Resistance to FSP Penetration of Some Transparent Materials

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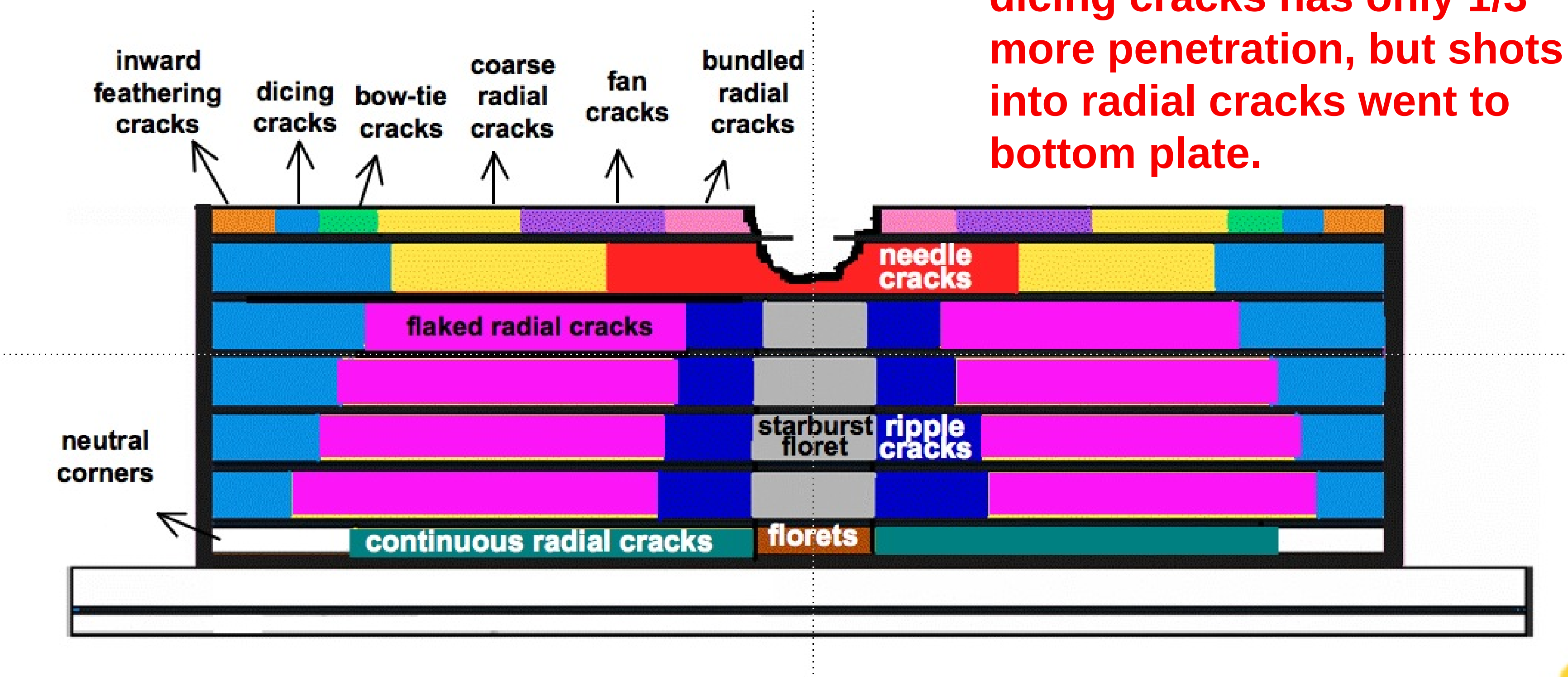
Last ISB: Experiments with .50 FSP into 7-layer glass targets.

Subsequent shots into dicing cracks has only 1/3 more penetration, but shots into radial cracks went to bottom plate.



Experiments with 4-layer targets turned out to give very similar results.

Four-layer targets was tested. First 4 layers same as 7 layer target.

Damage patterns were the same as 7-layer target.

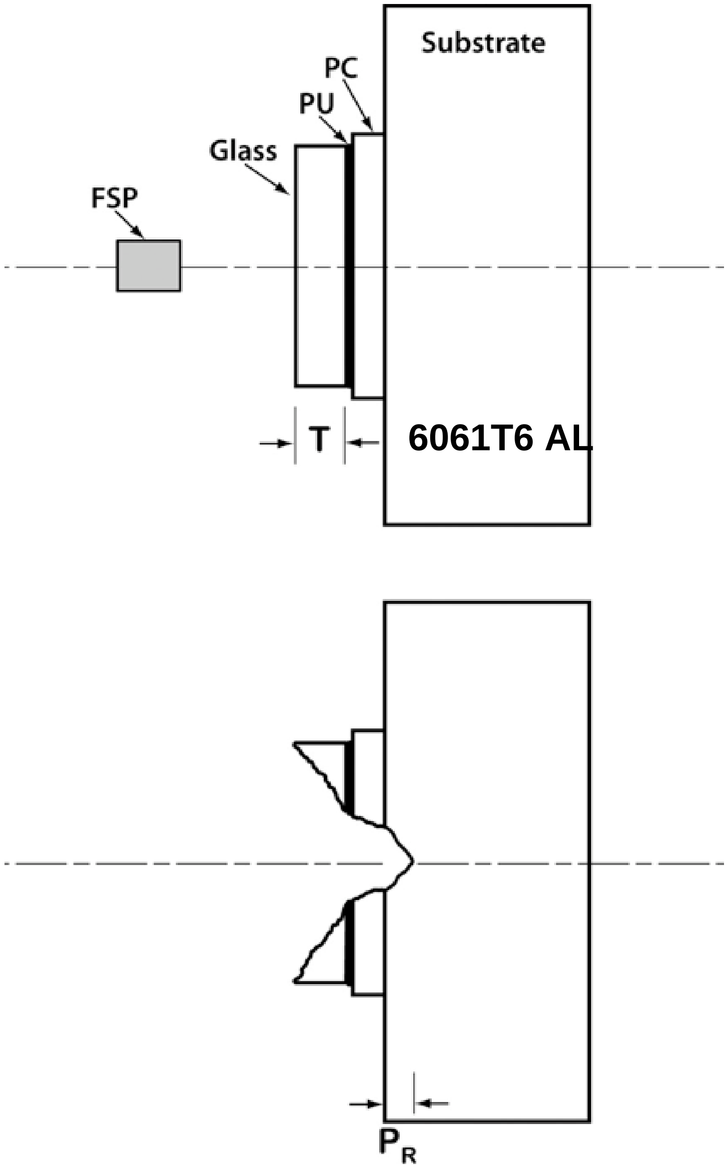
1st shot: P = 24mm. No bulge.

2nd shot into dicing cracks: No change in damage distribution except at impact point. P = 42mm. Slight bulge.

3rd shot into bundled radial cracks (surrounding first impact site): Result was complete penetration.

4th shot into dicing cracks: P=45mm, slight bulge.

DOP testing also gave same result

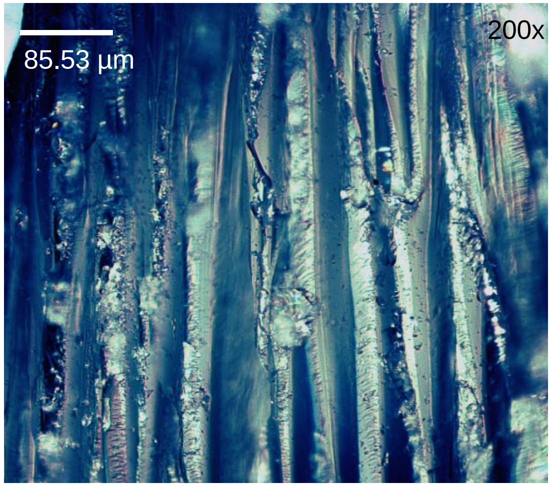


20-shot series.

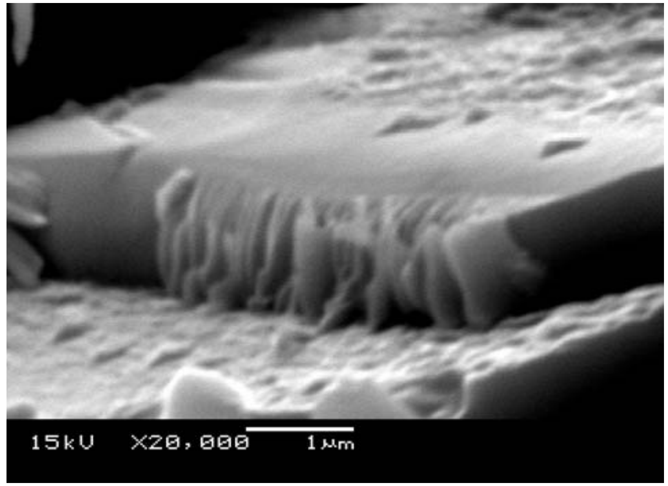
Mass efficiency (rel. to aluminum) was 1.2-1.4. Did not depend on thickness. Edge proximity had little effect.
Performance for 1st and 2nd hits very similar to what was seen in multilayer target.

Recovered particles show fast communition

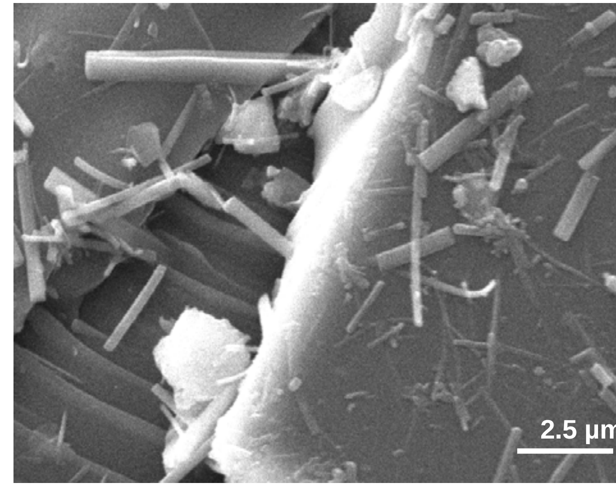
This material exhibited many features indicating very fast fracture, but very few grains showed the FW structure: e.g. conventional elastic-brittle cavity expansion.



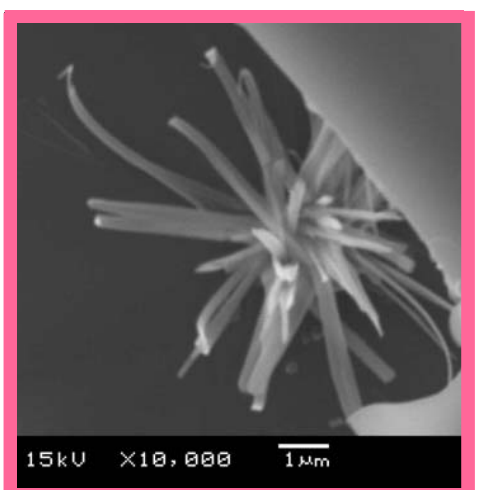
Long parallel hackles



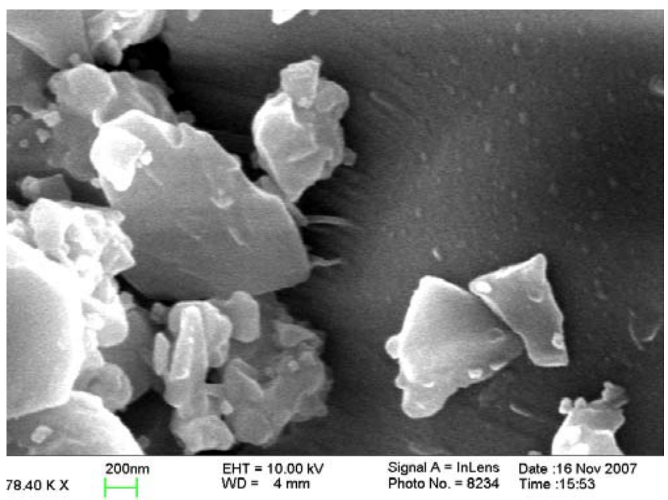
Nano “stairsteps” with hackle on steps.



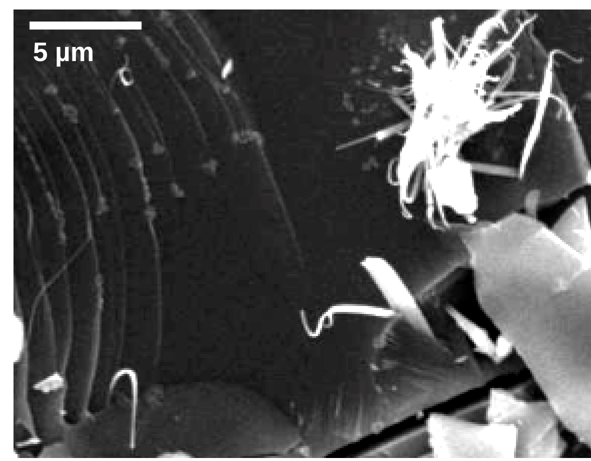
Fields of nano whiskers
*Note that whiskers may be associated with adjacent hackles



Agglomerated whiskers

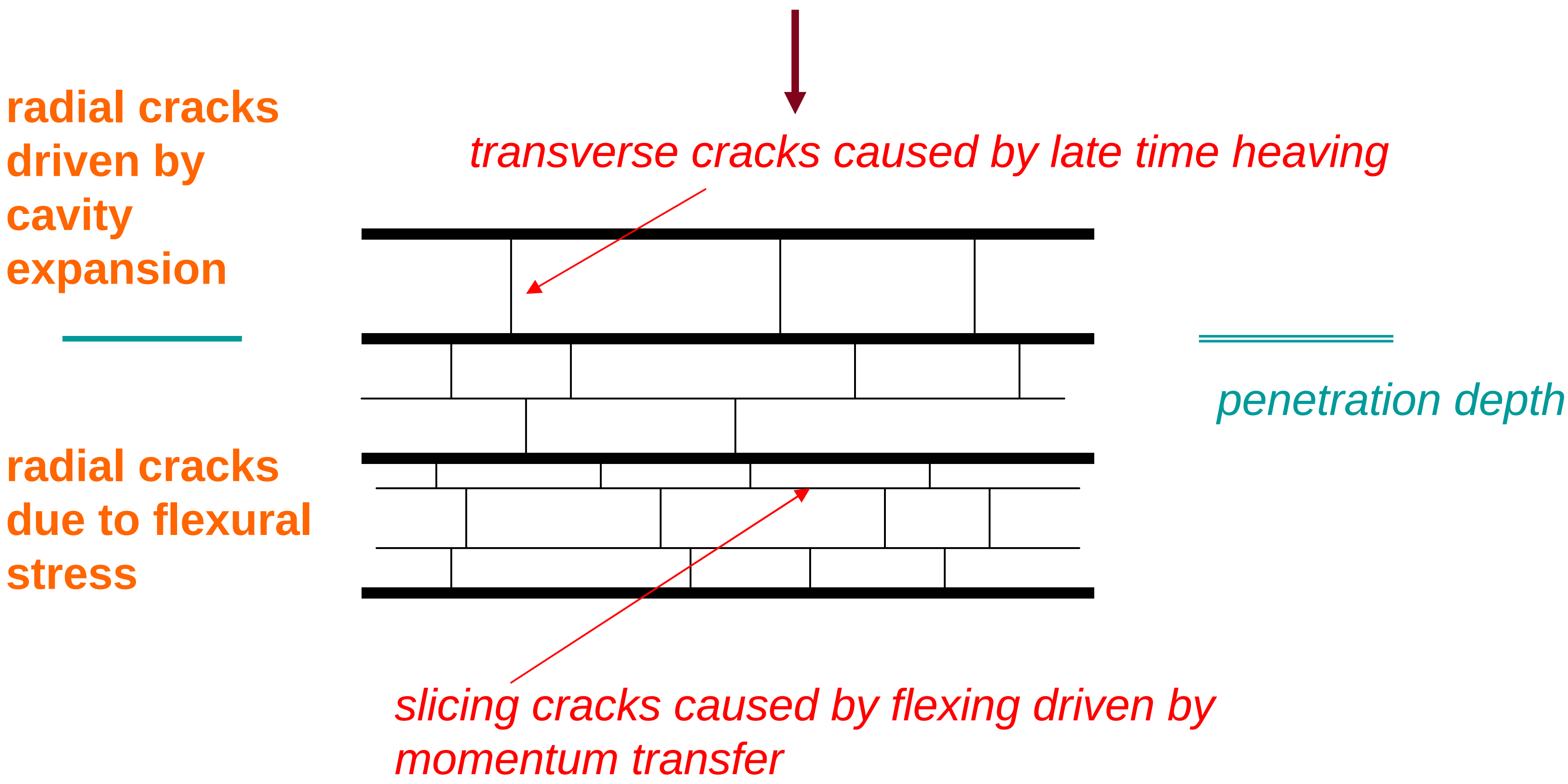


Rounded nano particles



Curvature of whiskers

Hypothesis for radial crack structure within the targets



Summary of results concerning how damage degrades multi-layer glass targets

Close in cavity expansion transitions to far-reaching radial crack pattern.

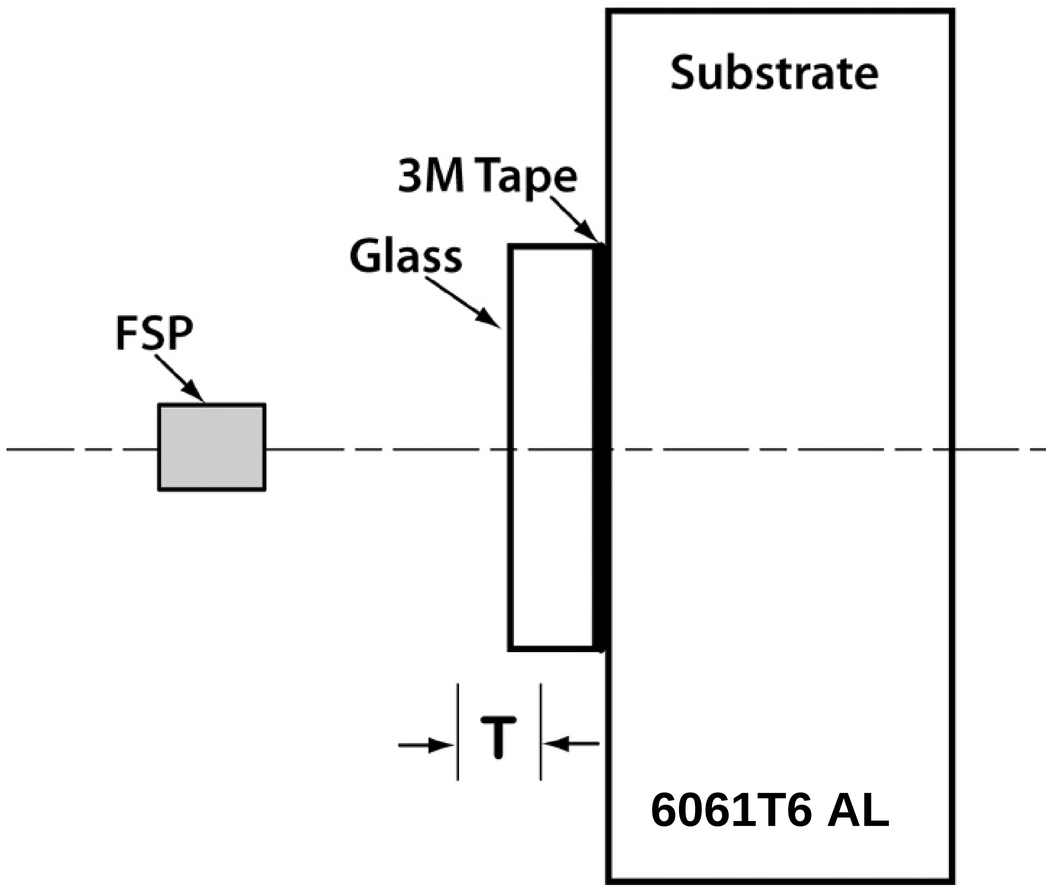
First shot sets up damage pattern. Two basic kinds of crack damage: dicing cracks and radial cracks, which are flaked in inner layers and pie-sections in outer layers. This pattern does not change significantly in subsequent shots.

The radial cracks very seriously degrade ballistic performance. The dicing cracks do not.

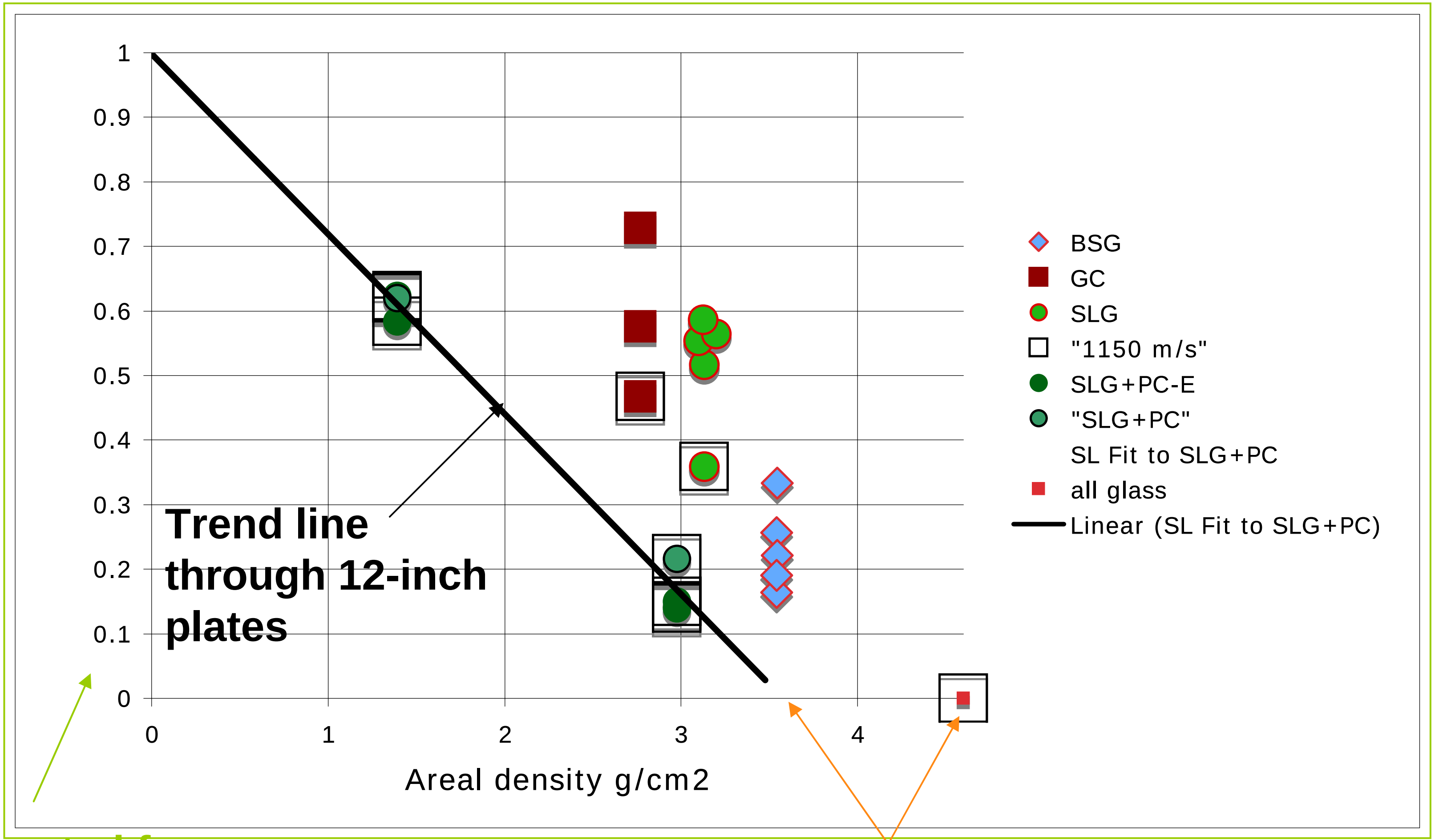
3 Materials compared to investigate effect of properties

Parameter	Soda lime glass	Boro-silicate glass	Glass ceramic (Corning)
Density (g/cm3)	2.5	2.2	2.78
E (GPa)	72	61	72

Modified DOP test geometry for 4-inch test coupons



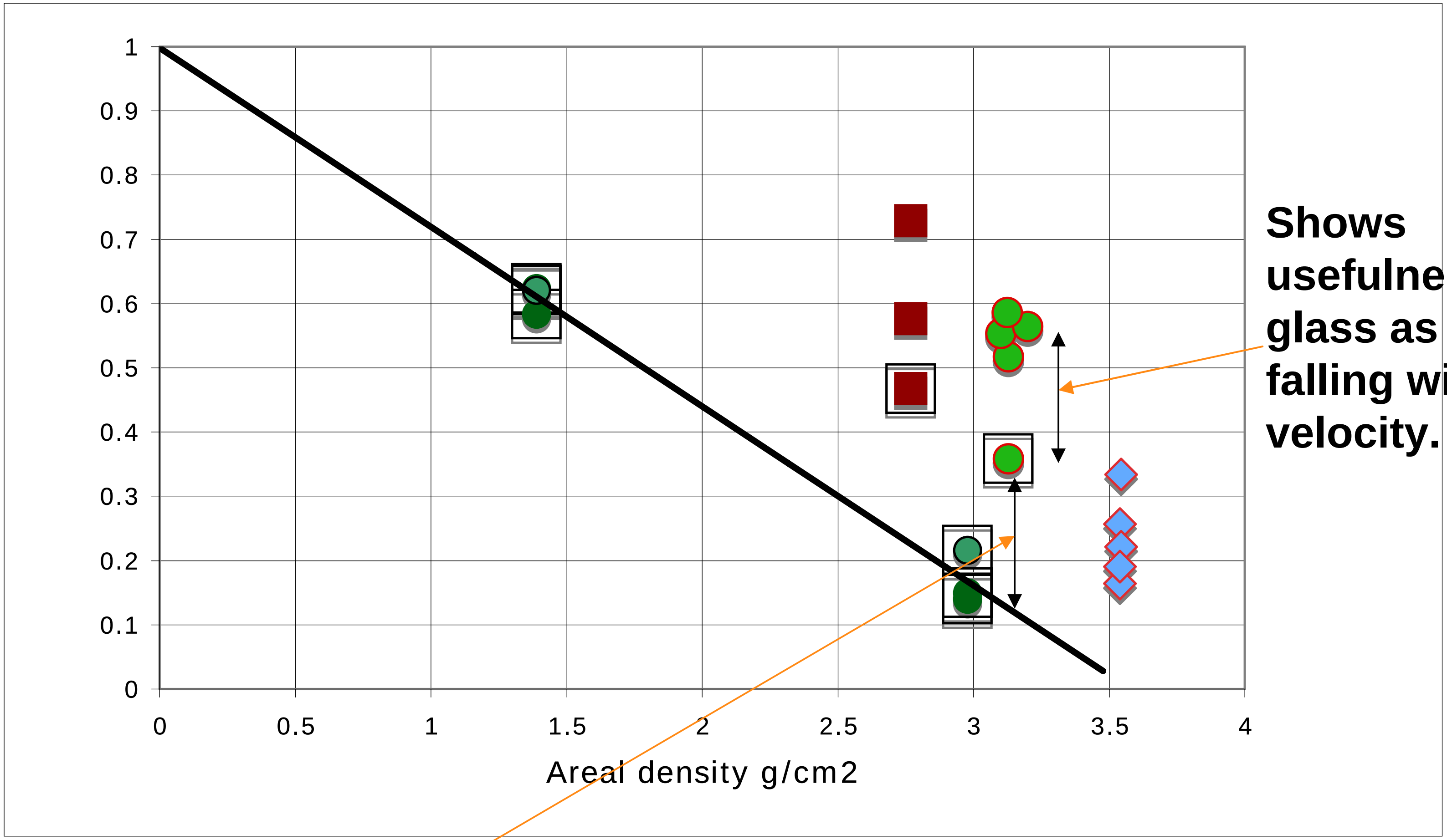
Connection of DOP tests and laminate target tests



Corrected for effect of PC.

Penetration is more in an all glass target than would be predicted from DOP trend. This is probably due to loss of strength which allows projectile to “coast” to s stop in glass.

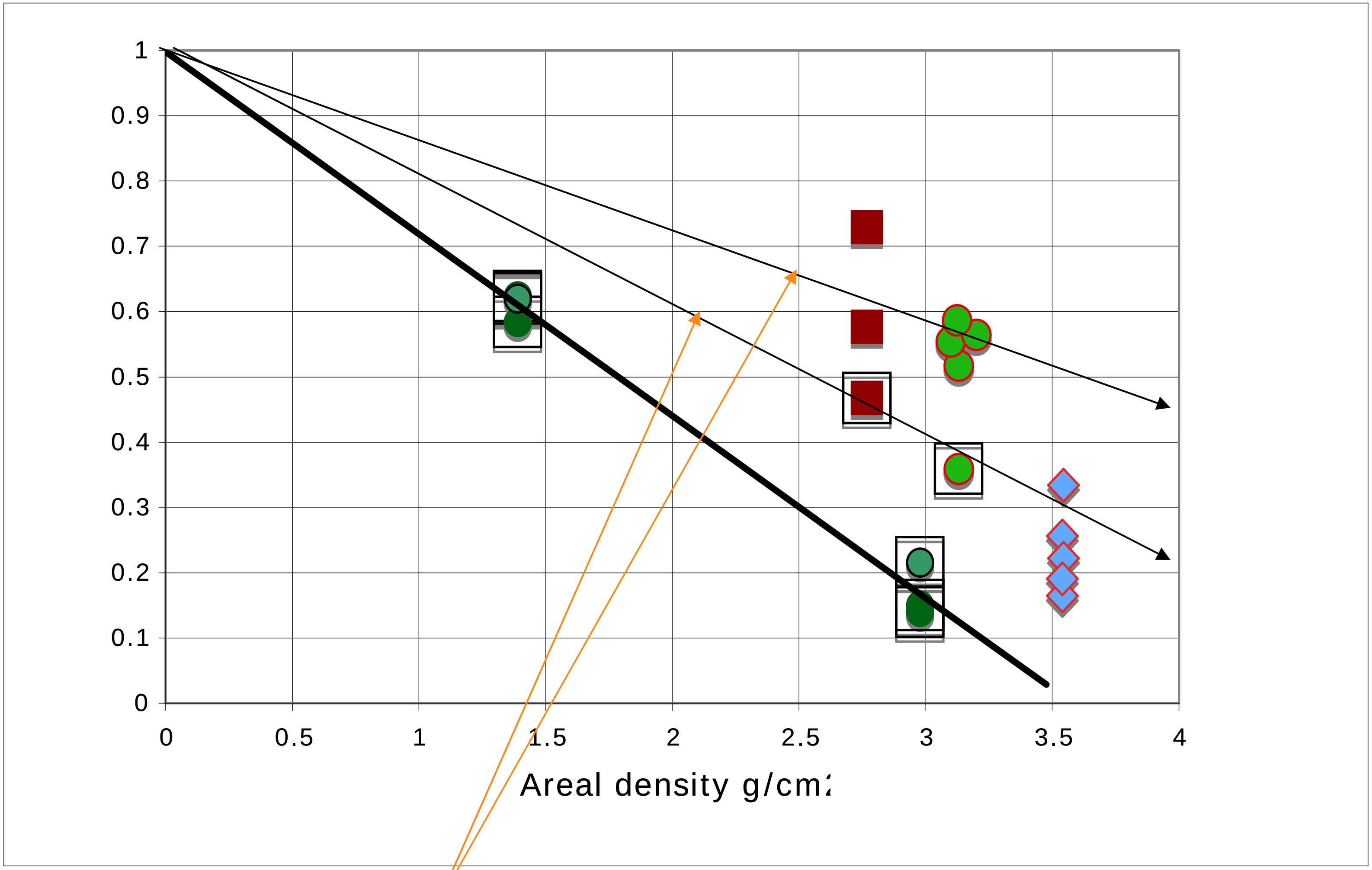
Effects of Mounting and Velocity



Shows usefulness of glass as armor falling with velocity.

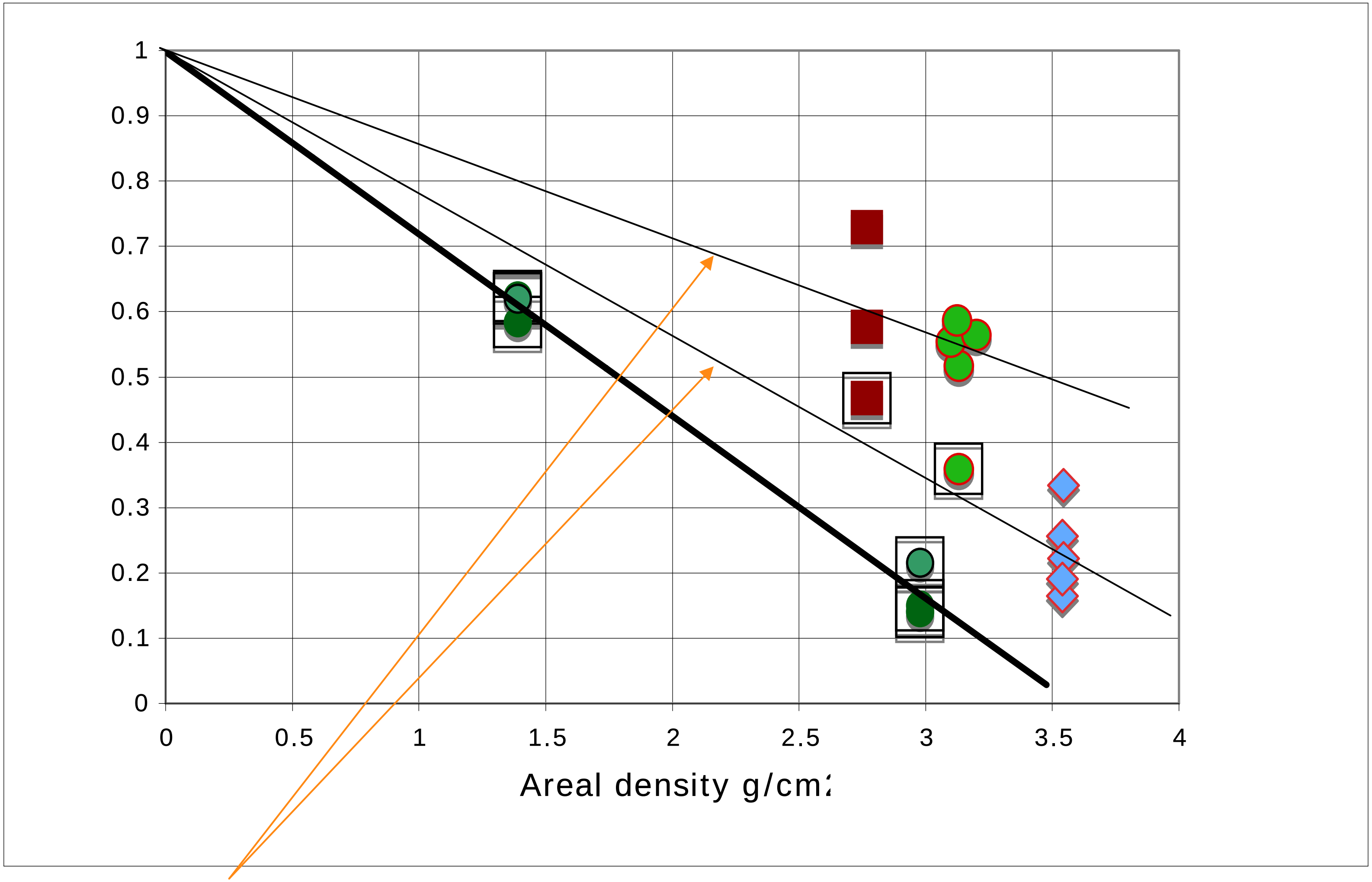
Shows SLG with 3M tape was about 34% less effective than with PU/PC mounting.

Comparison SLG and GC



Shows the efficiencies of SLG and GC are very similar.

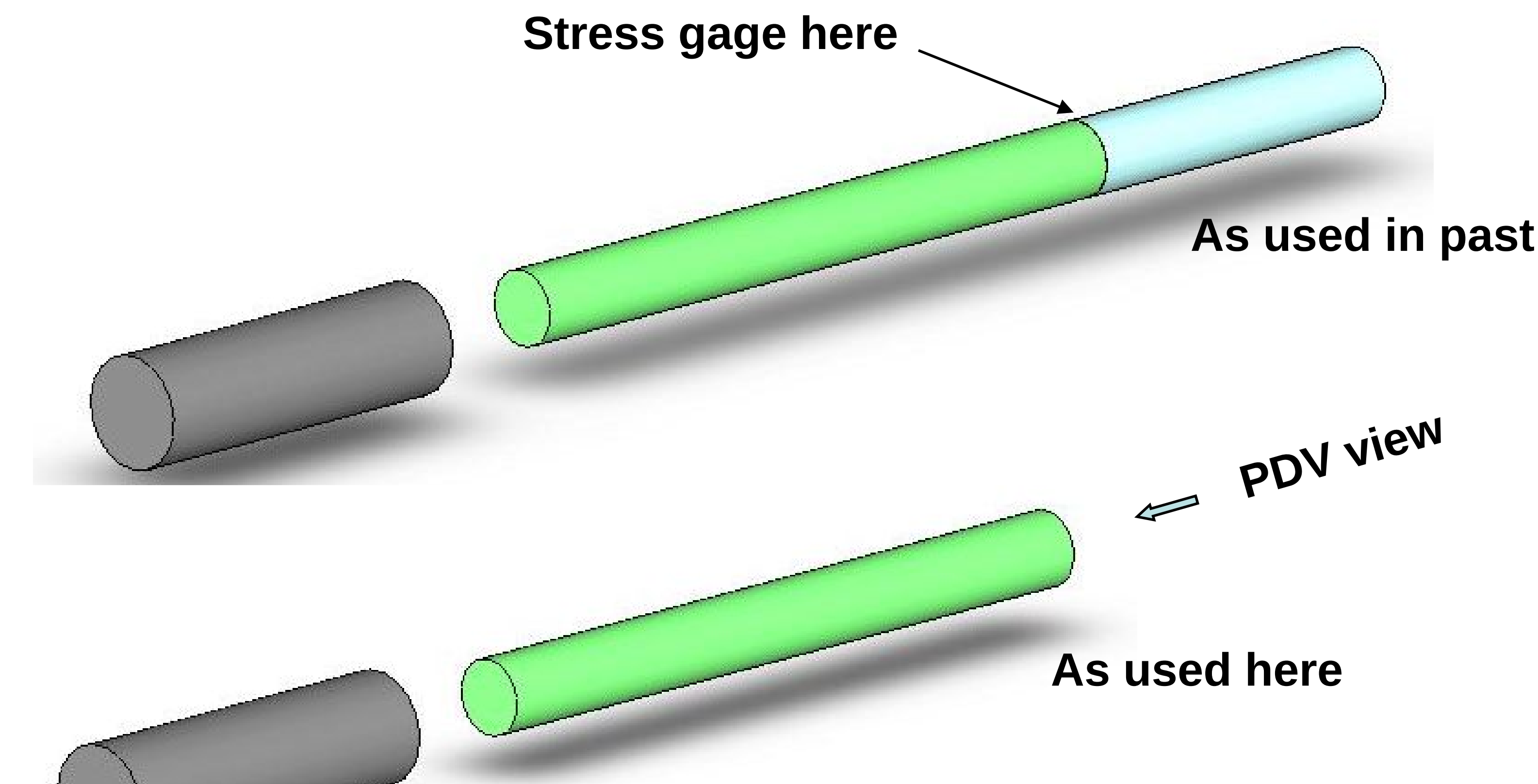
Comparison BSG and SLG



Shows that BSG is much better than SLG. Probably due to the importance of density.

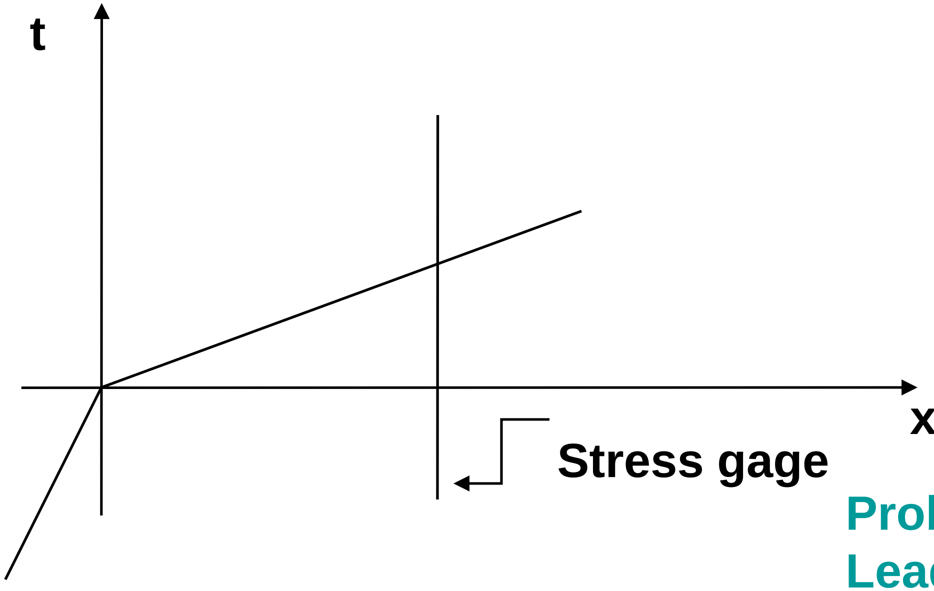
Strength Measurements on Glass

Goal: Develop technique to measure strength of glasses

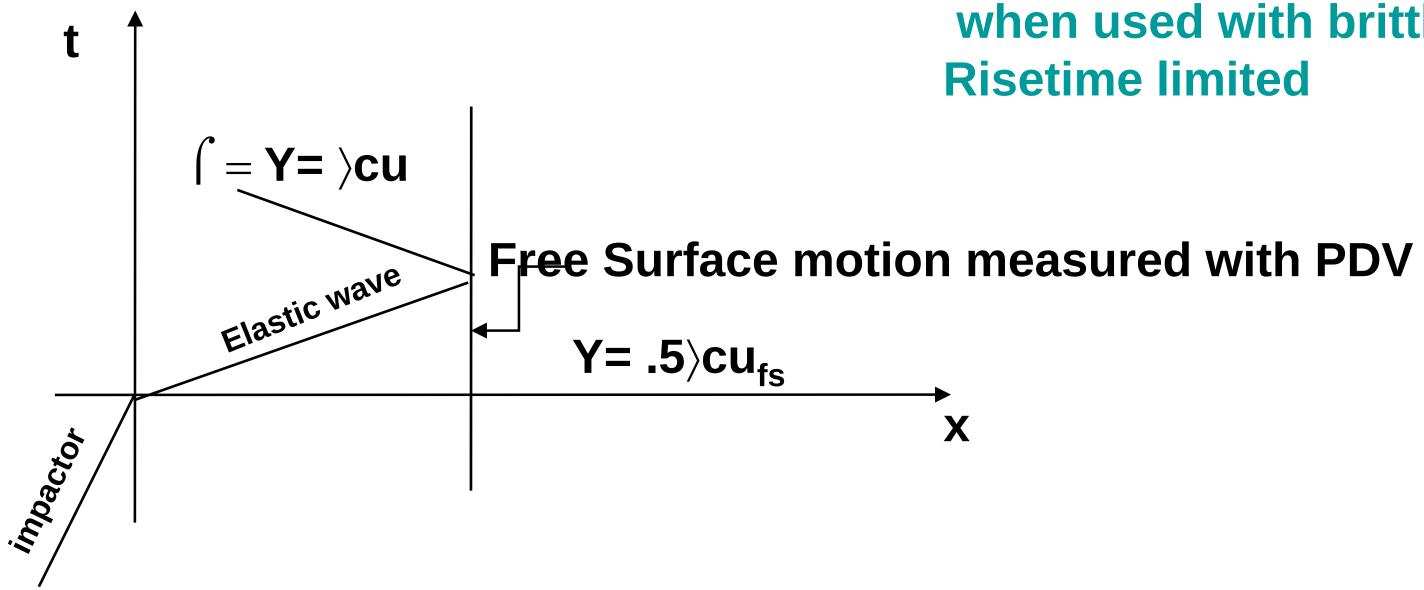


These experiments: observe free surface motion with hi speed camera and PDV.

Theory (for ductile materials)

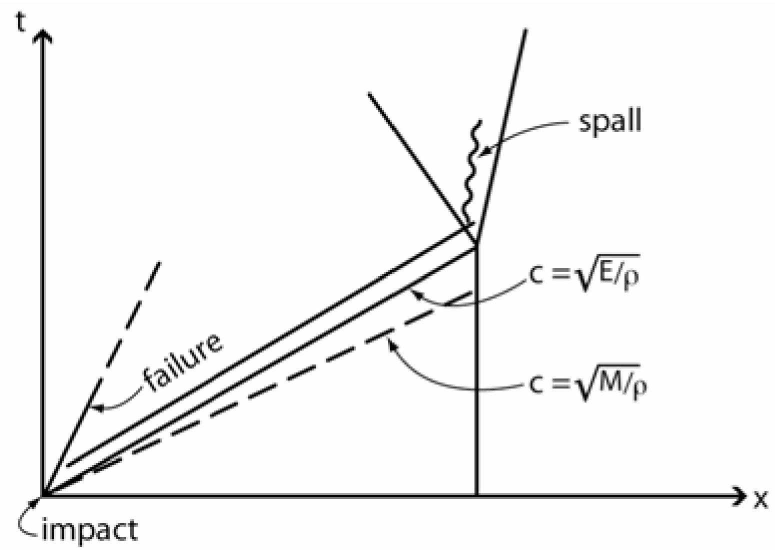


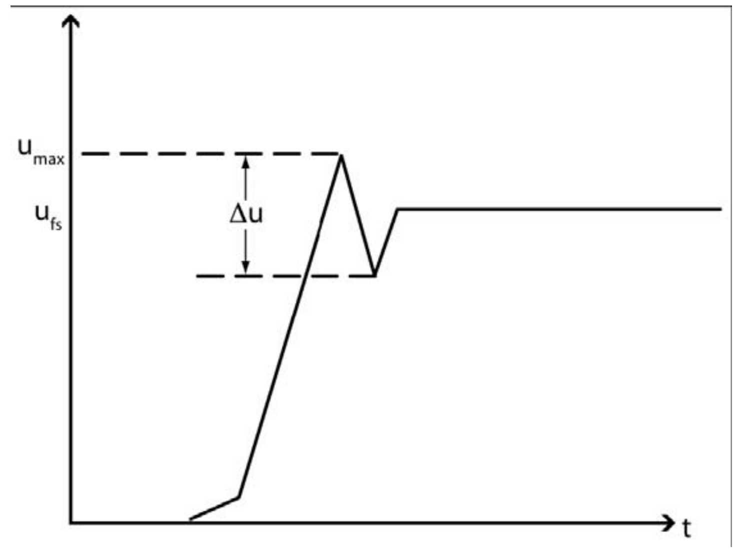
Problems with gauge –
Leads break
Very short lifetime
when used with brittle materials
Risetime limited



Theory for brittle materials

Spall equaiton



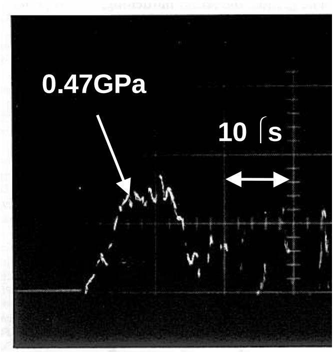


Failure causes release near impact, resulting in triangular instead of square pulse. For many brittle materials, spall strength is less than compressive strength, resulting in a "spall signal" at free surface.

(M=K+4G/3. K,G,E are elastic moduli)

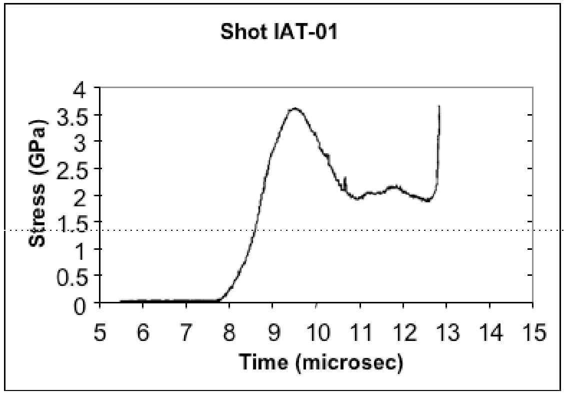
Examples of Previous work

Strength of a Mild Steel



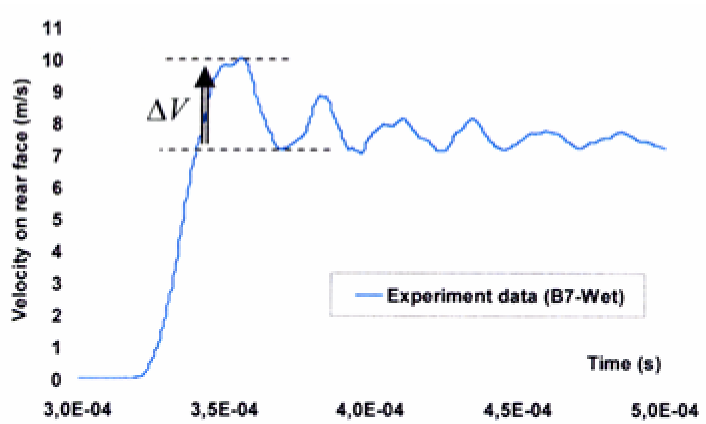
Rosenberg & Bless, 1986

Strength of Alumina



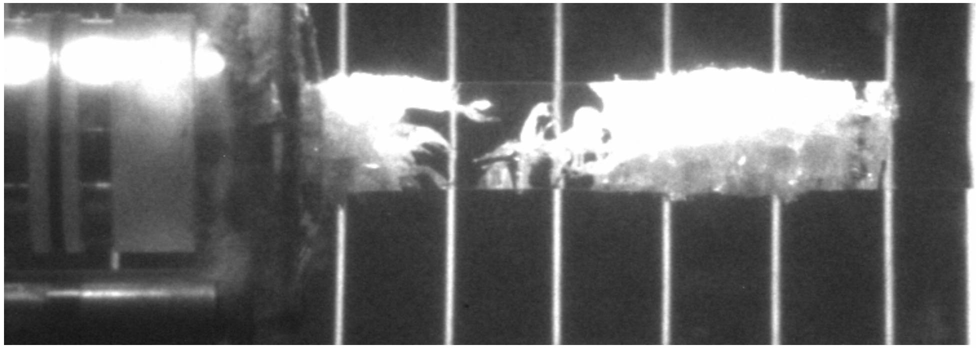
T. Beno at al, 2006, strength of alumina = 3.6 GPa

Spall in Concrete



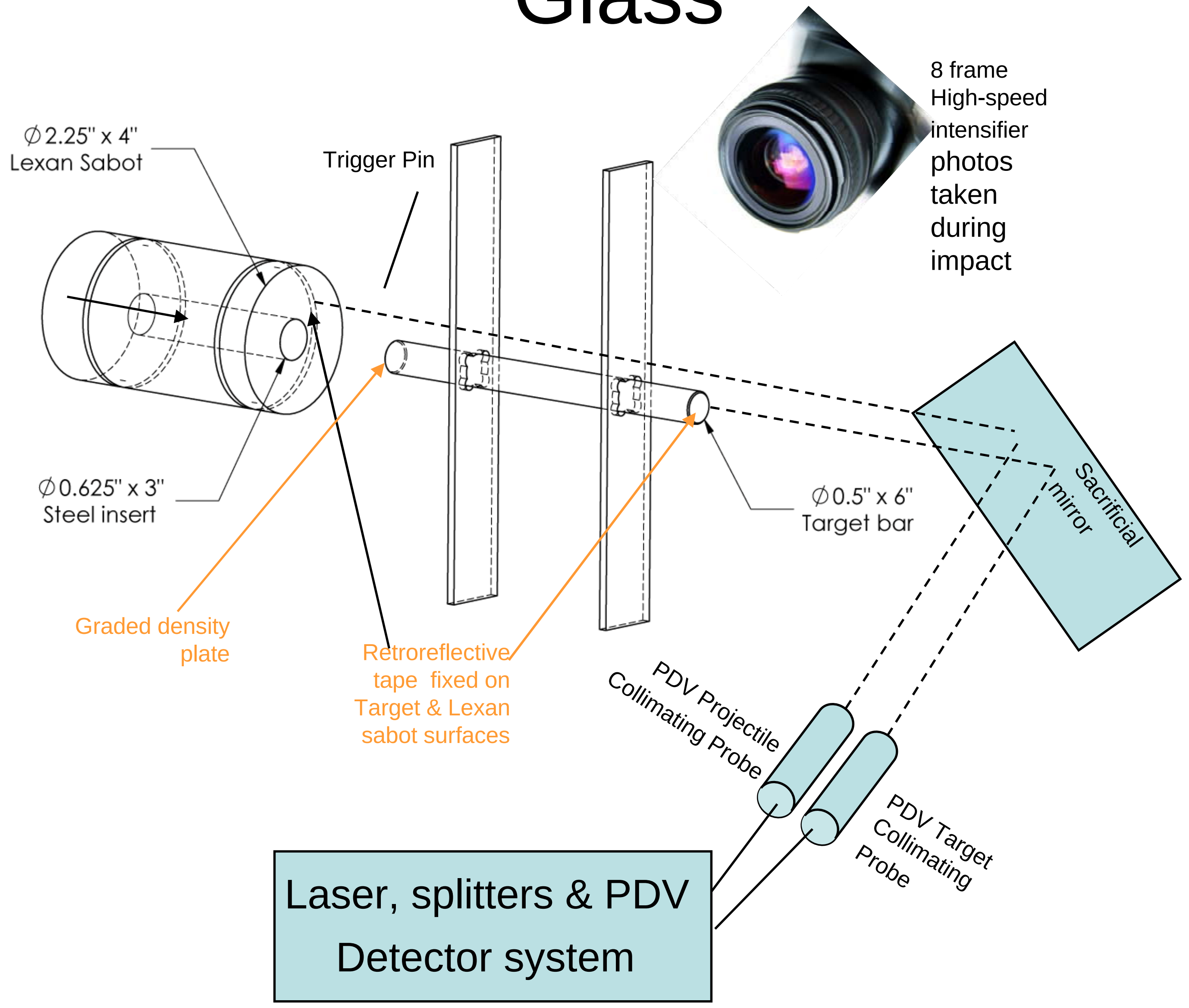
P. Forquin, & Erzan, 2008

Failure in homalite bar



Bless, 2003

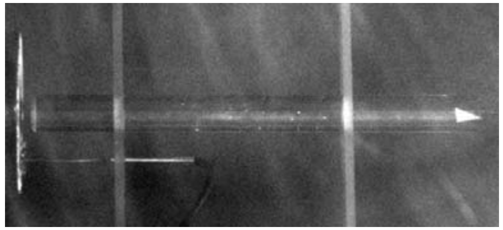
Experimental Setup for Glass



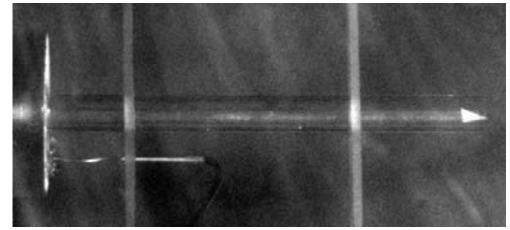
Failure process in BSG

shot A1008
borosilicate glass

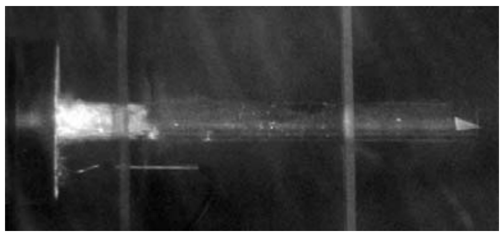
Direction of travel



150 ✪s



160 ✪s



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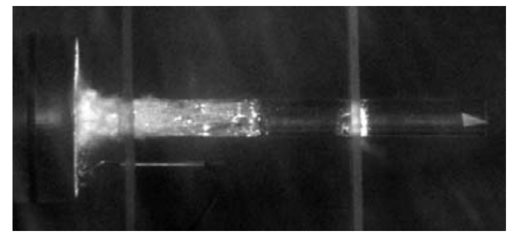

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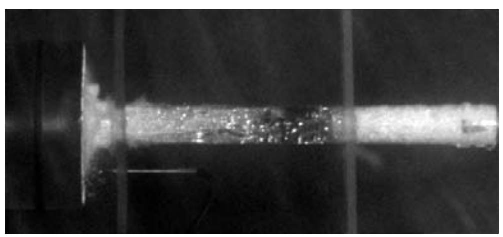

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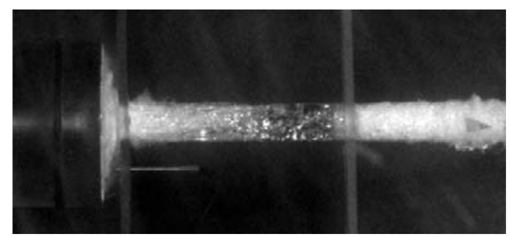

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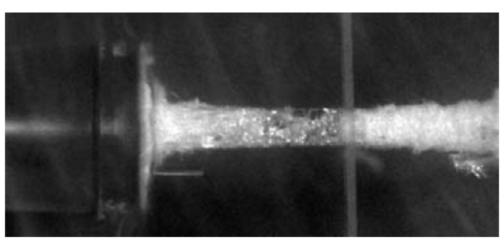
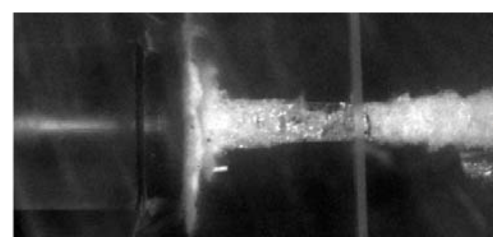


250 ✪s



300 ✪s

explosive tensile failure

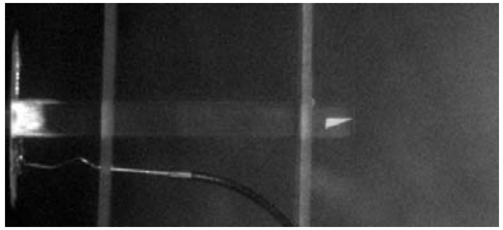
Failure of GC rod generally very similar to glass rod

Direction of travel

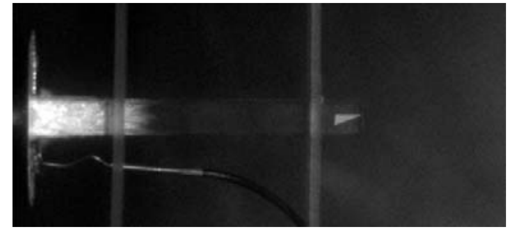
shot A1011
glass ceramic

No damage-free zone in middle

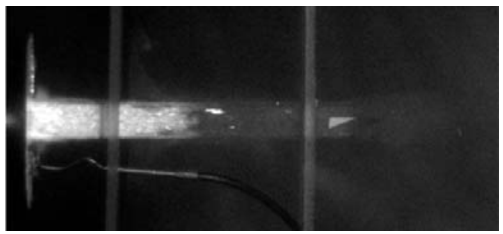
More expansion in compressive zone



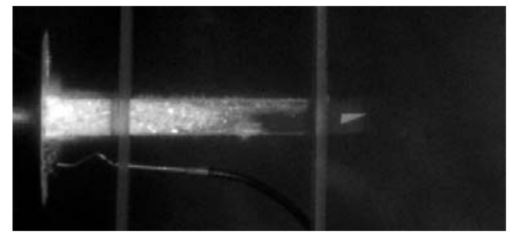
145 ✪s



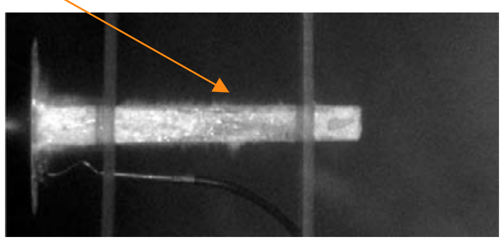
150 ✪s



153 ✪s



175 ✪s



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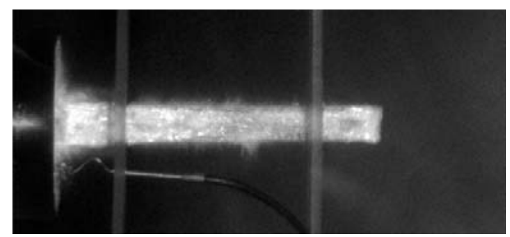

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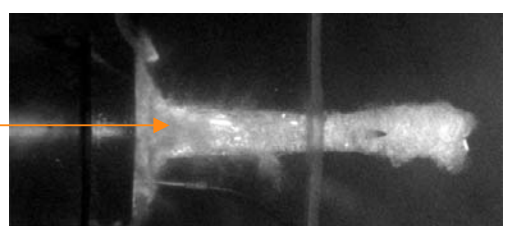
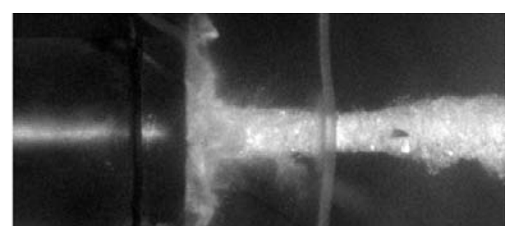
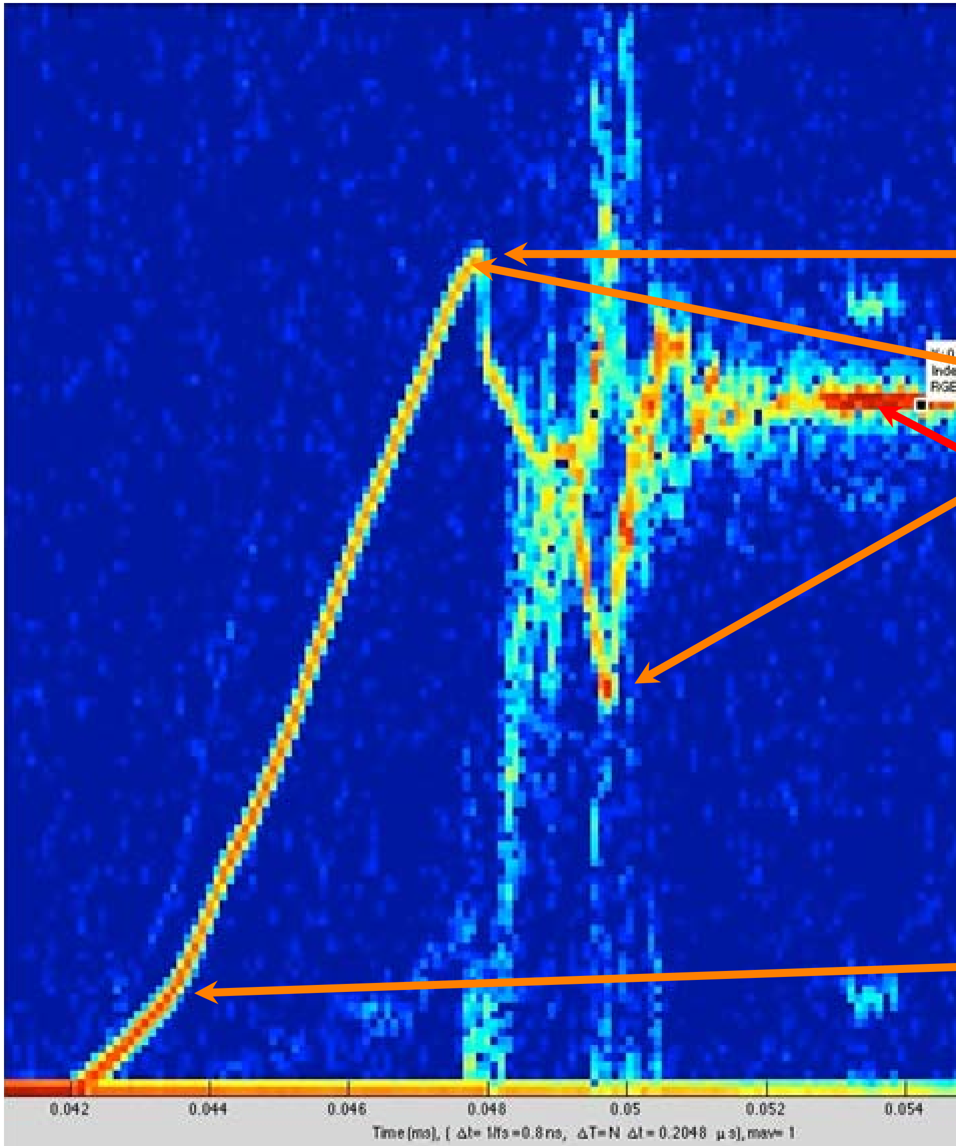


250 ✪s



300 ✪s

Free surface velocity data



Borosilicate glass

Peak stress = 2.2 GPa

spall pull back? = 187 m/s
spall stress = 1.1 GPa

final velocity = 307 m/s

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Break between 1-D strain and 1-D stress waves.

10 Tests conducted

All impact velocities between 250 and 310 m/s

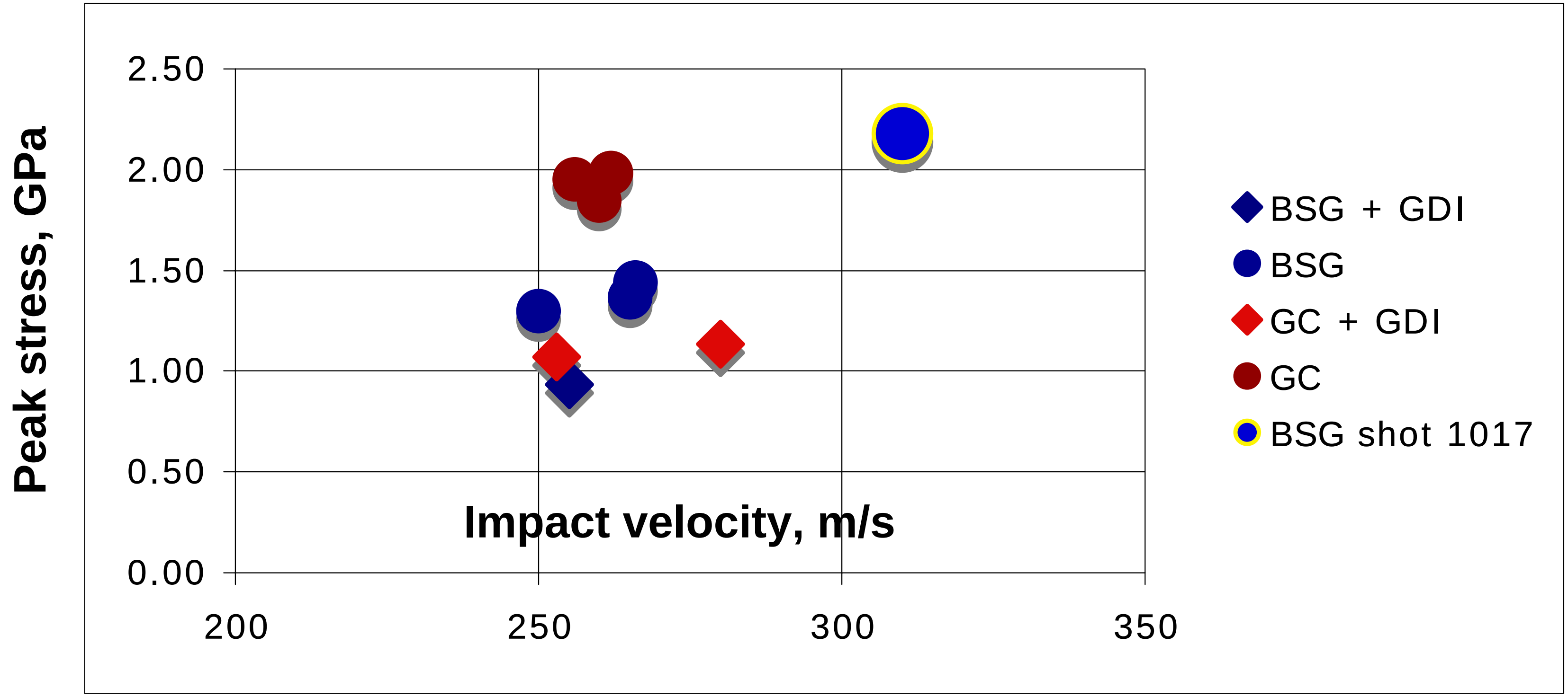
Values of stress plateau (after spall), from photos or PDV.

Test	Material	Impact Velocity (m/s)	Free Surface Velocity (m/s)	Stres (Gpa)
a1004	GC	260	287	1.84
a1007	GC	256	275	1.95
a1011	GC	262	280	1.99
a1013	GC+GDI	280	160	1.13
a1014	GC+GDI	253	151	0.84
a1015	BSG+GDI	255	160	0.93
a1003	BSG	266	247	1.44
a1008	BSG	250	223	1.30
a1012	BSG	265	235	1.37
a1017	BSG w/o Retro	310	374	2.18

GC = Glass Ceramic, BSG = Borosilicate glass

GDI=graded density impactor

Peak stress data (from PDV records)



For both materials, adding the GDI reduces measured stress.

GC is 30% stronger than BSG.

There appears to be a strong rate effect of measured peak stress.

Summary of what we learned

FSPs produce characteristic damage patterns in glass single sheets or laminates: generally radial cracks (many species) and dicing cracks.

Dicing cracks are relatively benign; not so radial cracks.

Density is much more important than strength in defeating FSP projectiles.

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