Optical and Photonic Glasses

Lecture 9:

Cracking and Stress Corrosion

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For glass specimens with pre-existing surface flaws (usually due to handling), fracture is controlled by **crack propagation**. When a critical stress level, the applied fracture stress, σ_a^{fr}, is reached for the largest flaw with proper orientation (called the *critical flaw*, of length $2c_{cr}$), Griffith's criterion may be expressed as $\sigma_a \geq \sigma_a^{fr} = (E\gamma/c_{cr})^{1/2}$, indicating *catastrophic failure*.

However, if $\sigma_a < \sigma_a^{fr}$ (for example, for a glass window under a static load), there will be no failure. Unless the glass part exhibits *static fatigue*, or delayed failure, which consists of *slow crack growth*, under a sub-critical, static applied stress, until the most severe crack reaches the length $2c_{cr}$ and brittle fracture occurs.

Such phenomenon, in common silicate glasses, is usually attributed to *stress corrosion* at the crack tip, where strained bonds are broken, often by the combined action of stress and atmospheric humidity:

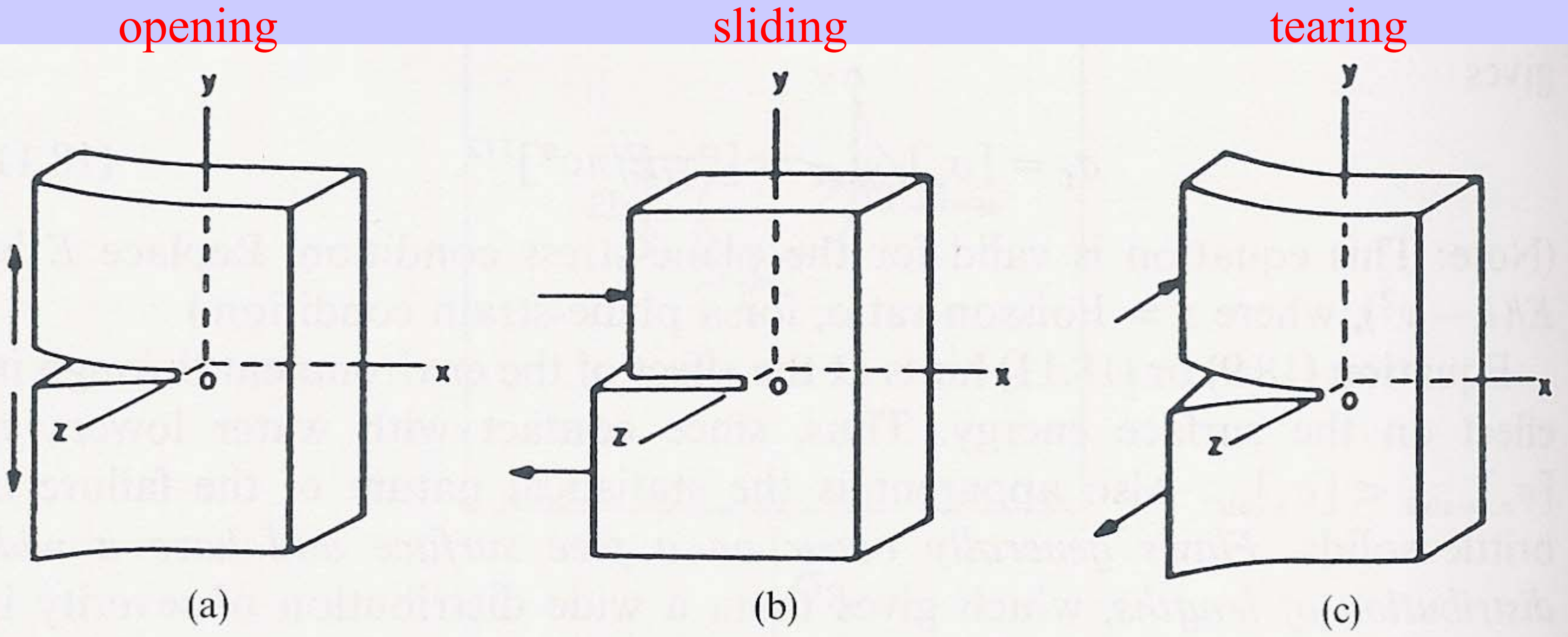
$$\text{Si-O-Si} + H_2O = \text{Si-OH} + \text{HO-Si}$$

forming a gel-like region where the crack is able to propagate under sub-critical conditions. It thus becomes important to follow the velocity of crack propagation as a function of the stress intensity factor K, for the three possible independent *modes of crack propagation*.

Most glasses actually fracture under the opening mode (I), at a **critical stress intensity factor** value K_{Ic}:

$$K_{Ic} = Y\, \sigma_a^{fr}\, c_{cr}^{1/2} = (\pi\, E\, \gamma)^{1/2} \qquad (\text{ since: } \sigma_a^{fr}\, c_{cr}^{1/2} = (E\gamma)^{1/2}\,)$$

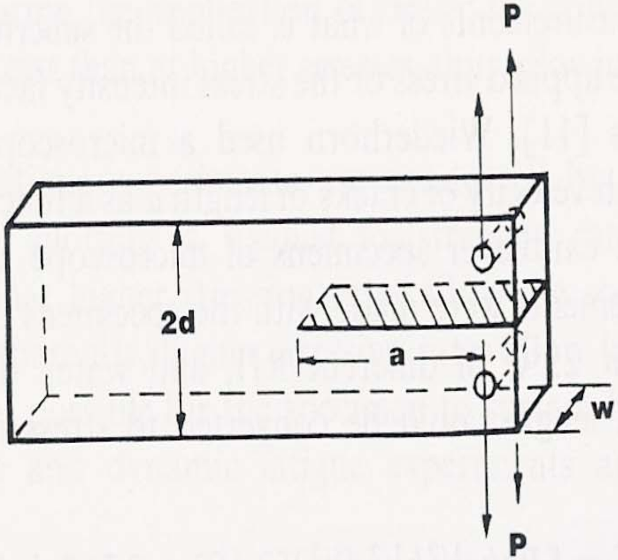
which is called the *fracture toughness*.



The different modes of crack extension. (a) Opening. (b) Sliding. (c) Tearing.

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)

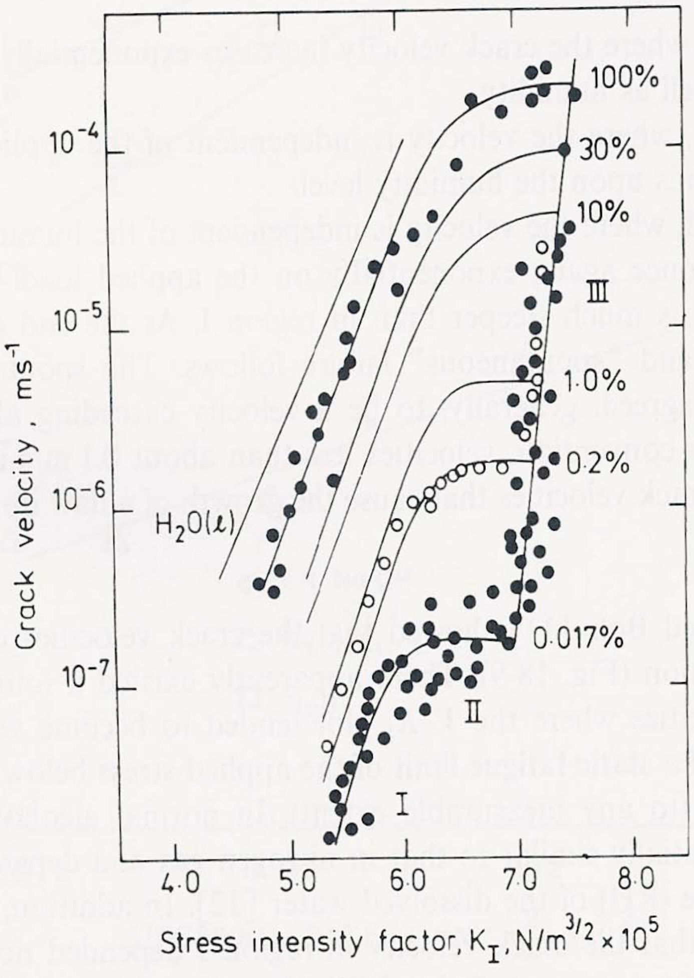
The fracture toughness, K_{Ic}, is an intrinsic property of the glassy material, which may, for example, be determined directly by measuring with a microscope the sub-critical velocity of a controlled propagating crack of length a, in a *double cantilever beam* specimen, or, indirectly, from measurements of the bending strength (three or four point methods) or the microhardness (Knoop or Vickers tests).



Double cantilever beam specimen configuration to measure crack velocity. Hatched areas represents the uncracked portion of the specimen ("web") between the guiding notches. (After Wiederhorn [11a]. Reproduced with permission of The American Ceramic Society.)

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)

Crack velocity, v = dc/dt, as a function of K, for soda-lime-silica glass, in a nitrogen atmosphere with humidity values between ~ 0 – 100 %.



Crack velocity vs. applied intensity factor for soda lime silica glass in N_2 gas of varying levels of humidity. (After Wiederhorn [11a]. Reproduced with permission of The American Ceramic Society.)

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)

Region I – crack velocity increases exponentially with the applied load and the humidity; the dependence on the applied load may be expressed as:

$$v = A\, K_I^{\,n}$$

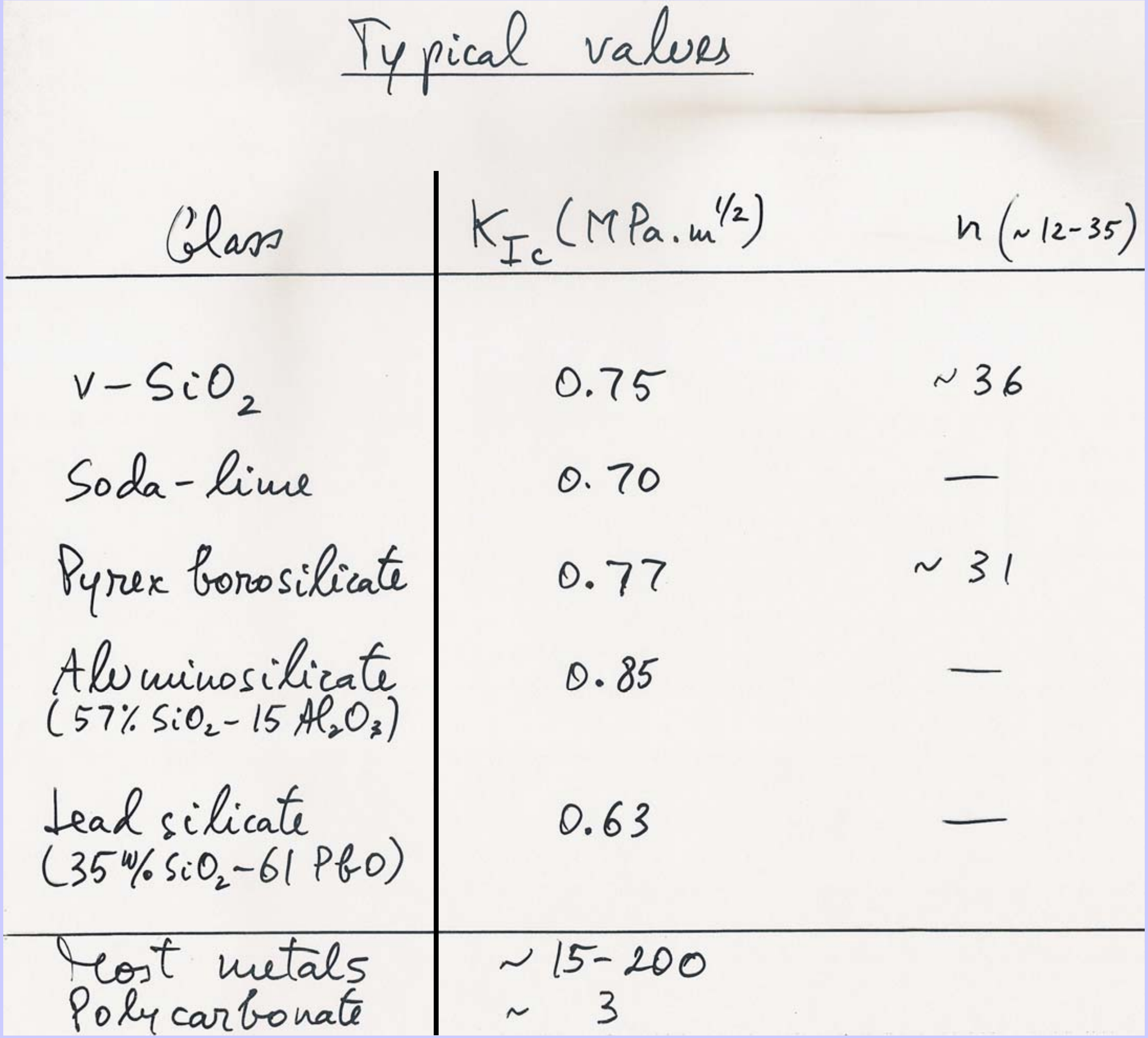
where n is the so-called *stress corrosion susceptibility* parameter, varying between ~ 12 - 35 for most (modified) glasses, but reaching a value of 72 for v-SiO_2.

The lower n is, the larger is the stress corrosion susceptibility of the glass. The NBO bonds in modified glasses are especially prone to breaking under the combined influence of an applied stress and water vapor in the ambient atmosphere. The temperature has also an influence on the v – K_I curves.

Region II – crack velocity depends on the humidity level, but is independent of the applied stress.

Region III – crack velocity depends on the applied stress, but it is independent of the humidity. The slope is steeper than in region I. At the end of region III, crack velocity reaches ~ 0.1 m/s and K_I reaches the critical value K_{Ic}, causing spontaneous failure.

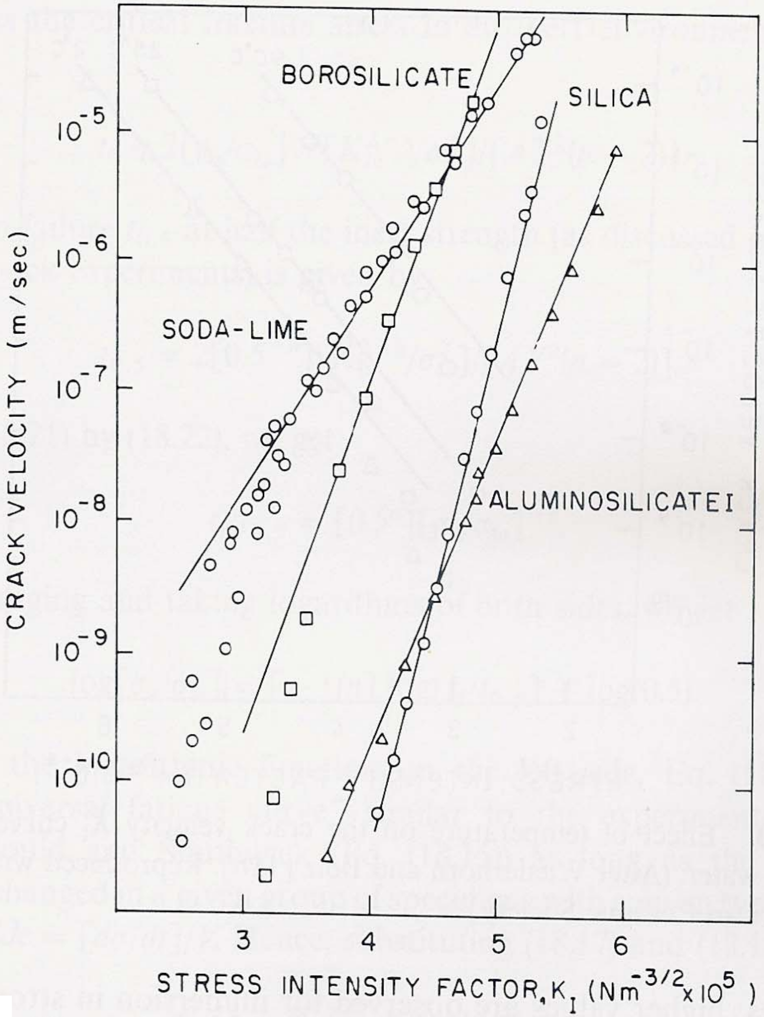
Silica, Vycor and Pyrex glasses exhibit only region I prior to catastrophic failure.



Typical values

Glass	K_{Ic} (MPa.m$^{1/2}$)	n (~12-35)
v-SiO_2	0.75	~36
Soda-lime	0.70	—
Pyrex borosilicate	0.77	~31
Aluminosilicate (57% SiO_2-15 Al_2O_3)	0.85	—
Lead silicate (35 w% SiO_2-61 PbO)	0.63	—
Most metals	~15-200	
Polycarbonate	~ 3	

High silica glass compositions have high values of n, whereas typical window/container glasses are more susceptible to stress corrosion and thus to static fatigue (or delayed failure).

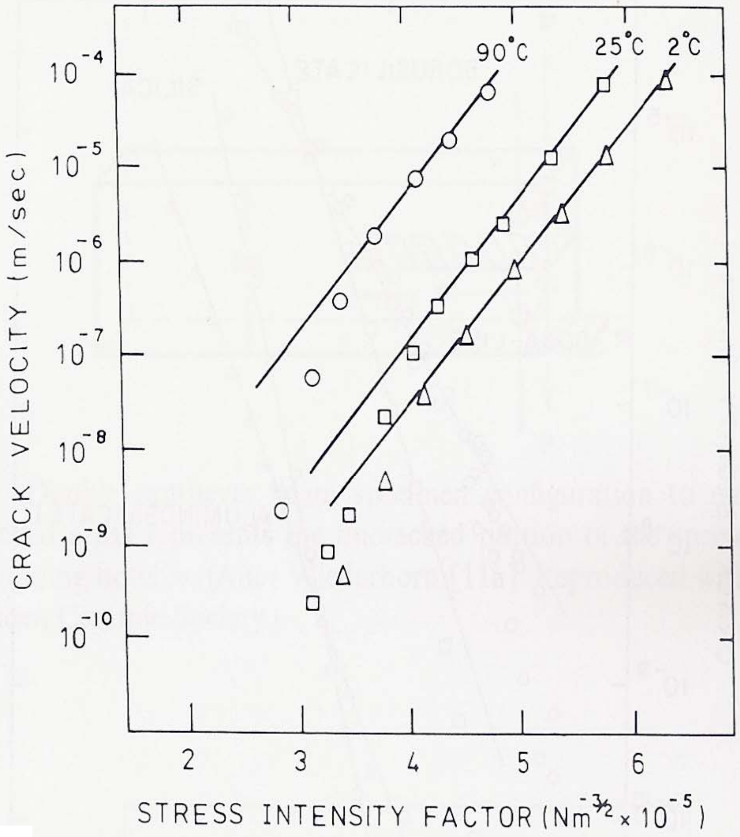


Effect of glass composition on crack velocity–K_I behavior of the various glasses tested in water at room temperature. (After Wiederhorn and Bolz [11b]. Reproduced with permission of The American Ceramic Society.)

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)

An increase in **temperature accelerates** the **stress corrosion** phenomenon and, hence, it increases v = dc/dt.

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)



Effect of temperature on the crack velocity–K_I curves for a soda lime glass in water. (After Wiederhorn and Bolz [11b]. Reproduced with permission of The American Ceramic Society.)

An integration of the equation $v = A\ K_I^n$ eventually leads to an estimate of the *time-to-failure* for a given glassy material under a constant applied stress, σ_a, provided that A, K_{Ic}, n and σ_a^{fr} have been determined. The *time-to-failure* is found to vary inversely with the applied stress.

This analysis may be coupled with *proof-testing*, by subjecting the glass specimens to a stress, σ_{pr}, higher than the known service stress, σ_{serv}. One then obtains an estimate of a *minimum time-to-failure*, as a function of both σ_{serv} and the $\sigma_{pr}/\sigma_{serv}$ ratio, for those specimens which survived the the proof stress, σ_{pr}.