
- Reduction to practice and possible uses

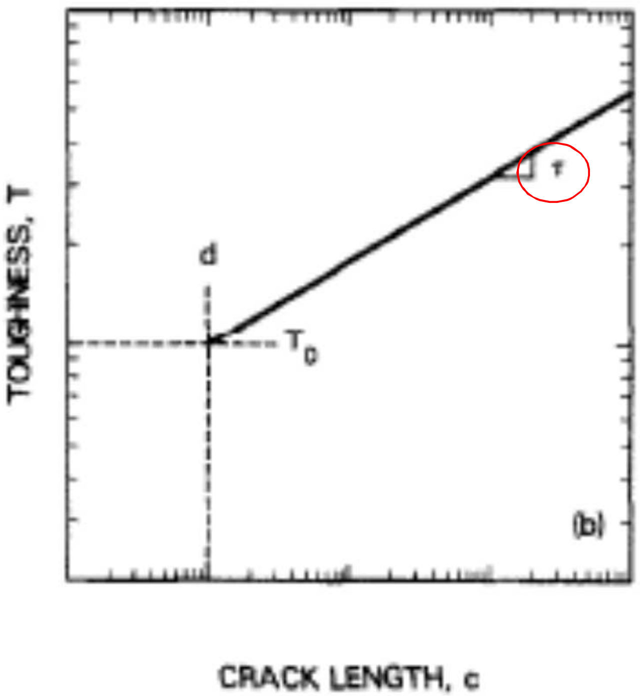
Crack initiation under indentation in Stressed Glass

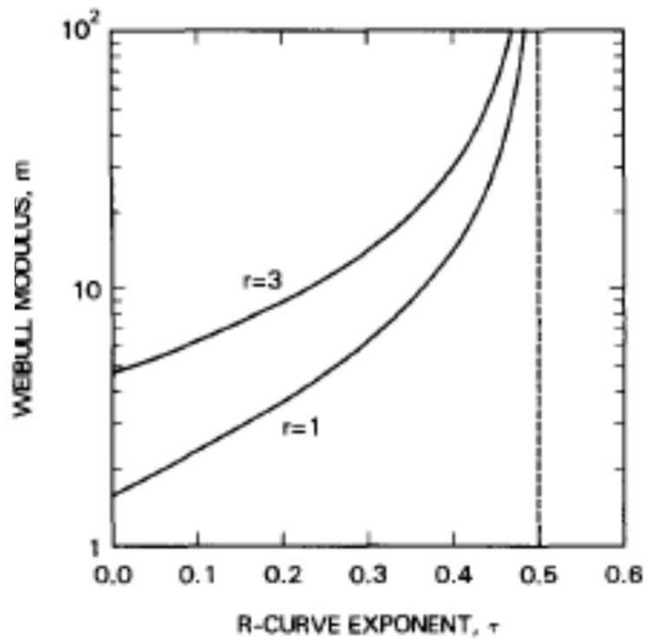
- Fragmentation of glass
- Cracking under load, and load-unload
- Analysis of stress states under indenter
- Possible use of results

Crack Stability, R-Curves and Variability

FRACTURE STABILITY, R-CURVES AND STRENGTH VARIABILITY

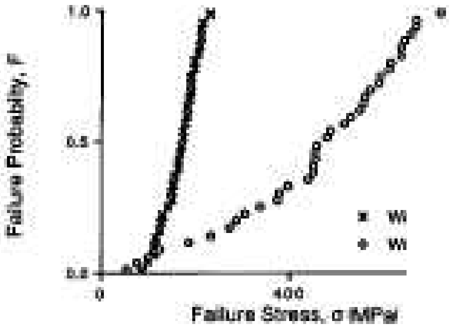
R. F. COOK and D. R. CLARKE
IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598, U.S.A.





Higher exponent= higher Weibull modulus

Strength Variability in Resistance Fields



STRENGTH VARIABILITY IN BRITTLE MATERIALS WITH STABILIZING AND DESTABILIZING RESISTANCE FIELDS

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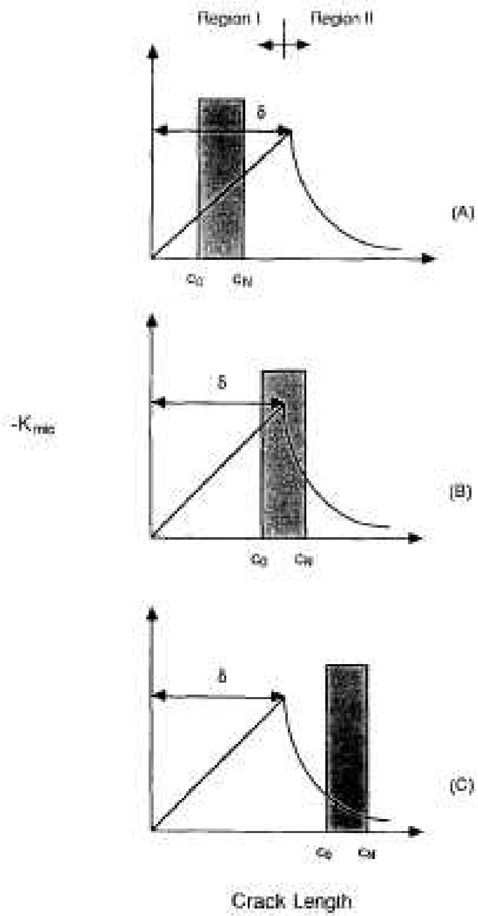

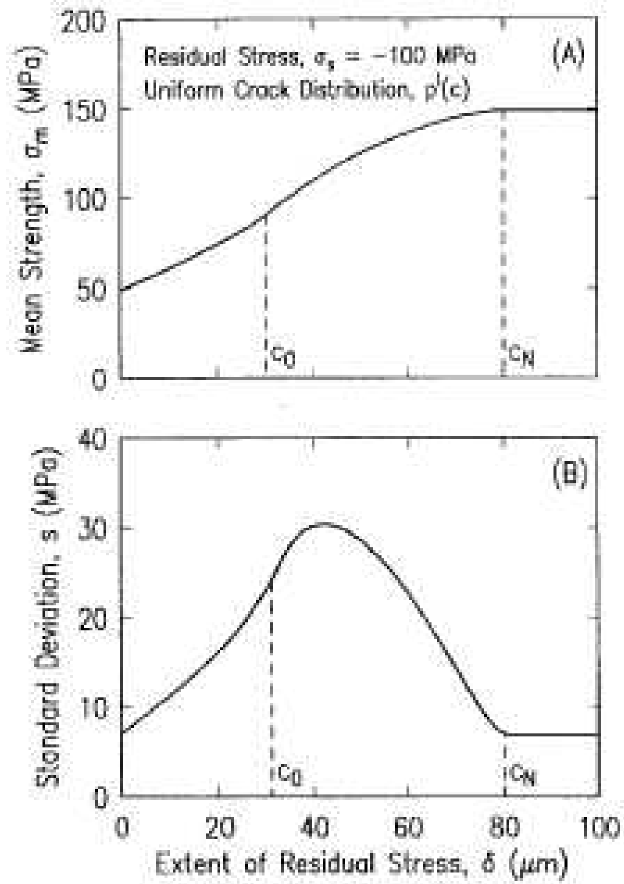

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J. Am. Ceram. Soc., 74 [8] 1981–86 (1991)

Crack Stability and *T*-Curves Due to Macroscopic Residual Compressive Stress Profiles

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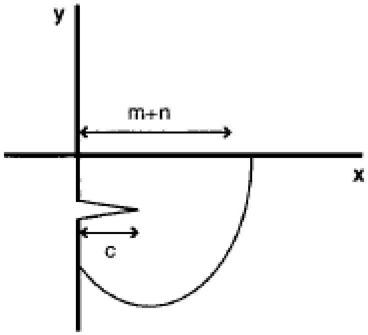

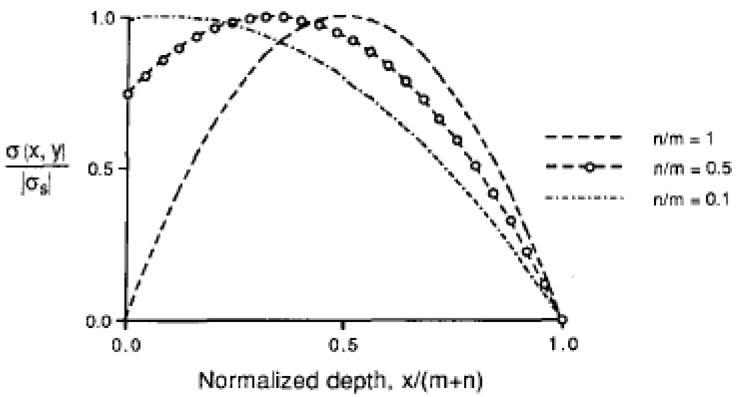

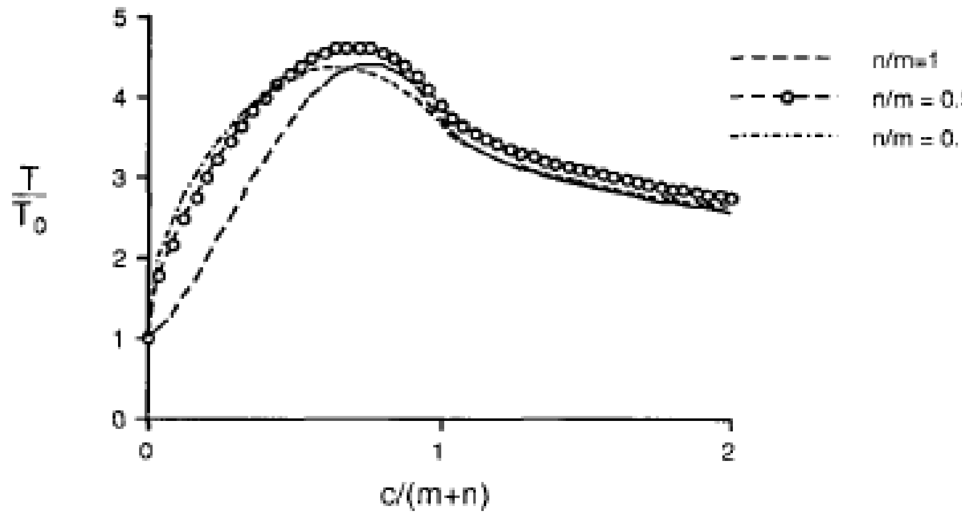

tion of microstructure-based mechanisms of inducing crack stability. Hence, upon introduction of a suitable stress profile, such an approach could be used even for glass, in order to improve the mechanical reliability in ways which are usually associated with microstructural toughening mechanisms.

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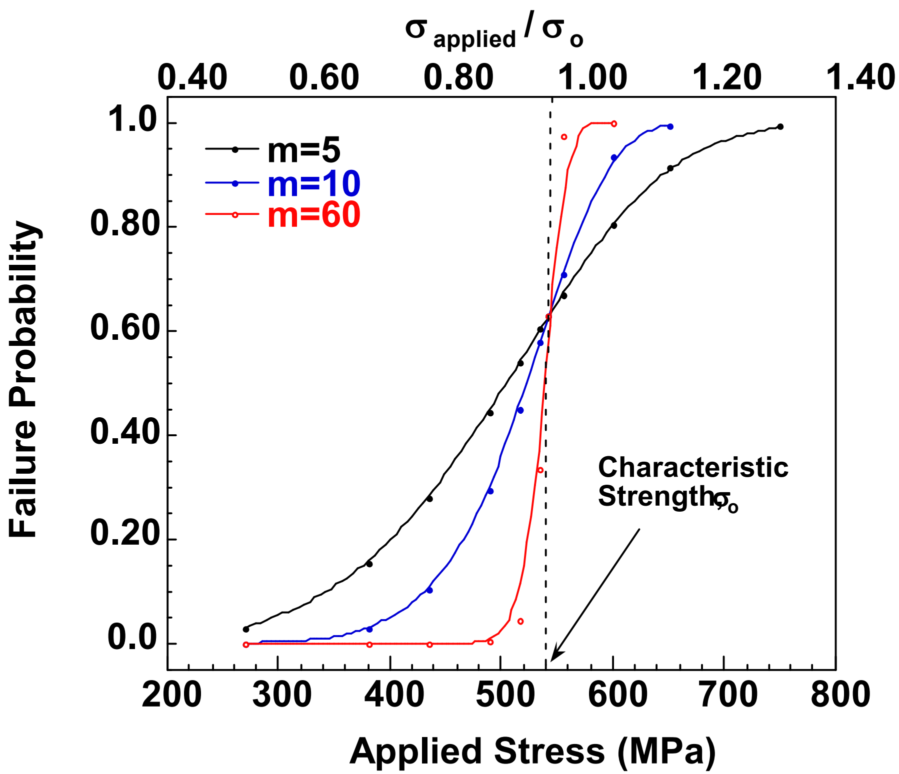
Engineered Stress Profile (ESP)

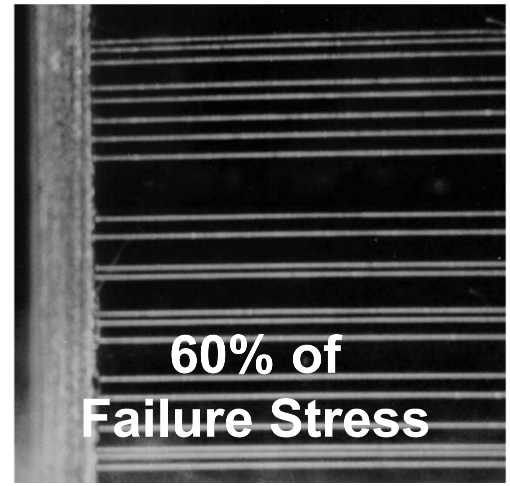
Crack Arrest and Multiple Cracking in Glass Through the Use of Designed Residual Stress Profiles

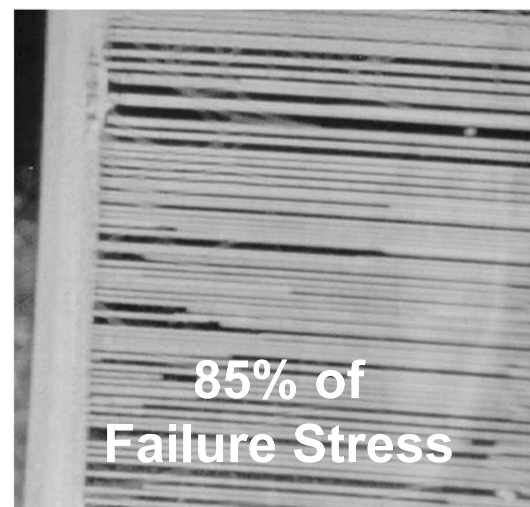
D. J. Green,[1*] R. Tandon,[2] V. M. Sglavo[3]

Science, 1996



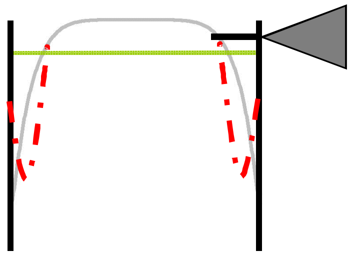
- ESP glass cracks non-catastrophically prior to failure (provides warning!)

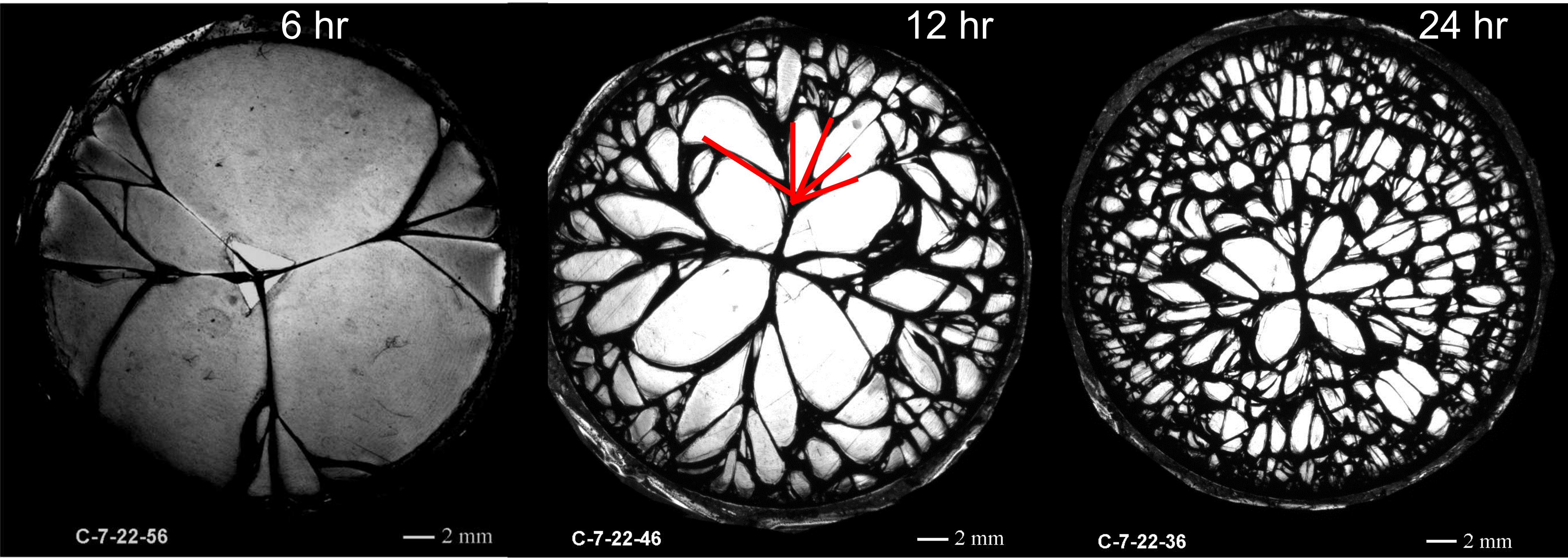




Fragmentation in IE Glass

When a crack penetrates into central tension, fragmentation can ensue





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J. Am. Ceram. Soc., 73 [4] 787–817 (1990)

Direct Observation and Analysis of Indentation Cracking in Glasses and Ceramics

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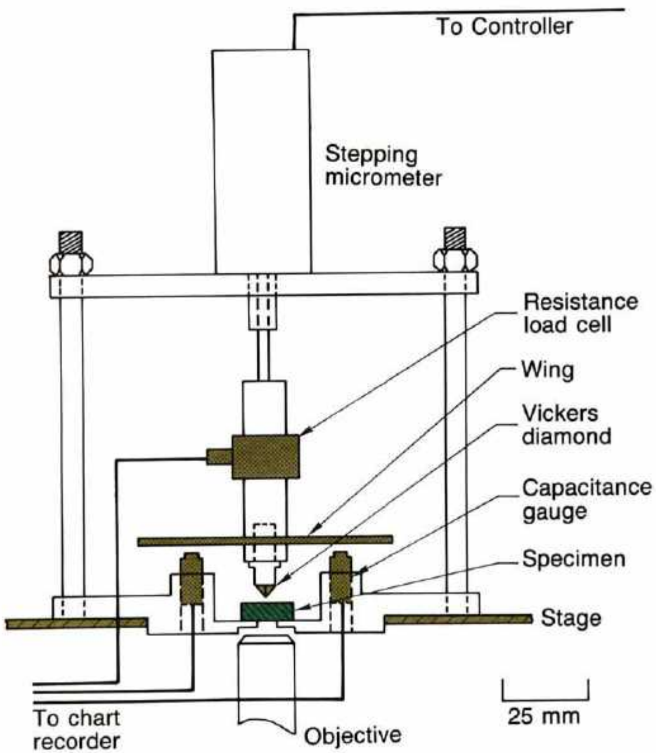
Department of Materials Science, Rice University, Houston, Texas 77251



$$\sigma_{rr} = \frac{P}{4\pi r^2}(1 - 7\cos\theta) + \frac{B}{r^3}(19\cos^2\theta - 7) \quad (1a)$$

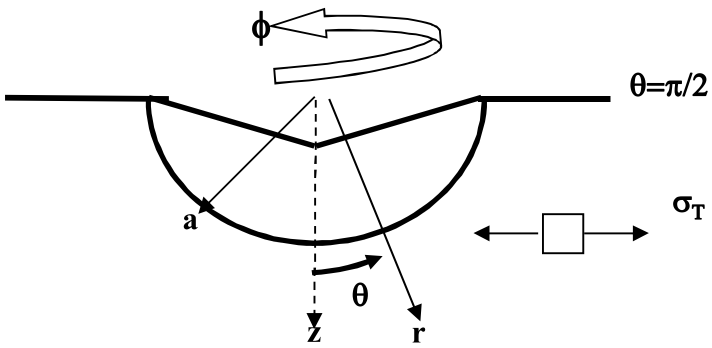
$$\sigma_{\theta\theta} = \frac{P}{4\pi r^2}\frac{\cos^2\theta}{(1+\cos\theta)} - \frac{B}{r^3}\cos^2\theta \quad (1b)$$

$$\sigma_{\phi\phi} = \frac{P}{4\pi r^2}\left(\cos\theta - \frac{1}{(1+\cos\theta)}\right) + \frac{B}{r^3}(2 - 3\cos^2\theta) \quad (1c)$$

$$\tau_{r\theta} = \frac{P}{4\pi r^2}\frac{\sin\theta\cos\theta}{1+\cos\theta} + \frac{B}{r^3}5\sin\theta\cos\theta \quad (1d)$$

$$\tau_{r\phi} = \tau_{\theta\phi} = 0 \quad (1e)$$

Stresses at Indentation Site



$$\sigma_{rr} = \frac{P}{4\pi r^2}\left(1 - 7\cos\theta\right) + \frac{B}{r^3}\left(19\cos^2\theta - 7\right)$$

$$\sigma_{\theta\theta} = \frac{P}{4\pi r^2}\frac{\left(\cos^2\theta\right)}{\left(1+\cos\theta\right)} - \frac{B}{r^3}\cos^2\theta$$

$$\sigma_{\phi\phi} = \frac{P}{4\pi r^2}\left(\cos\theta - \frac{1}{\left(1+\cos\theta\right)}\right) + \frac{B}{r^3}\left(2 - 3\cos^2\theta\right)$$

$$\sigma_{r\theta} = \frac{P}{4\pi r^2}\frac{\left(\sin\theta\cos\theta\right)}{\left(1+\cos\theta\right)} - \frac{5B}{r^3}\sin\theta\cos\theta$$

P= Instantaneous Load
B= Strength of Blister field

Asymmetry:
Loading: P and B increase
Peak Load: $P=P_{max}$, $B=B_{max}$
Unloading: $B=B_{max}$, $P \rightarrow 0$

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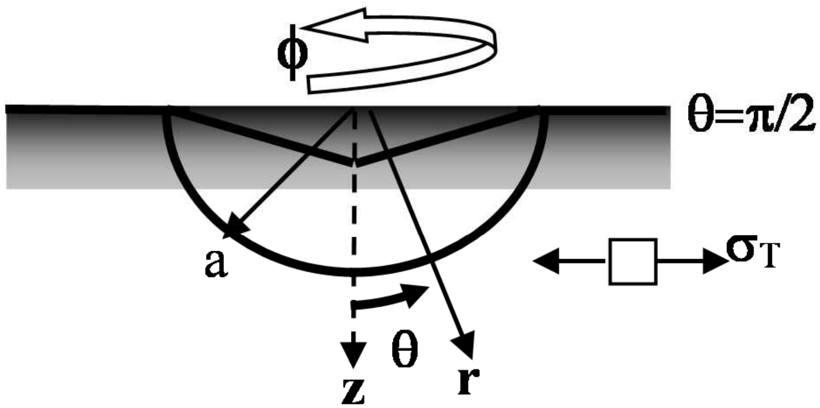
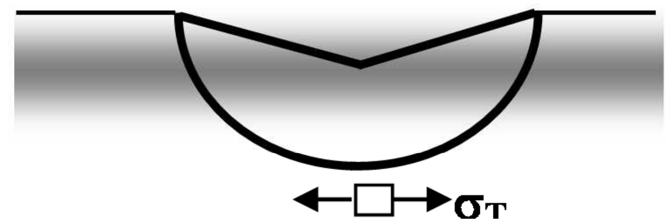
Superimposed Residual Stress





$$\sigma_x = \sigma_y = \sigma(z); \text{All other components} = 0$$

$$\sigma_{rr} = \sigma(z)\sin^2\theta$$

$$\sigma_{\theta\theta} = \sigma(z)\cos^2\theta$$

$$\sigma_{\phi\phi} = \sigma(z)$$

$$\sigma_{r\theta} = \sigma(z)\sin\theta\cos\theta$$

Crack Initiation- Median and Radial

Median crack initiation controlled by $\sigma_{\theta\theta}$ at $\theta=0$, r=a
Radial cracks initiation controlled by $\sigma_{\phi\phi}$ at $\theta=\pi/2$, r=a
At peak load

$$\sigma_{\theta\theta}\Big|_{\theta=0} = 0.065H > 0$$

$$\sigma_{\phi\phi}\Big|_{\theta=\pi/2} = -0.13H < 0$$

At complete unload, P=0, and we obtain

$$\sigma_{\theta\theta}\Big|_{\theta=0} \approx -0.06H < 0$$

$$\sigma_{\phi\phi}\Big|_{\theta=\pi/2} \approx 0.12H > 0$$

Median crack initiation stress at peak load is ~ ½ of the radial crack initiation at unload

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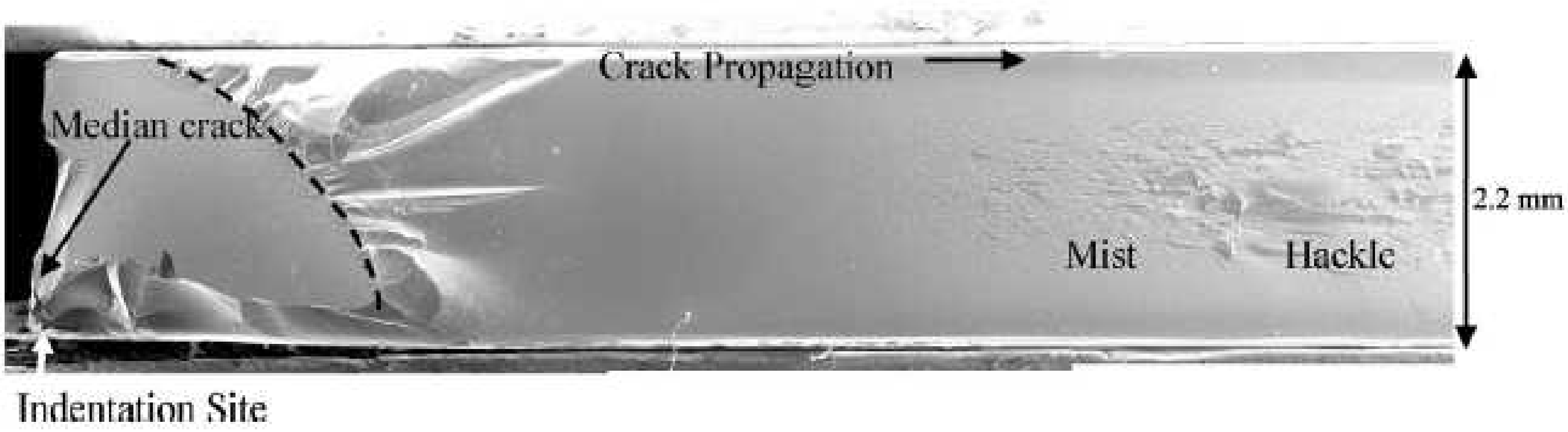
Fracture Surface Observations



Montage of images showing the fracture surface for a 24 hr., 450°C sample loaded monotonically to fracture. Bottom left is the fracture origin. The crack pops-in, propagates through the thickness, and then sweeps through the sample, from left to right.

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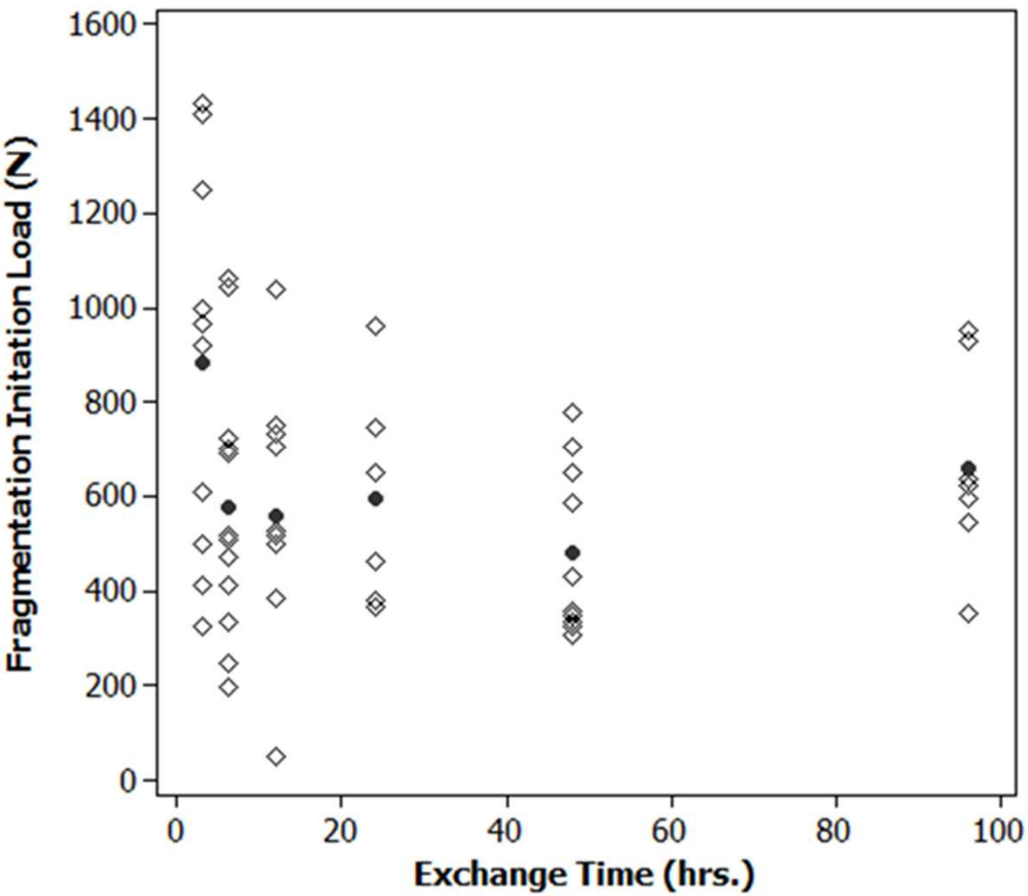
Fracture initiation and fragmentation in chemically tempered glass

Rajan Tandon *, S. Jill Glass

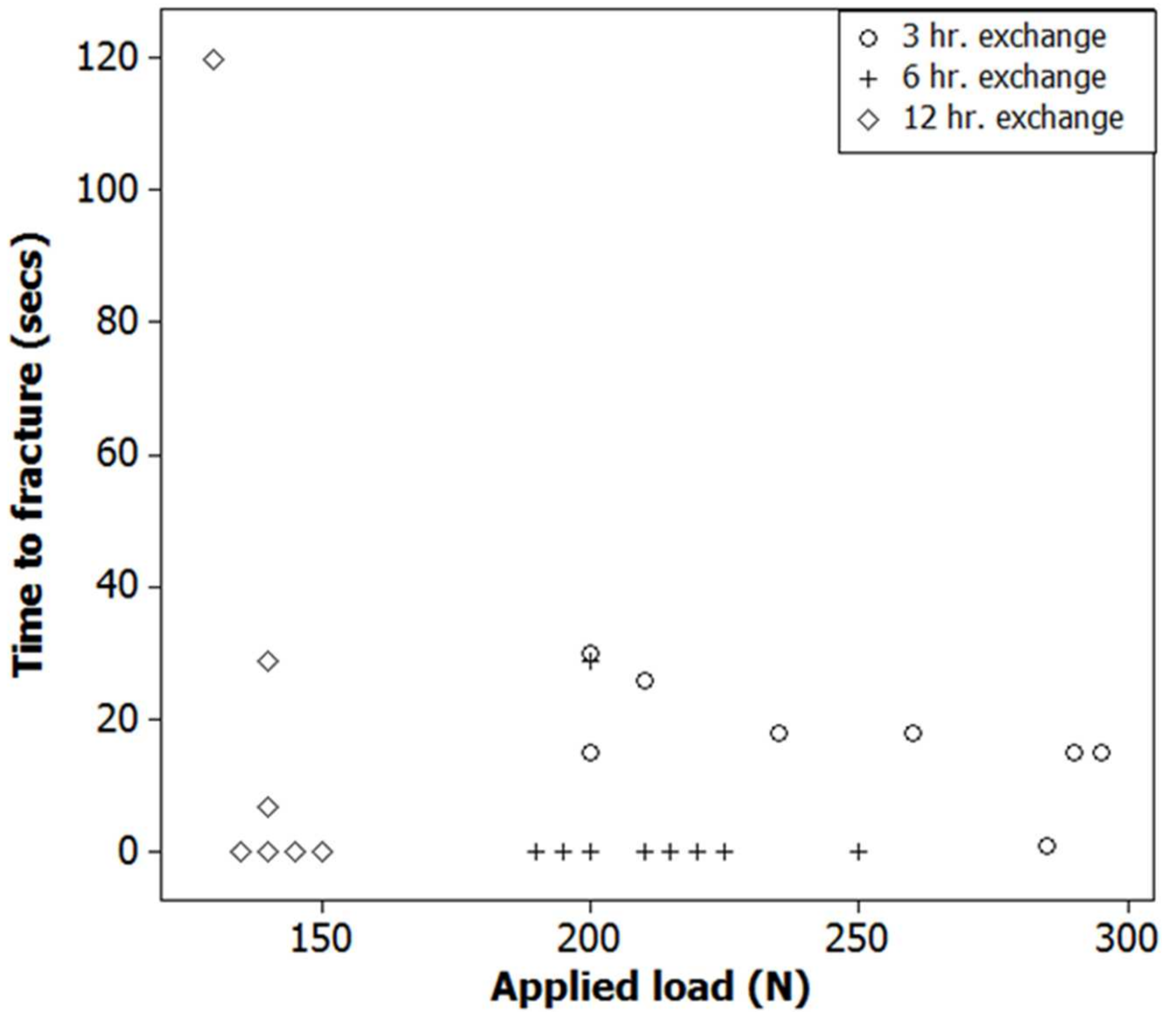


1. The average load to cause cracking during loading is approximately identical

Average stress to initiate median ~420 MPa

Continuously loading to failure-
Average load for different exchanges ~600 N

Load-Unload Cracking loads are much lower



2. Load required to cause cracking during/after unload is highest for the smallest exchange times

3. This load is much lower than the load to cause cracking during loading

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Conclusions

Crack stability, high strength and very low variability are possible by engineering stress profiles in materials

- Pressure switches

Indentation stress fields can be used to estimate crack initiation loads under load, load-unload conditions

- Understanding of load dependence opens up design space for pressure switch applications

Abstract

Crack Stability and Fracture Initiation in Chemically Tempered Glass

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Crack stability is usually observed in materials with pronounced R-curve behavior. However, crack stability can also be induced in ion-exchanged glasses by tailoring the residual stress profiles. This idea has led to the development of Engineered Stress Profile (ESP) glasses, and other laminated structures with similar behavior. Robert Cook's contributions to these developments will be described. The high central tension in these glasses also leads to applications where fragmentation upon fracture is needed. The fracture initiation by loading the glasses with a Vicker's indenter is described. By extending the Yoffe-Cook-Pharr analysis of stresses at the indentation site, a qualitative understanding of the load dependence of fracture initiation becomes possible.

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