Российская Академия Наук

SHOCK WAVES IN THE PHYSICS OF CONDENSED MATTER

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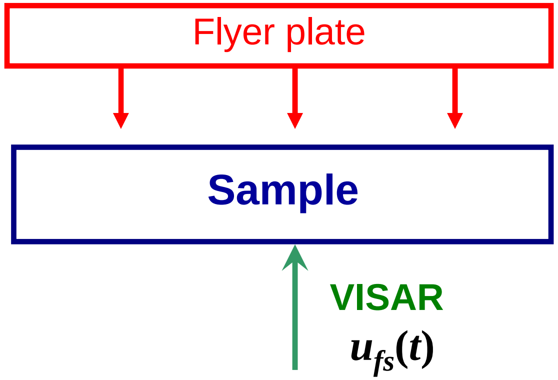
- **The method**
- **Polymorphic and phase transformations**
- **High-rate plastic deformation and fracture**
- **Approaching the ideal strength**
- **Failure waves**
- **Behavior of hard brittle materials**

ИВТАН

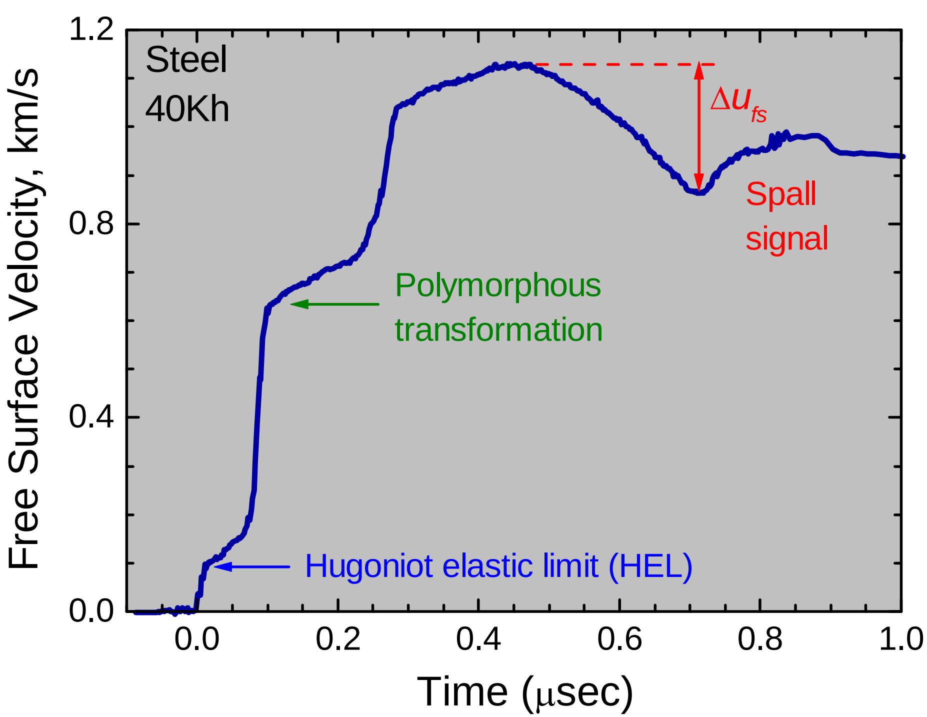
IPCP RAS

APPEARANCE OF MATERIAL PROPERTIES IN A FREE SURFACE VELOCITY HISTORY



Available loading conditions:

- Peak stresses: **0.1 – 100 GPa**
- Load durations: **10 ns –10 μs**
- Time resolution of the measurements: **< 1 ns**



Hugoniot elastic limit: $HEL = \rho_0 c_l u_{fs}^{HEL}/2$

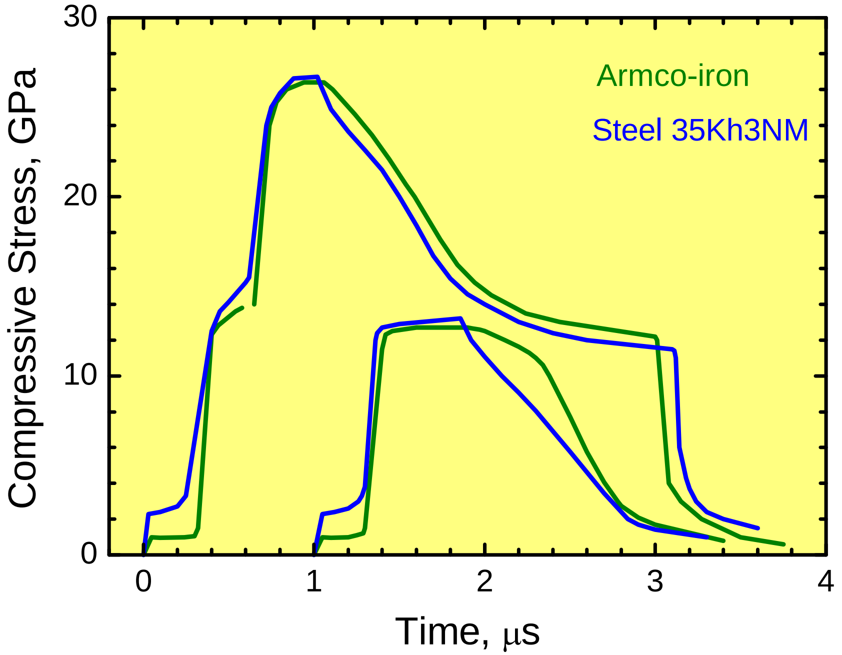
Yield stress: $Y = HEL\ (1\text{-}2\nu)/(1\text{-}\nu)$

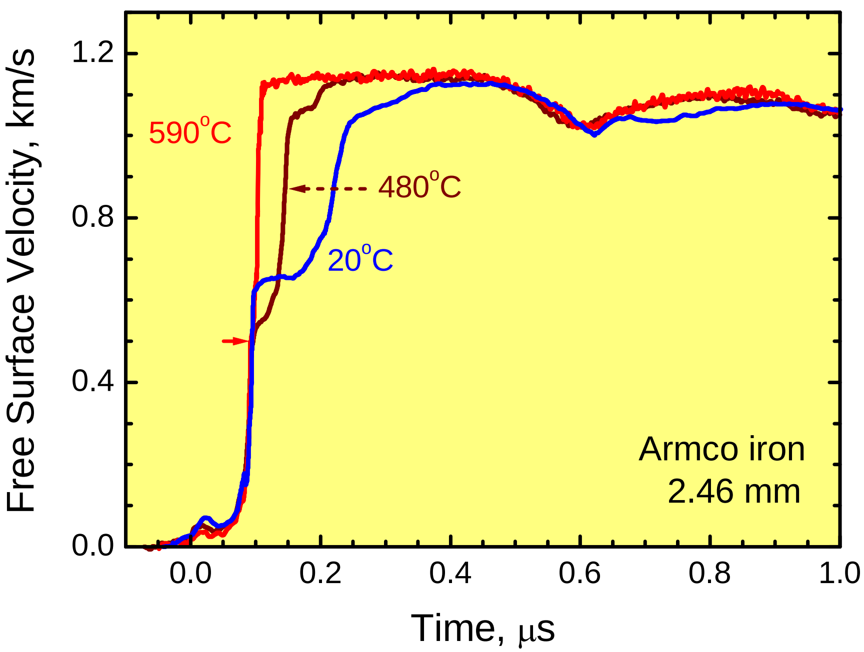
Spall strength: $\sigma_{sp} = \rho_0 c_b(\Delta u_{fs} + \delta)/2$

Phase transition pressure:

$$p_{\alpha\to\varepsilon} = \rho_0 D_1 u_{fs1}/2$$

DIAGNOSTICS:
measurements of pressure, tests at elevated temperatures



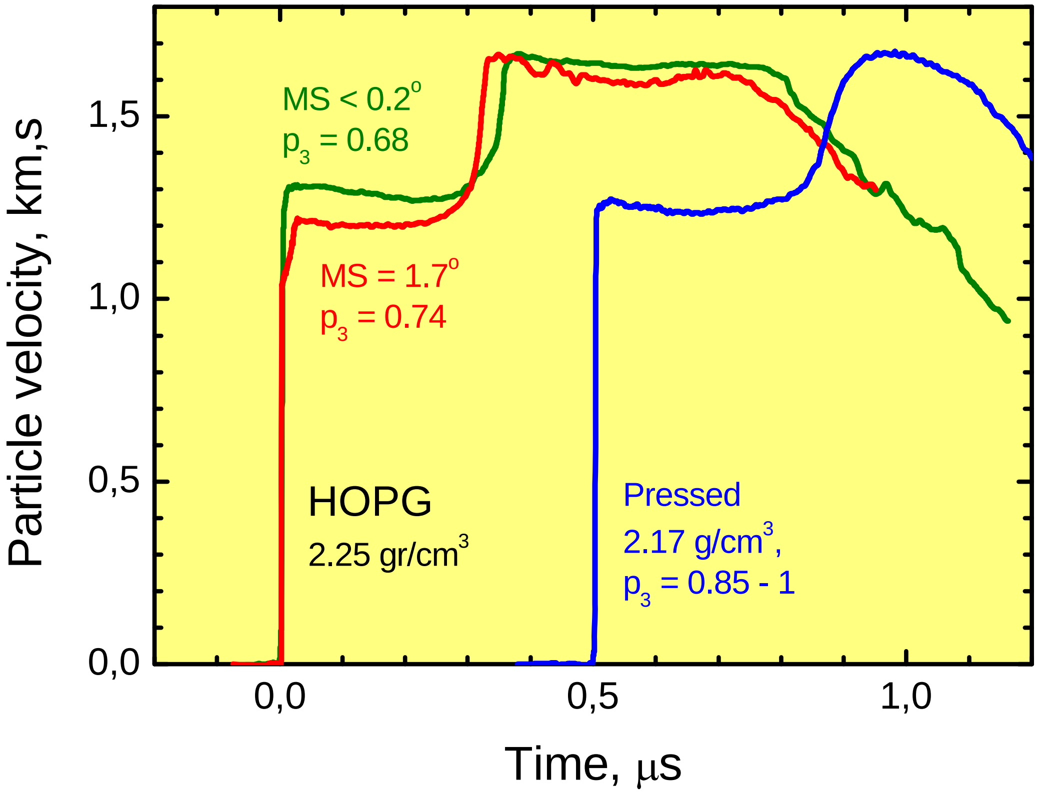


Extremely high transformation rate at shock-wave compression;

Sub-microsecond polymorphic transformations have been studied for iron and steels, titanium, tin, graphite, boron nitride, …

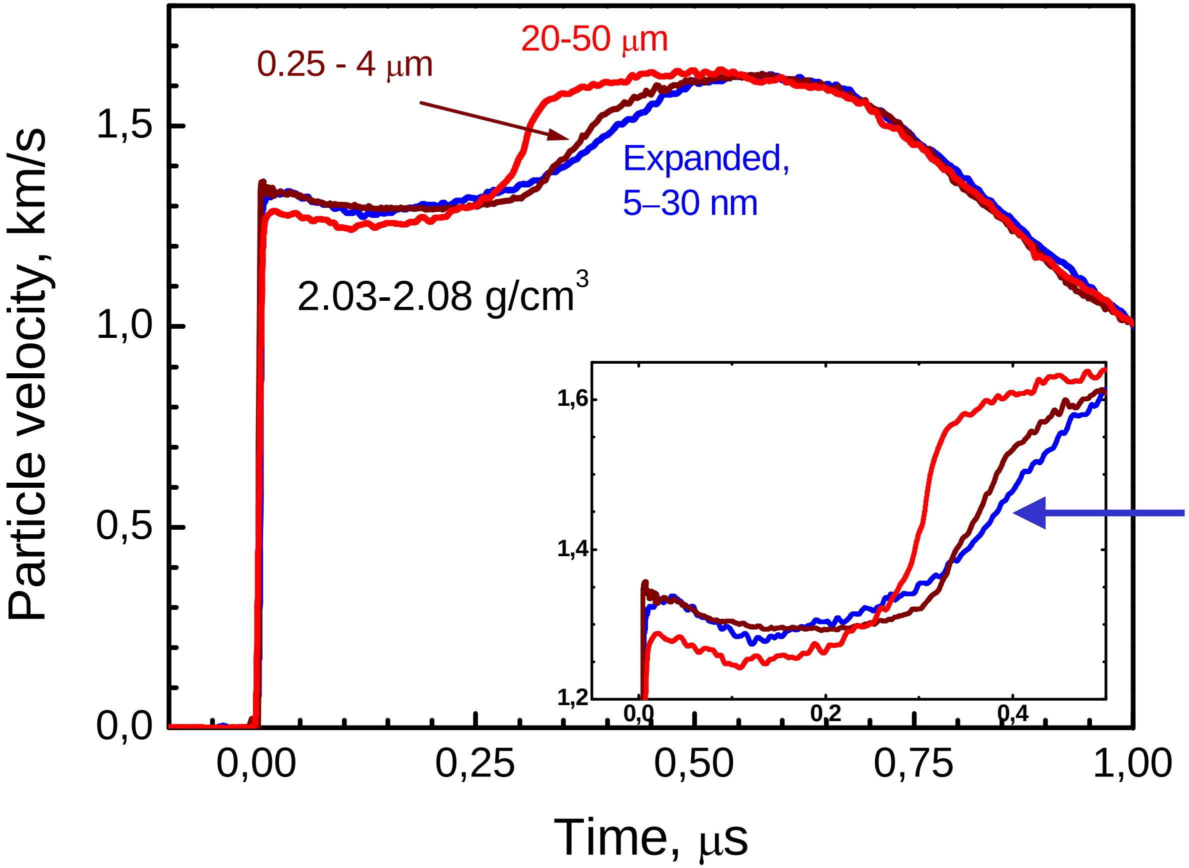
POLYMORPHIC TRANSFORMATIONS

Highly Oriented Pyrolitic Graphite (HOPG)

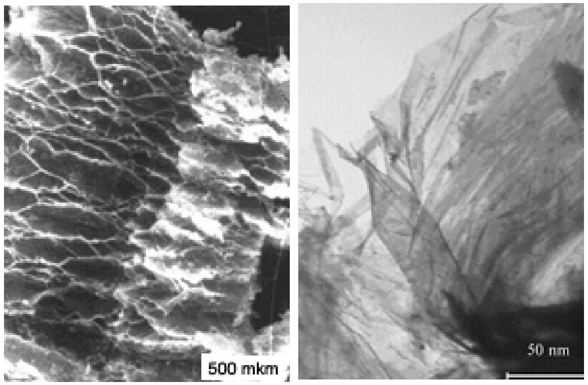


- The increase of mosaic spread decreases the transformation pressure.
- Transformation of HOPG occurs with acceleration whereas pressed graphite shows acceleration in initial stage and deceleration at the end.
- The maximum transformation rate is 2.5×10^{7} s^{-1} for HOPG and 8×10^{6} s^{-1} for pressed graphite.

Graphites of various grain size

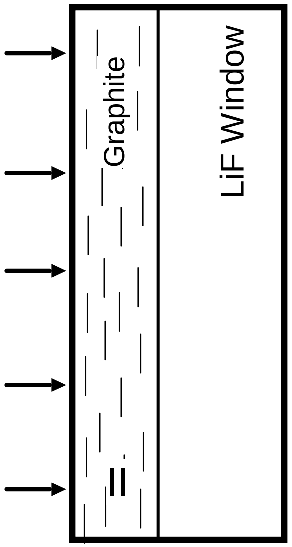


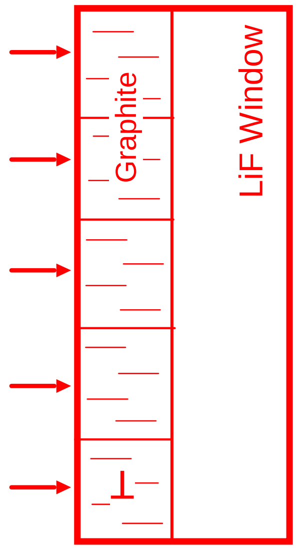
Expanded graphite

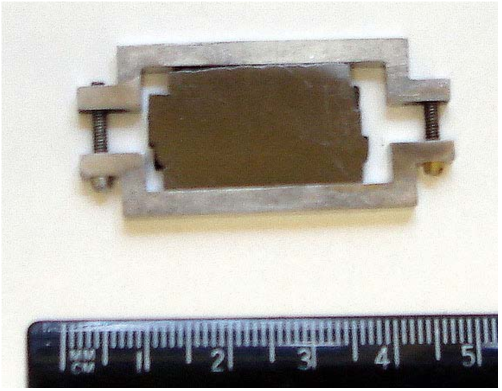


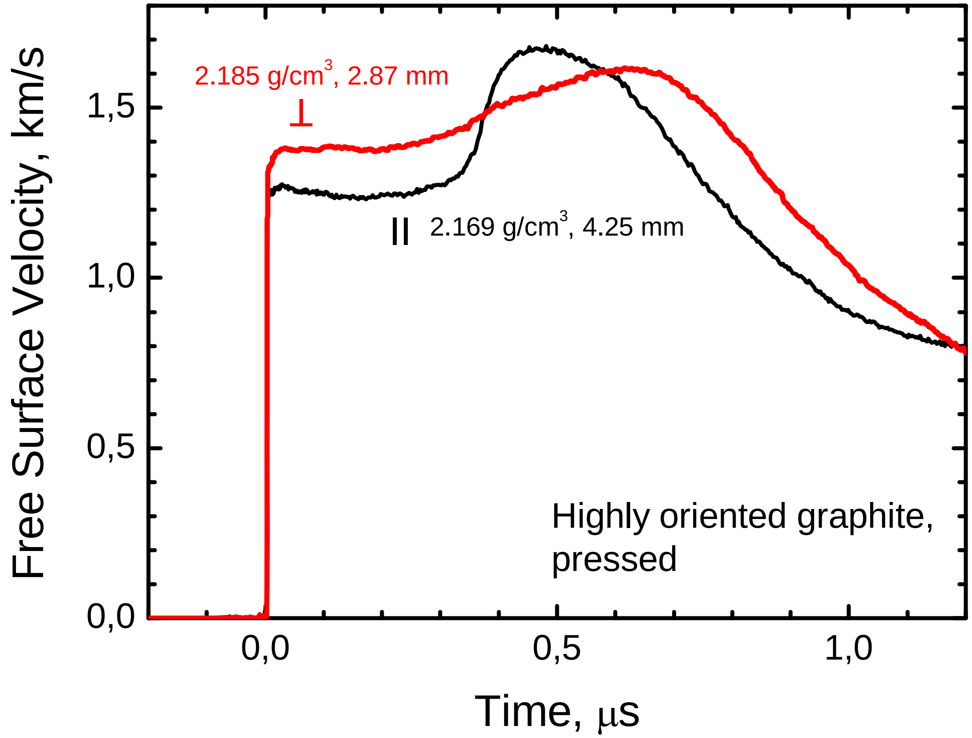
- **Fine-grained graphites demonstrate higher lower average transformation rate but faster stress relaxation in the initial stage.**
- **This may be interpreted as faster nucleation in the material with large intergranular surface.**

TRANSFORMATION GRAPHITE-DIAMOND UNDER SHOCK COMPRESSION



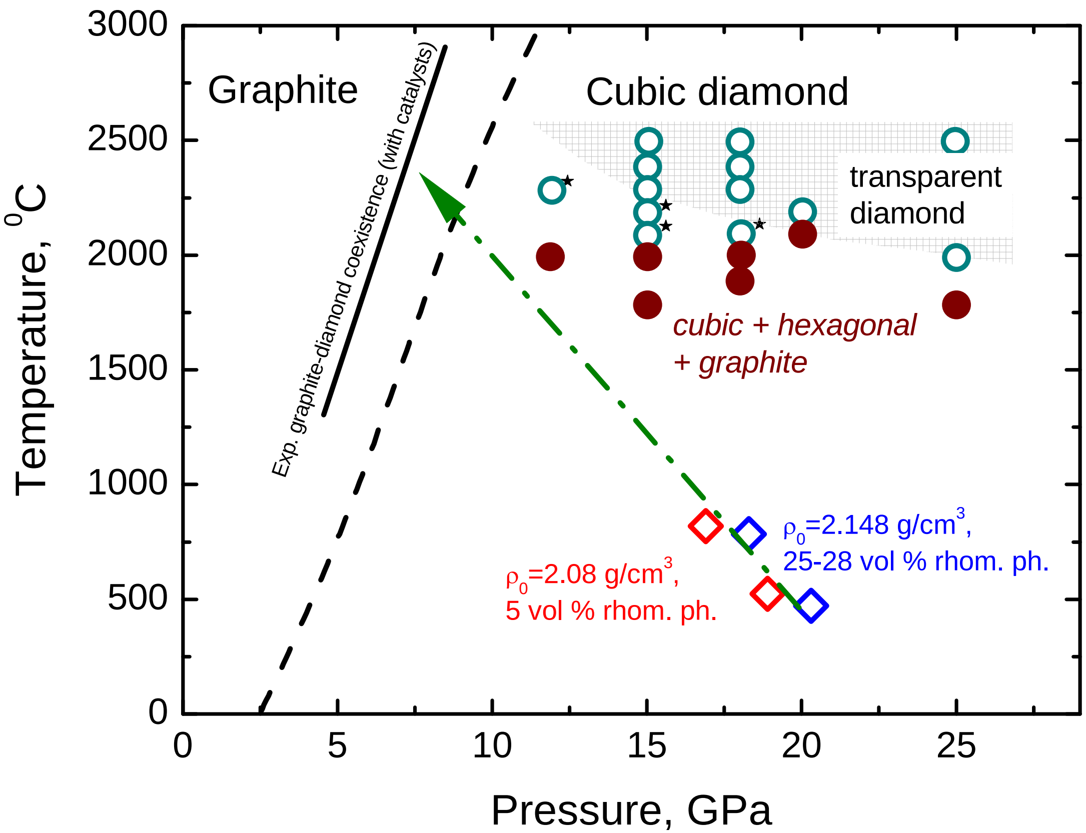






Dependence of the transformation pressure and rate on the load direction confirms the martensitic nature of the transformation.

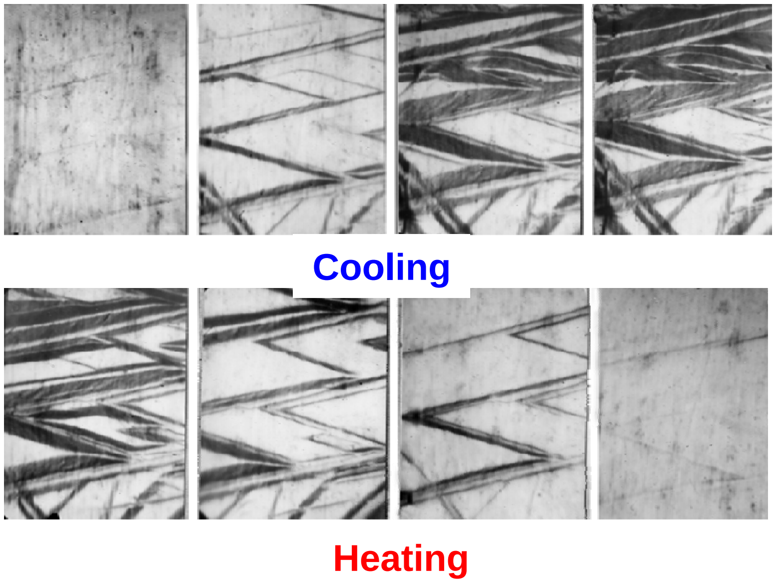
Temperature dependences of the transition pressure

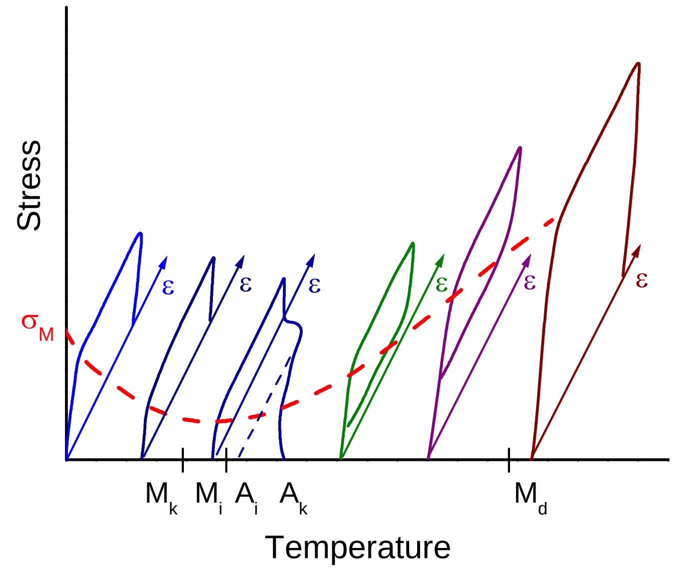


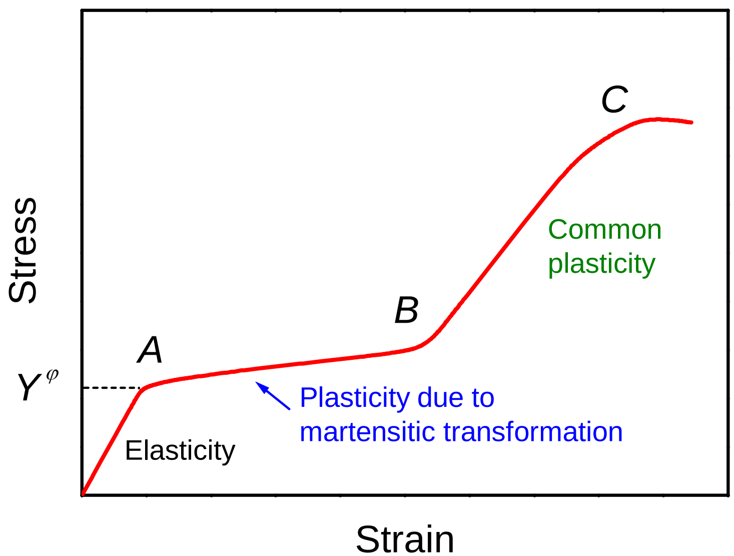
The two kinds of graphite with different transformation pressures demonstrate the same slope of their p_{tr} (*T*) dependences.

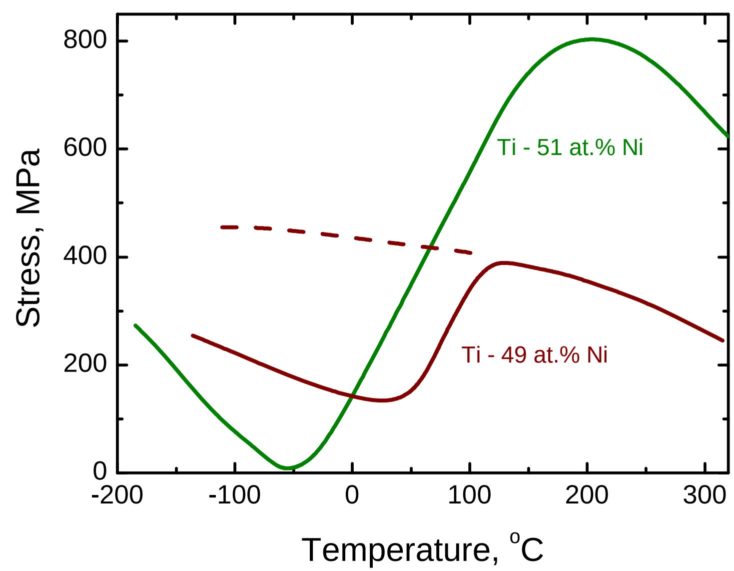
Extrapolated *ptr* (*T*) dependences intersect the graphite-diamond coexisting line at the lower temperature of formation of quenchable cubic diamond.

Shape memory materials

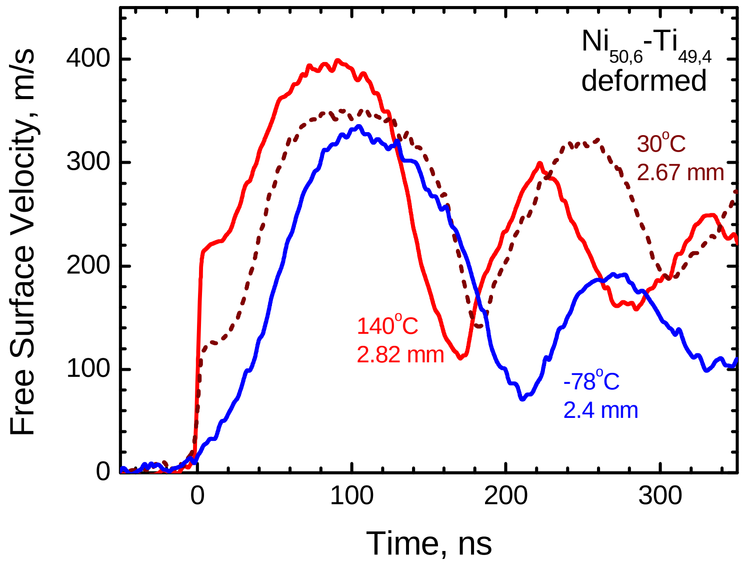


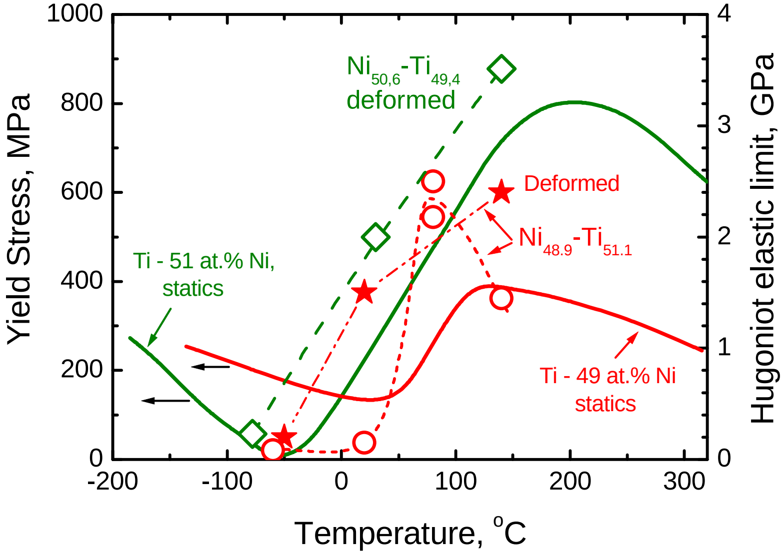


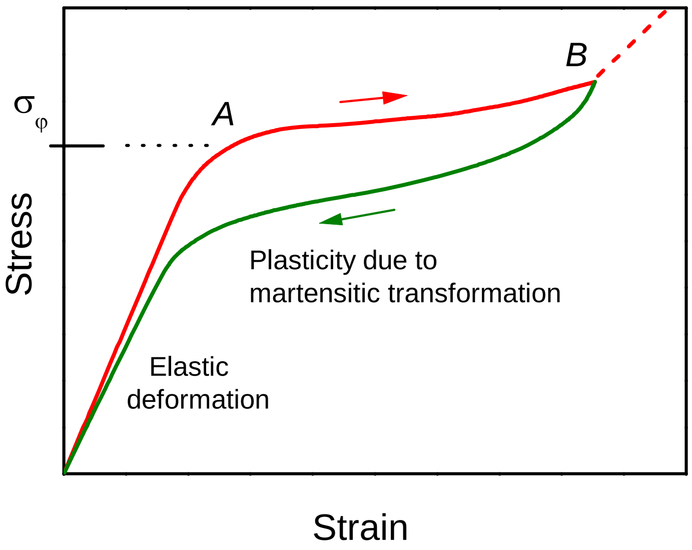


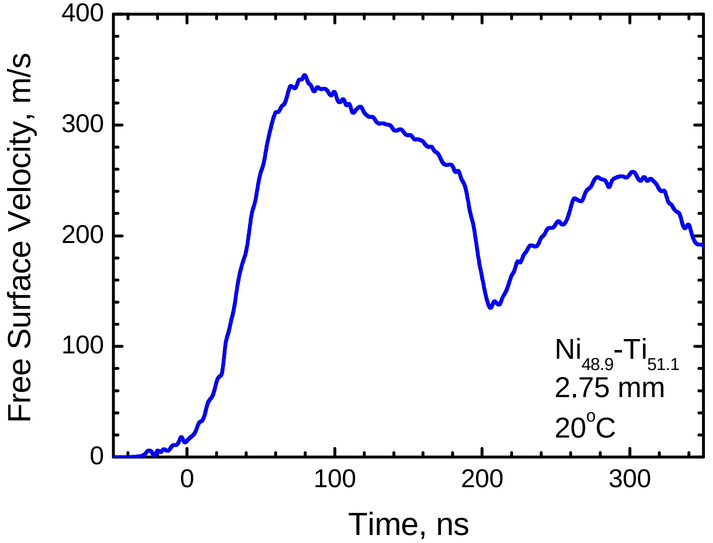


DEFORMATION OF THE SHAPE MEMORY MATERIALS





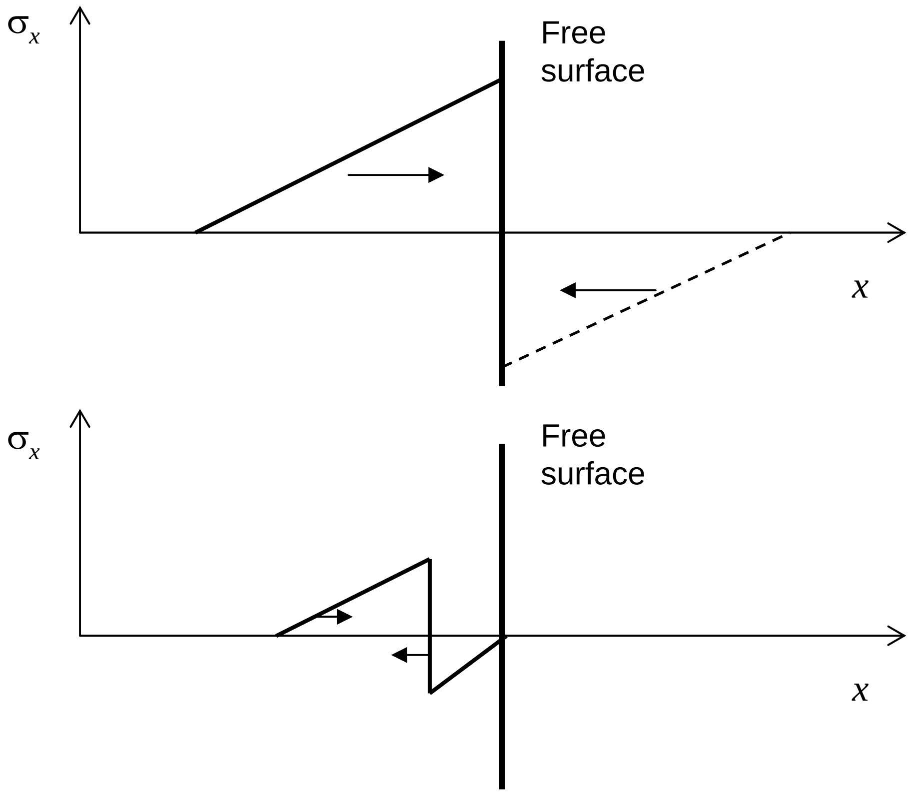


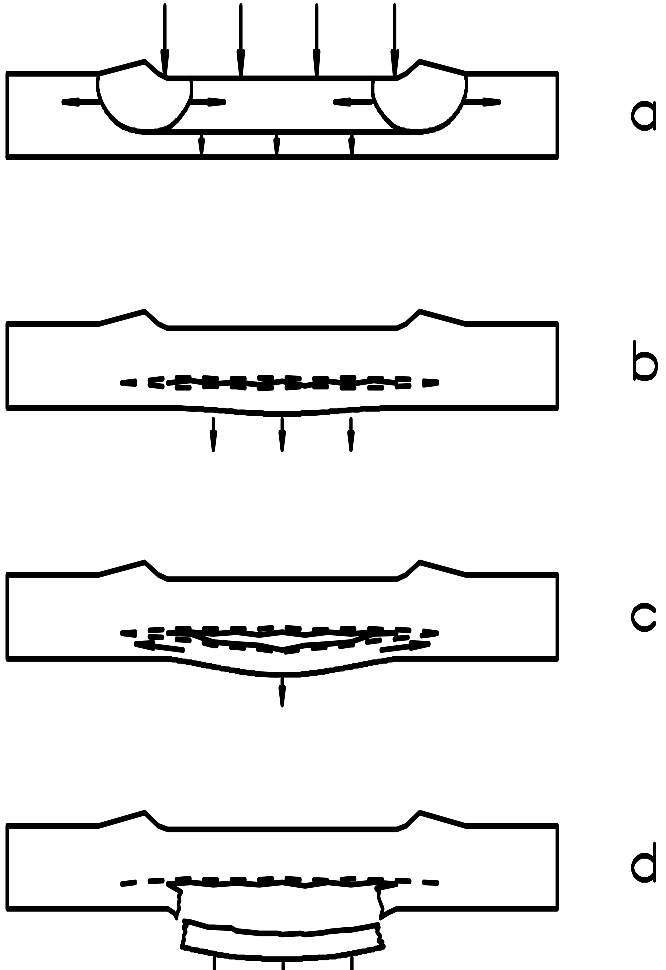


DYNAMIC STRENGTH

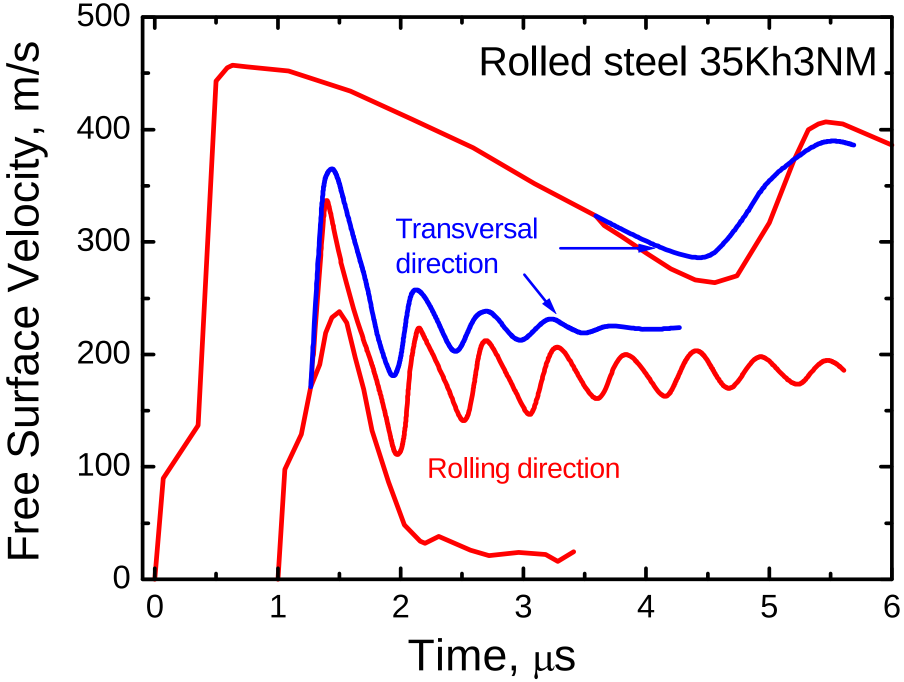
SPALL PHENOMENA UNDER SHOCK LOADING

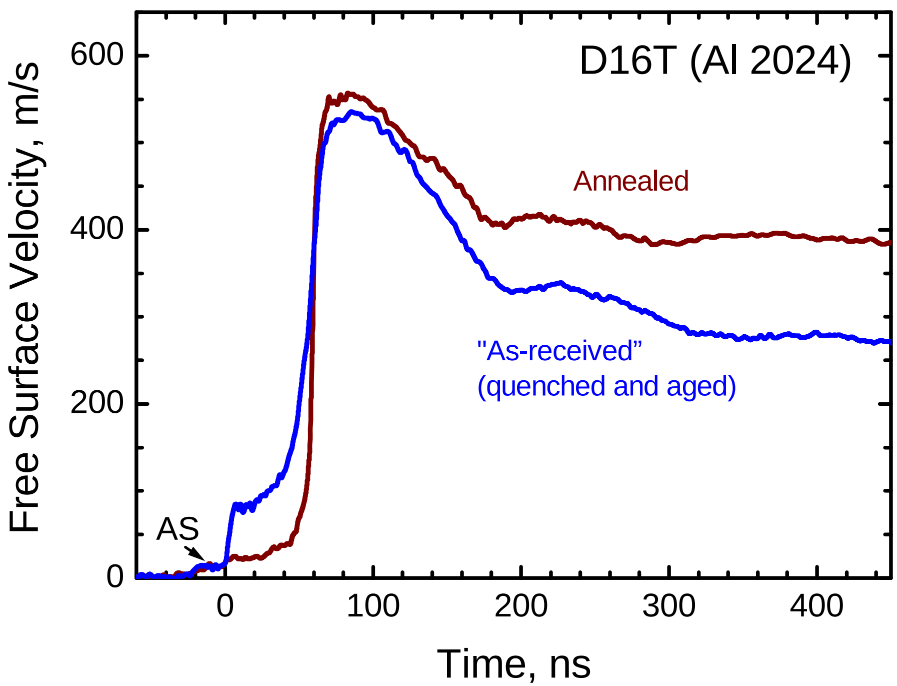
Spalling is the process of internal rupture of a body due to tensile stresses generated as a result of a compression pulse reflected from the free surface.





MANIFESTATIONS OF STRUCTURAL FACTORS AT SPALLING

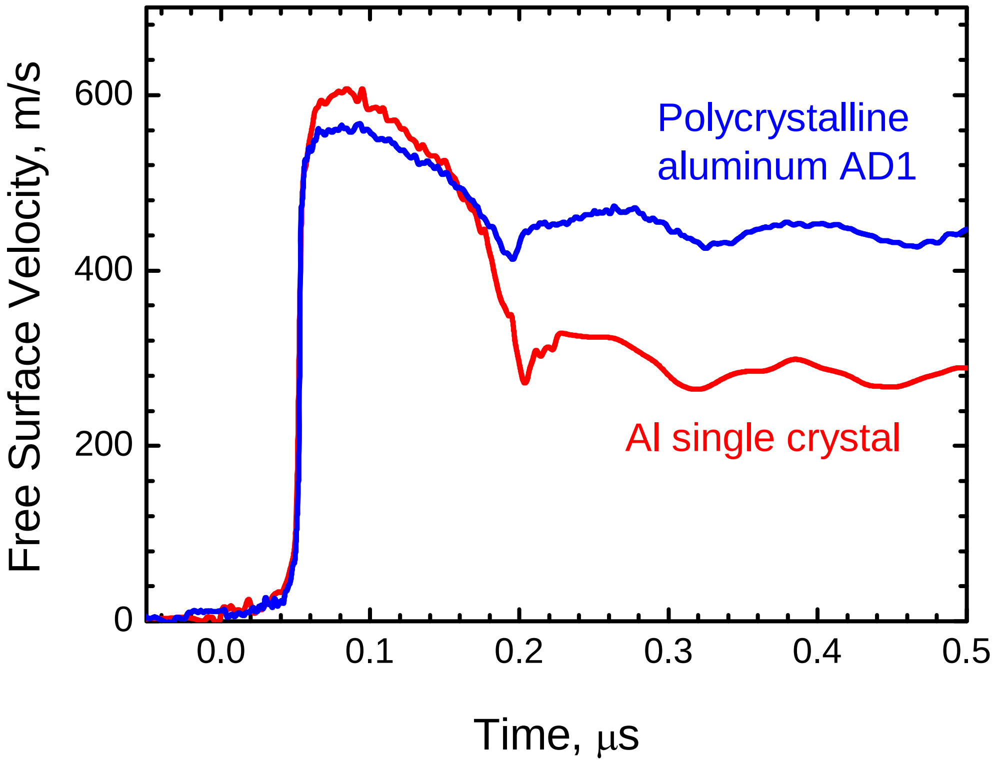




- The spall strength is by ~15% less in the case of loading in the lateral direction;
- Faster decay of the velocity oscillations correlates with a more highly developed fracture surface;

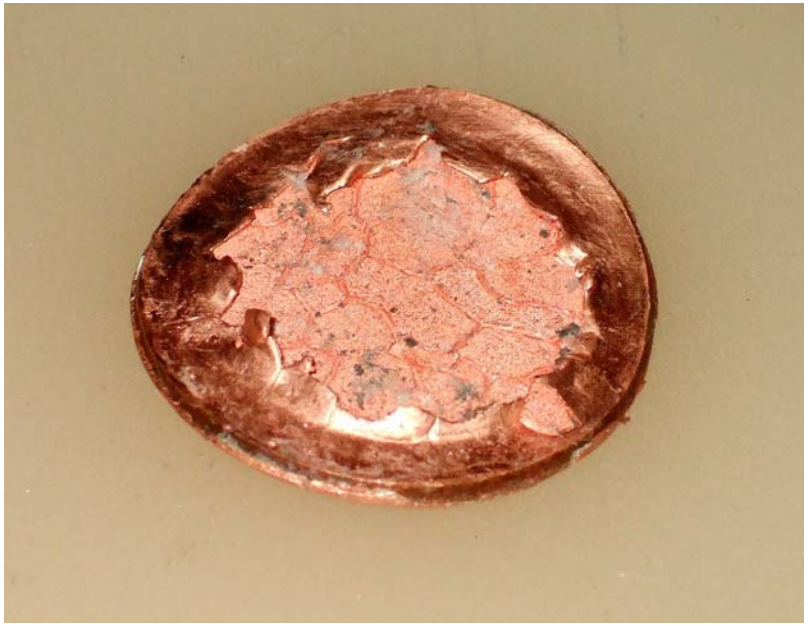
- The “as received” alloy demonstrates high spall strength and relatively slow fracture process;
- Annealing resulted in decrease of the spall strength and fasten the fracture process;

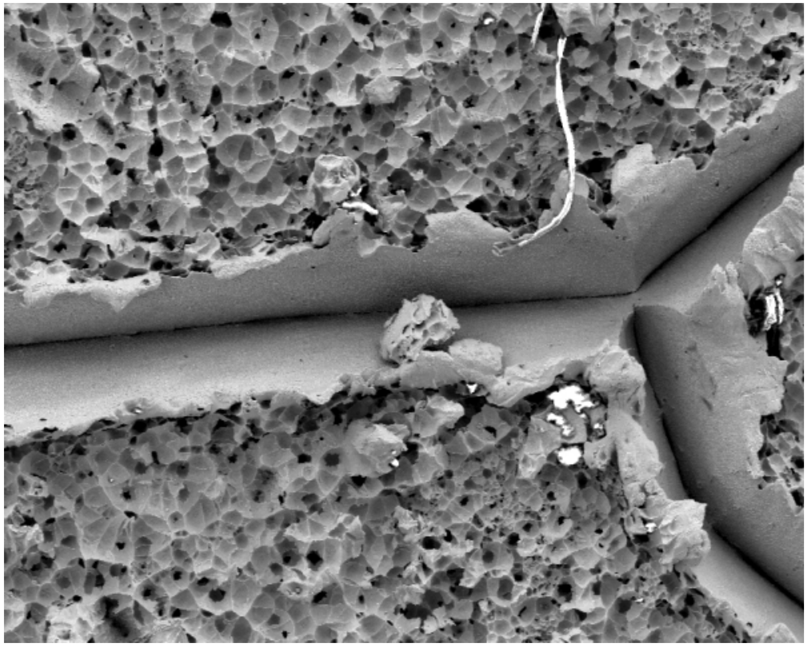
Polycrystalline metals and metal single crystals

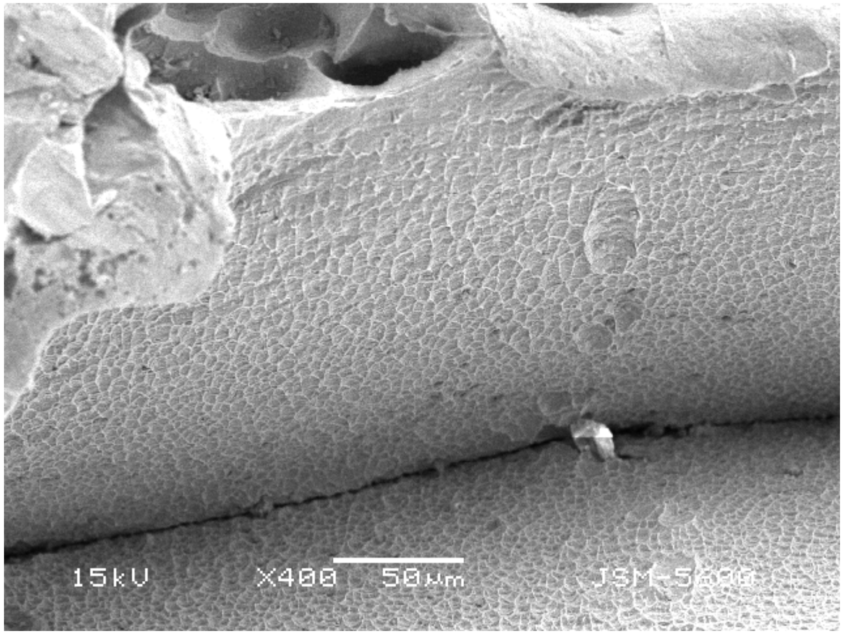


Highly homogeneous single crystals are free of potential fracture nucleation sites and demonstrate much higher spall strength than that of polycrystalline material.

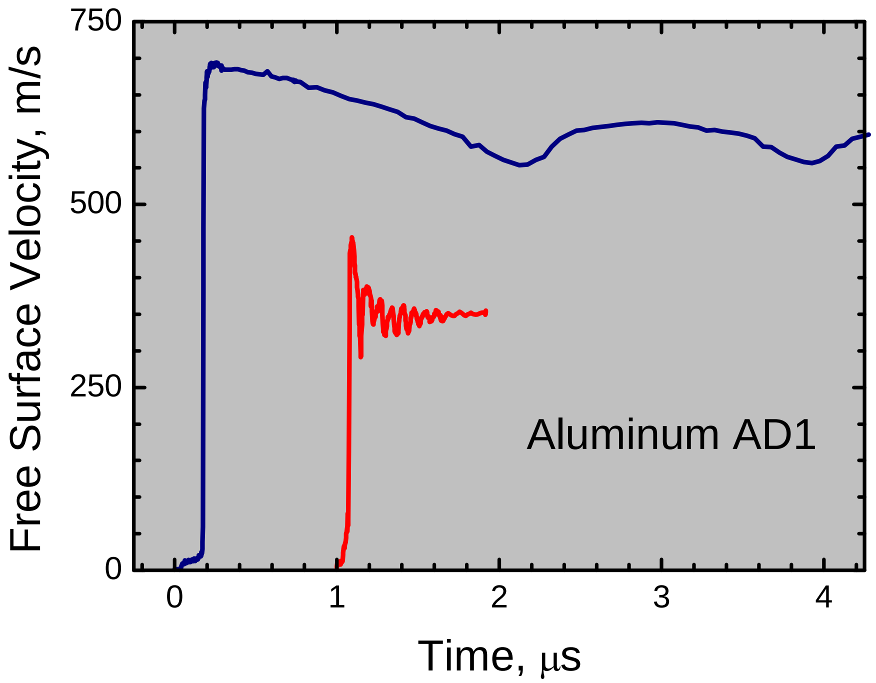
Intragranular and intergranular fracture of copper

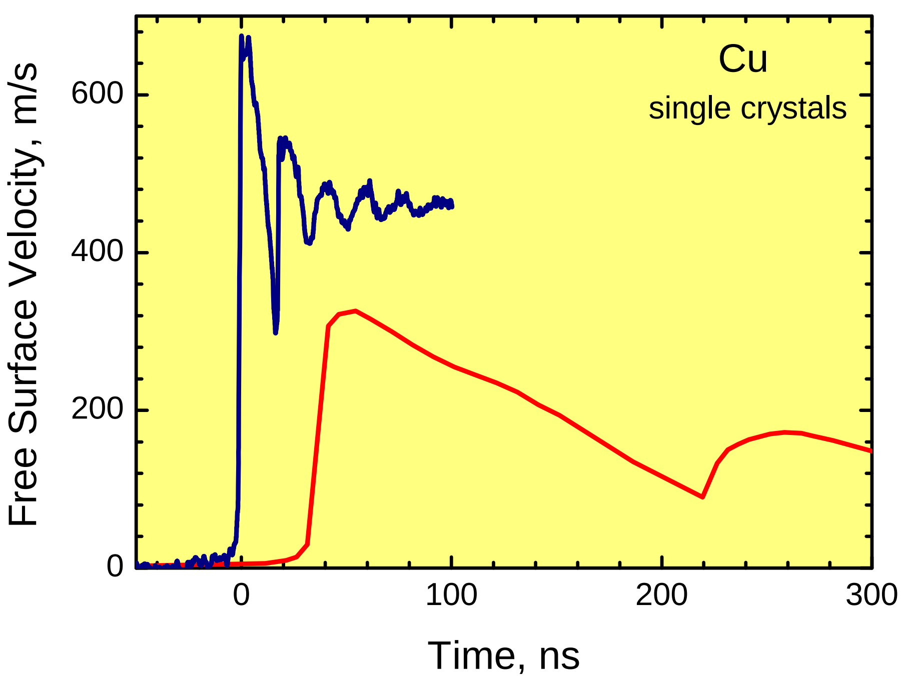






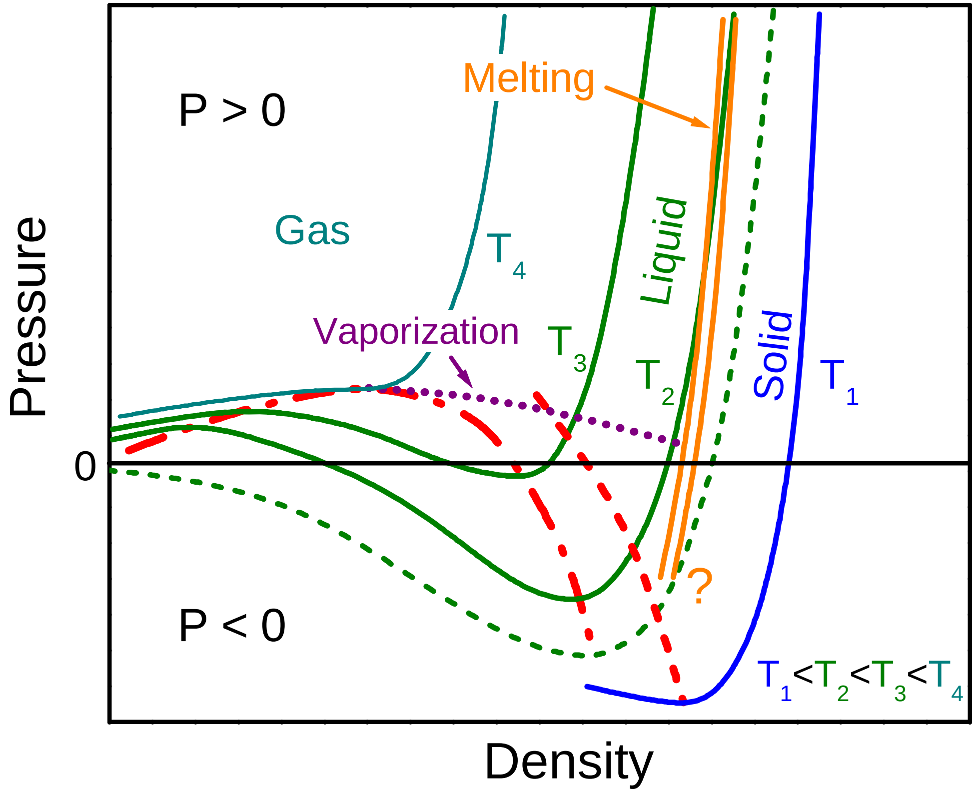
SPALL FRACTURE OVER WIDE RANGE OF THE LOAD DURATION





The load duration is varied from ~10 ns to ~10 μs

The resistance to spall fracture grows with increasing the strain rate

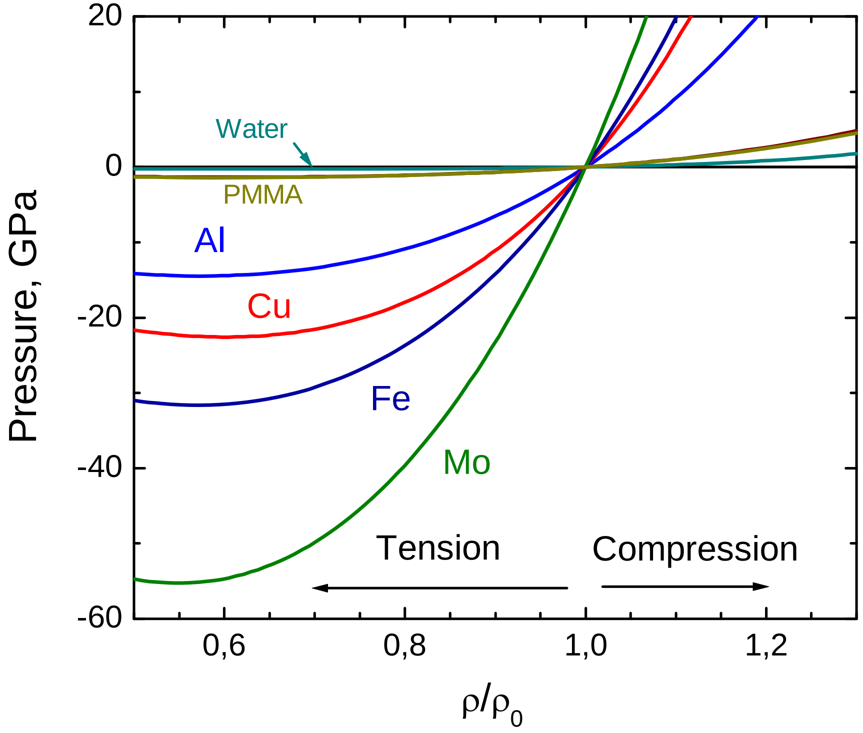


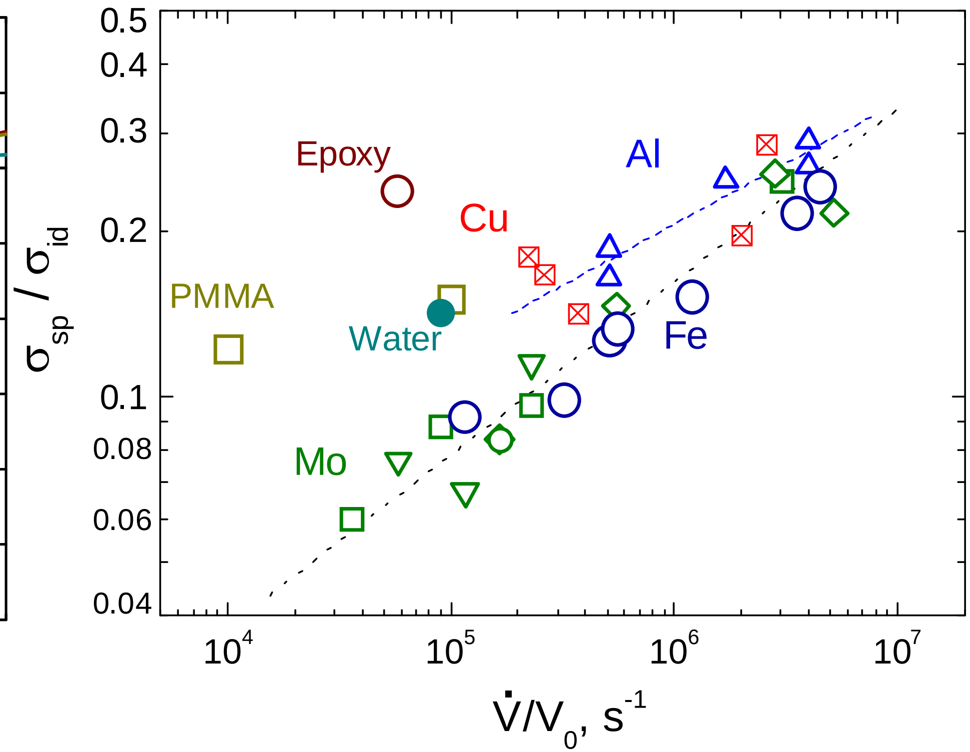
- The pressure of a gas cannot be negative.
- Unlike gases, liquids and solids have a finite density at zero pressure due to attractive intermolecular interactions.
- Stretching **a liquid** or **a solid** means applying a negative pressure to it.
- The stretched states are bounded by the **spinodal.**

$$J = J_0 \exp\left(-E_a / kT\right)$$

$$p_c(T) = -\left[\frac{16\pi\gamma^3}{3kT\ln\left(J_0 V \Delta t\right)}\right]^{1/2}$$

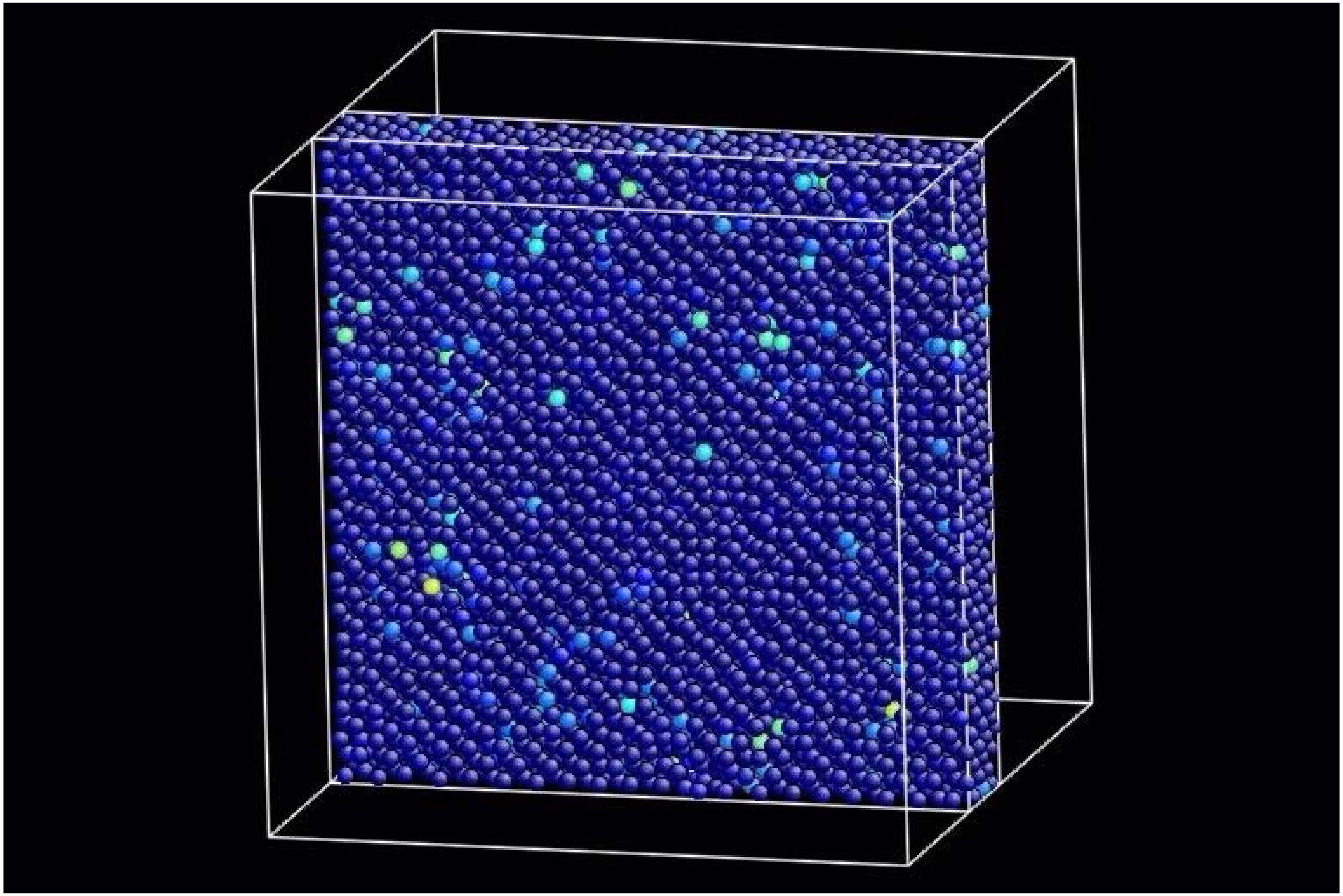
APPROACHING THE IDEAL STRENGTH





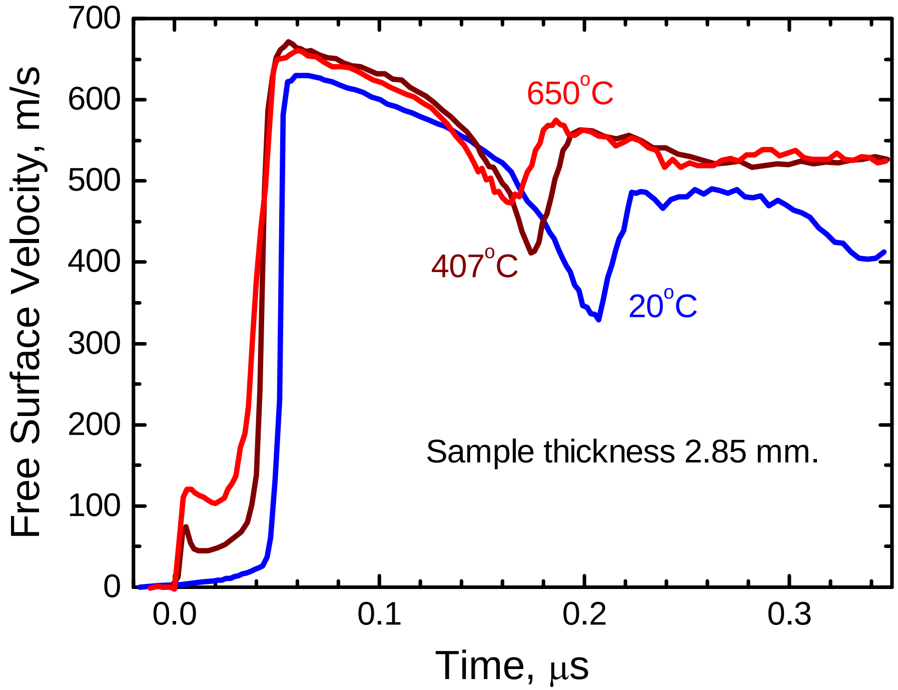
- **As much as 30 % of ideal strength is reached at load duration of a nanosecond range.**

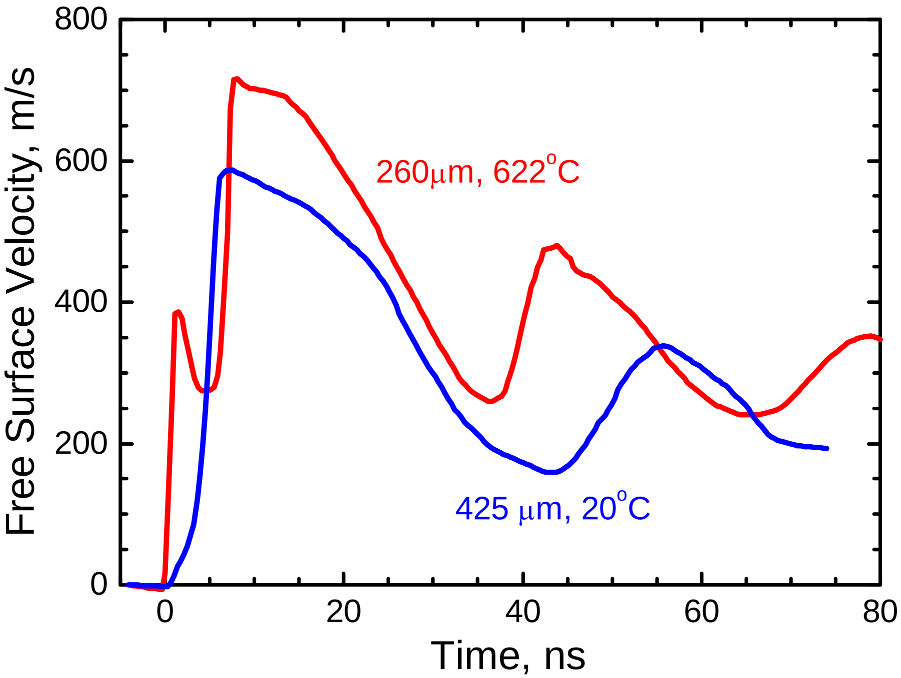
NUCLEATION OF FRACTURE.
Molecular-dynamic simulations.



Thermal effects

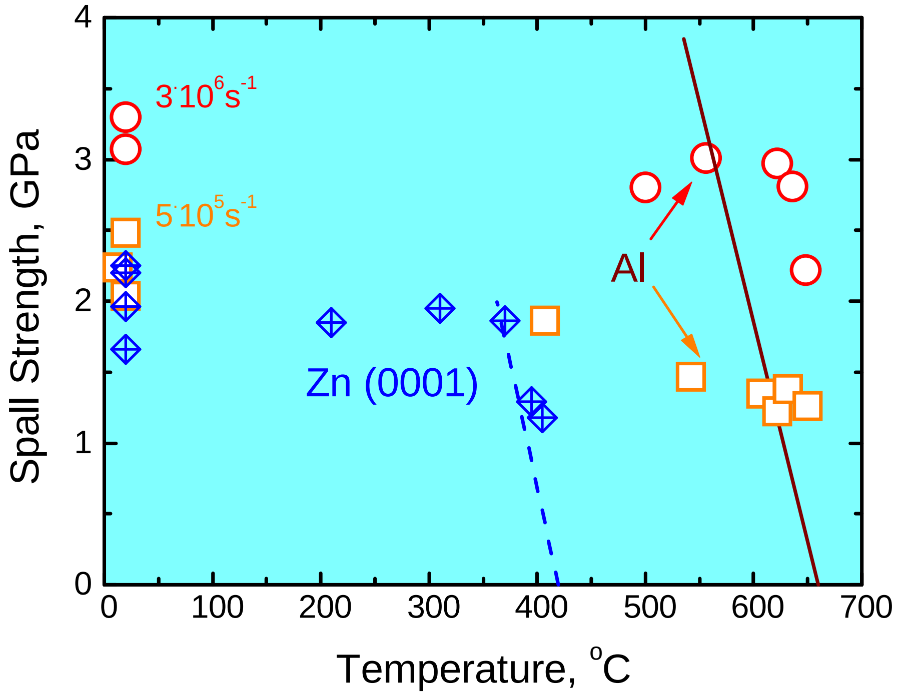
SHOCK-WAVE LOADING OF ALUMINUM SINGLE CRYSTALS AT ELEVATED TEMPERATURES

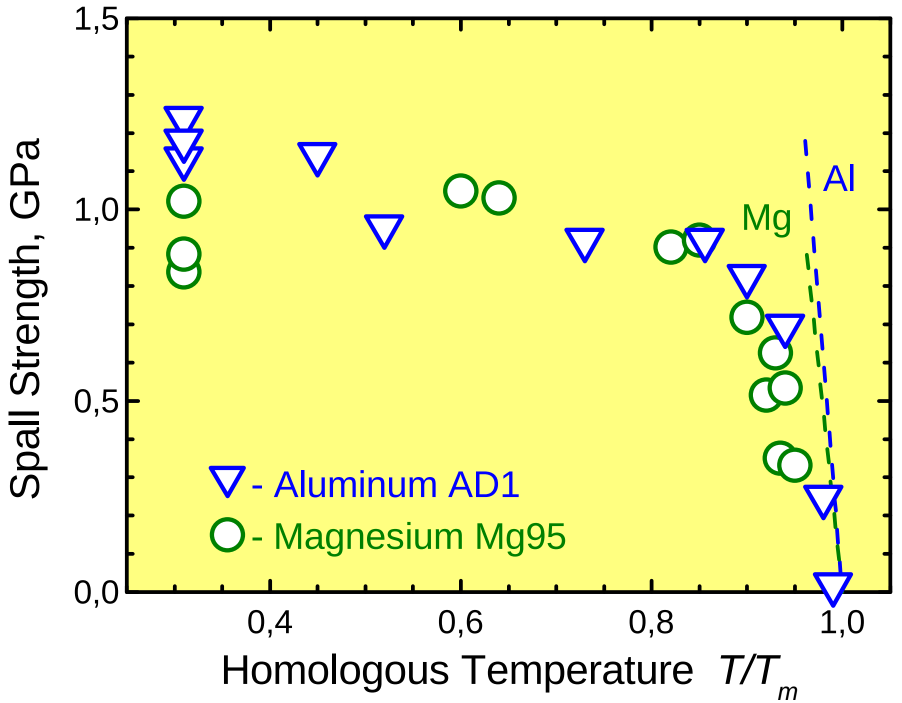




- **High spall strength is maintained up to temperatures just by 10° below the melting point;**
- **The Hugoniot elastic limit unexpectedly grows with increasing the temperature;**
- **The velocity pullback (spall strength) decreases whereas the HEL increases with heating;**
- **A strong rate sensitivity results in a strong decay of the elastic precursor wave.**

SPALL STRENGTH OF SINGLE CRYSTALS AND POLYCRYSTALLINE METALS AT MELTING

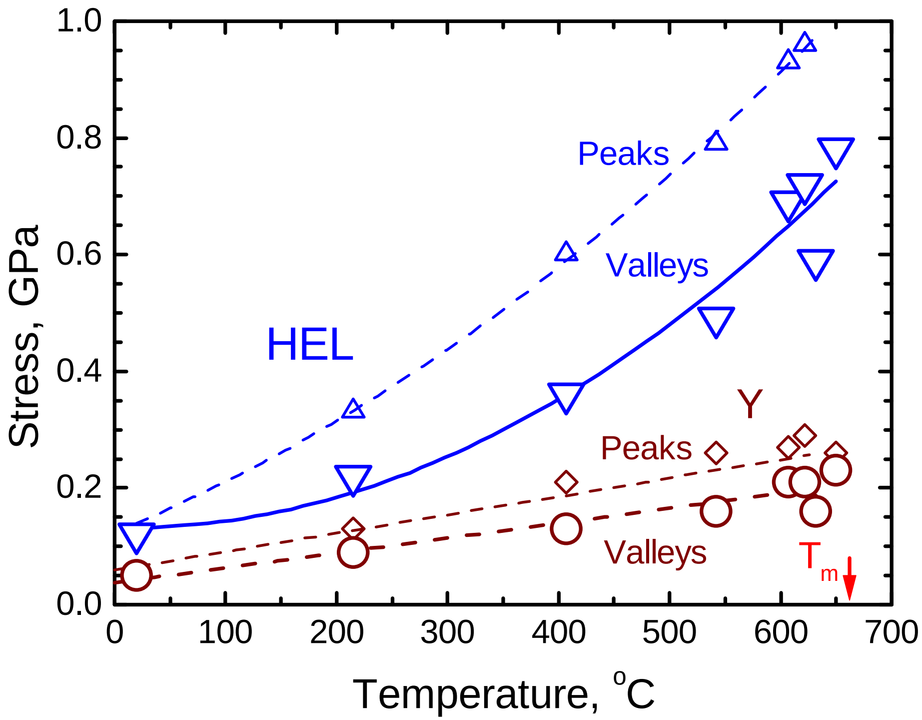


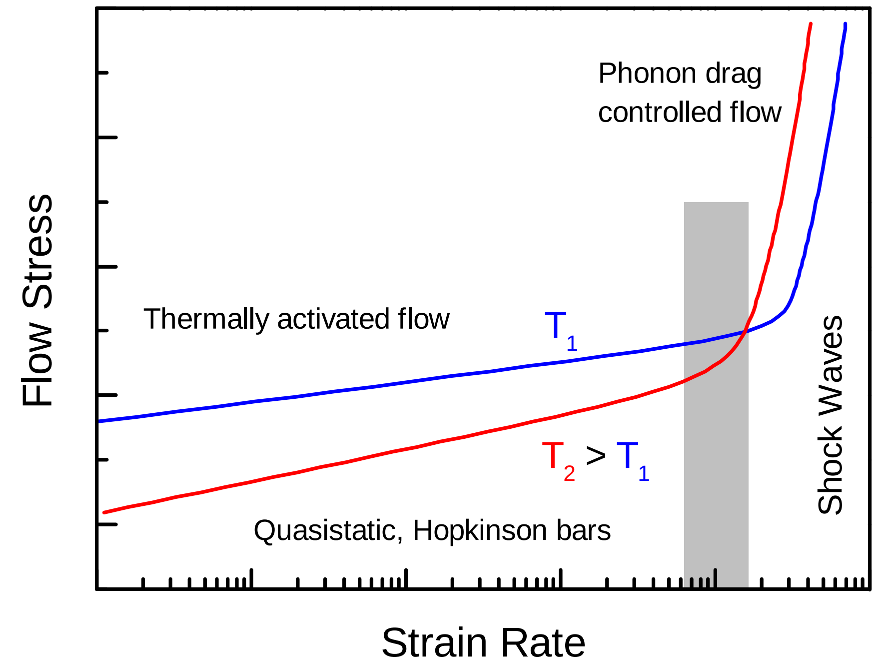


- **The strength of polycrystalline metals drops when the material begins to melt whereas single crystals maintain a high resistance to spall fracture when melting should start;**
- In polycrystalline solids melting may start along grain boundaries at temperatures below the melting temperature of the crystal: pre-melting phenomenon;
- **Superheated solid states were realized in the crystals under tension**

ANOMALOUS GROWTH

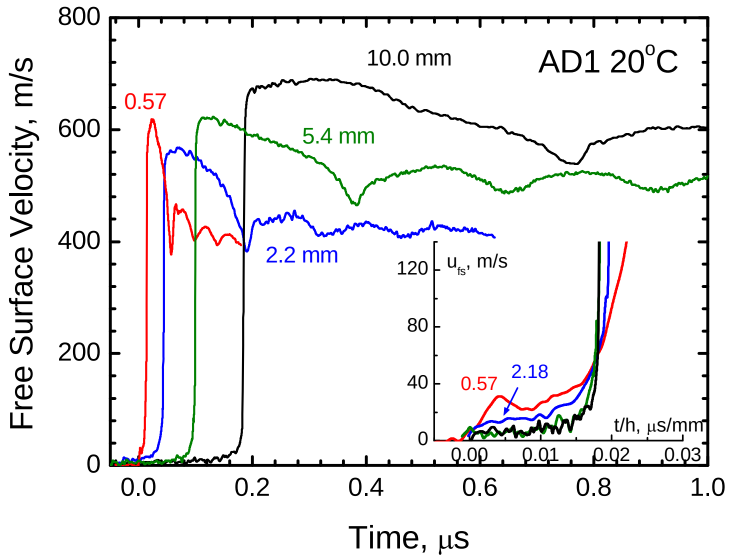
OF THE DYNAMIC YIELD STRENGTH OF ALUMINUM SINGLE CRYSTALS WITH INCREASING THE TEMPERATURE

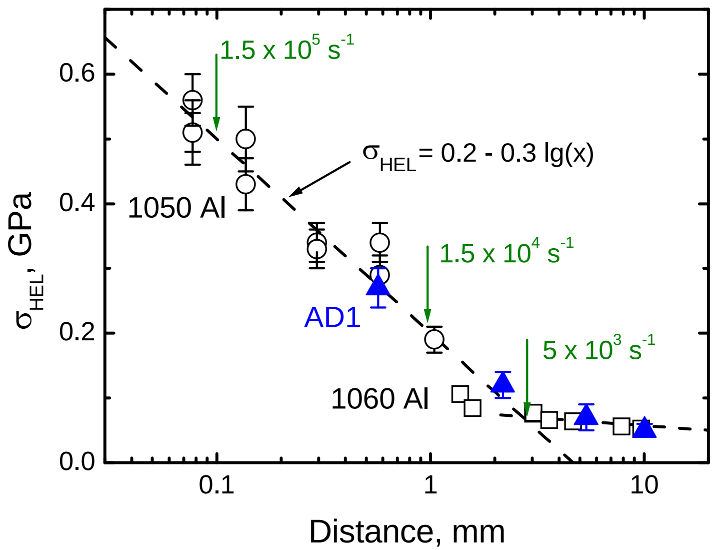


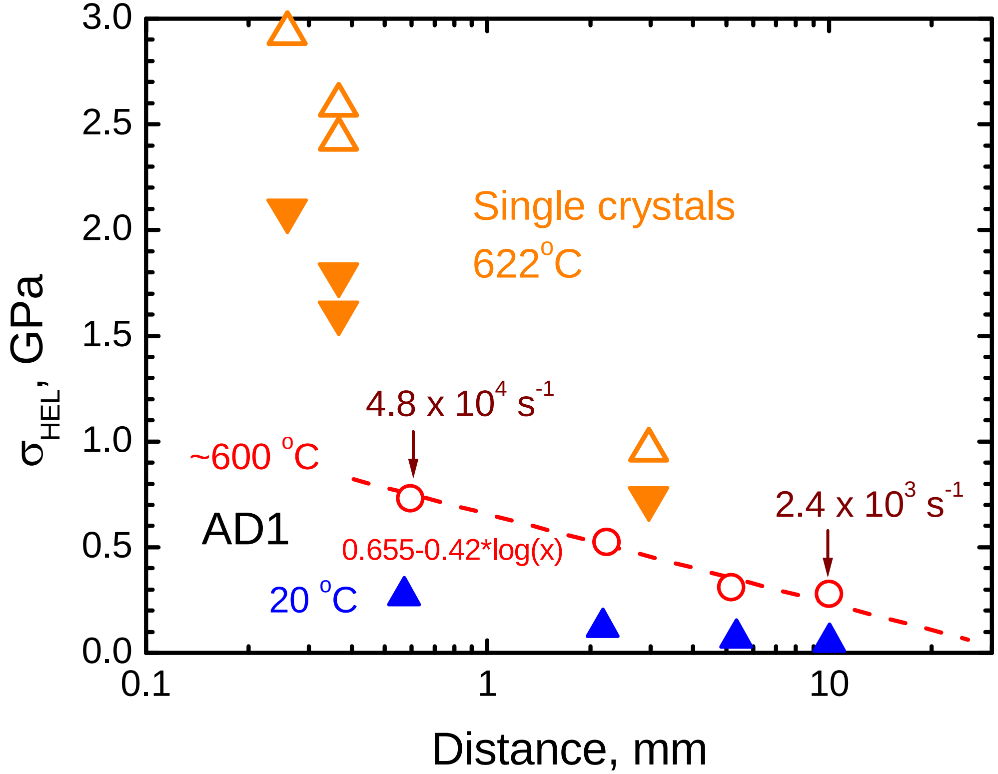


- Dynamic yield strength increases linearly with increasing temperature;
- Yield strength near the melting temperature exceeds its value at room temperature by a factor of four and the ratio of the yield strength to the shear modulus increases by an order of magnitude (at low strain rates this ratio decreases to half of this value as the temperature is increased to 900K)
- **Under conditions of shock deformation of aluminum the dislocation drag is determined by thermal oscillations of atoms.**

Anomalous thermal hardening

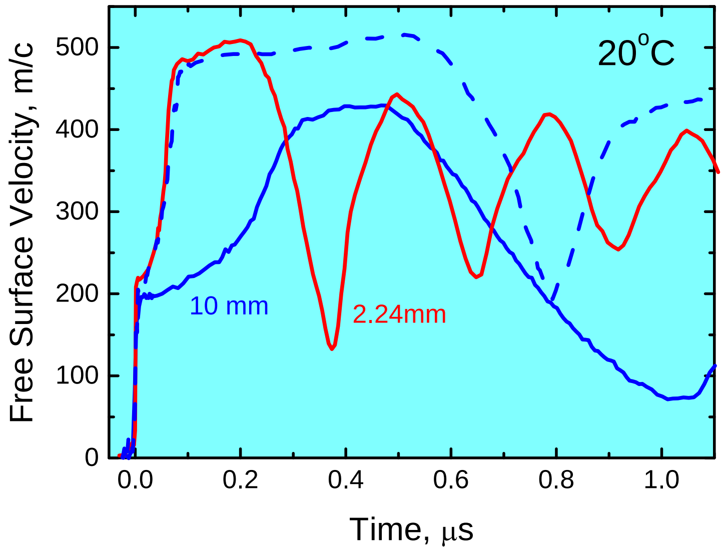


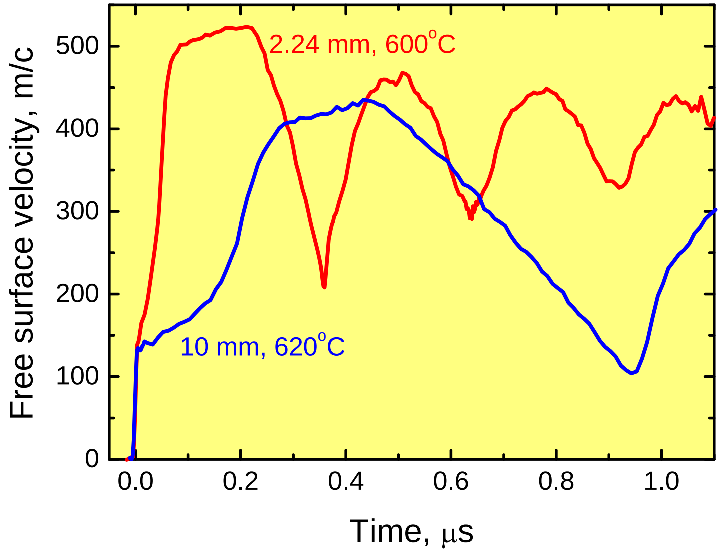


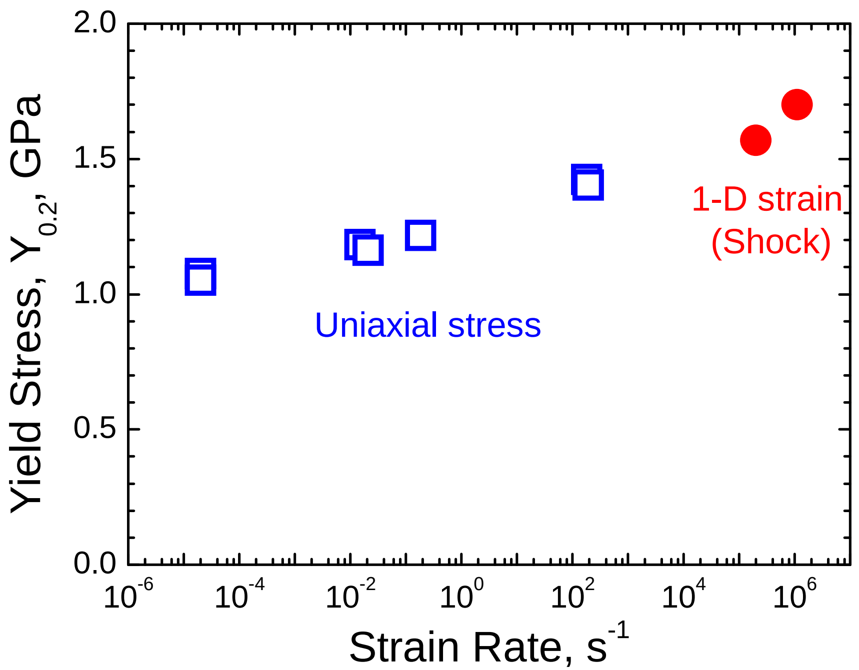


$$\frac{d\sigma_{HEL}}{dh} = -\frac{1}{2}\rho_0 c_l \dot{\gamma}$$

SHOCK WAVES IN TI-6-22-22S SAMPLES AT NORMAL AND ELEVATED TEMPERATURES







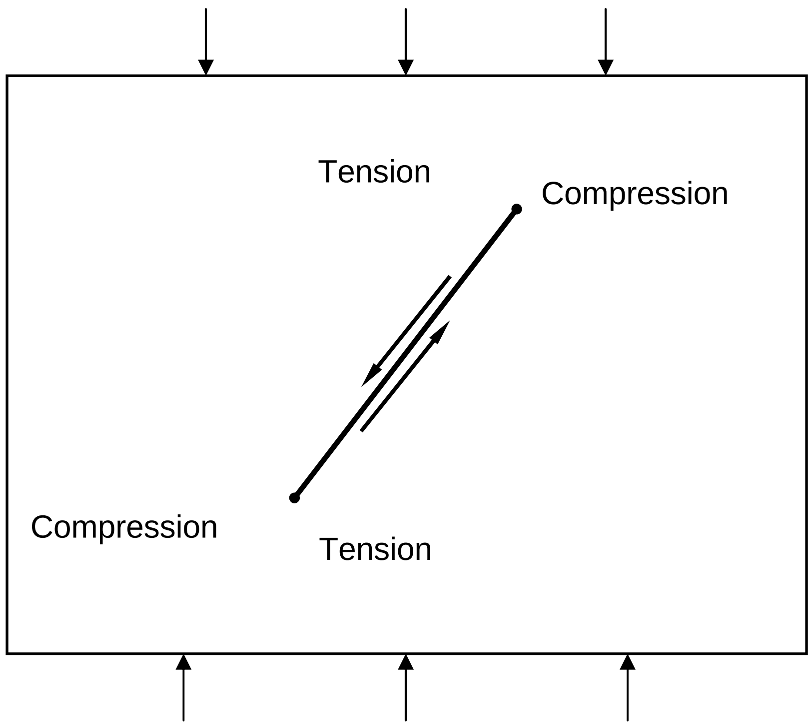
General dependence and dominating mechanism of dislocation motion are maintained at highest strain rates

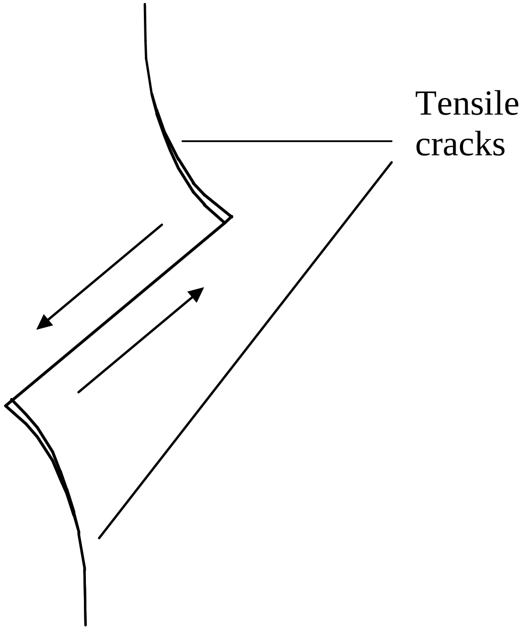
BEHAVIOR OF BRITTLE MATERIALS

COMPRESSIVE FRACTURE OF BRITTLE MATERIALS

Open cracks may appear only under tensile stresses.

Even when applied stress is wholly compressive, the local stress may become tensile at certain points at pre-existing crack tip.

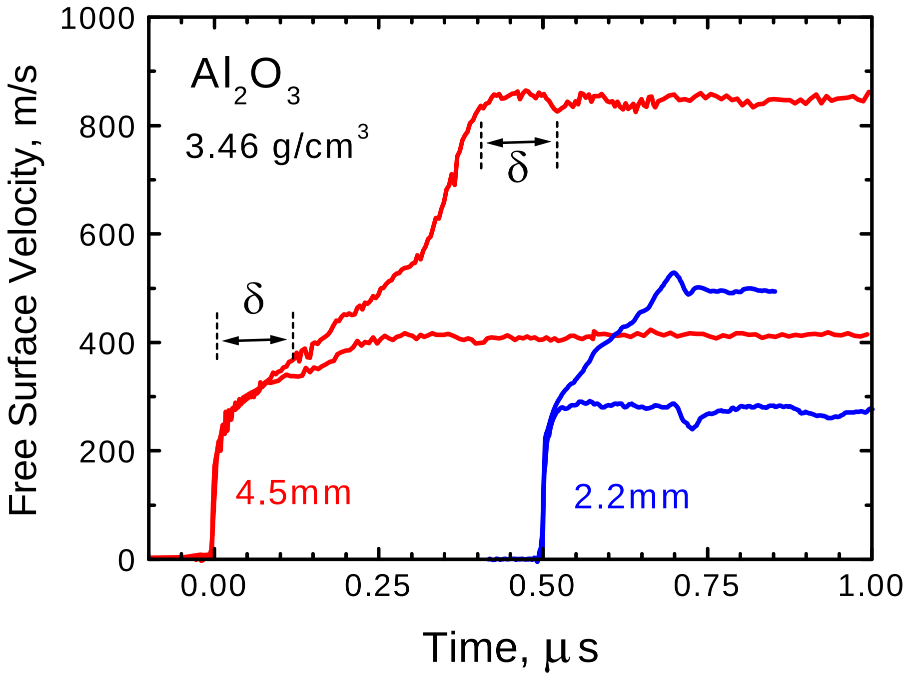




Wing crack

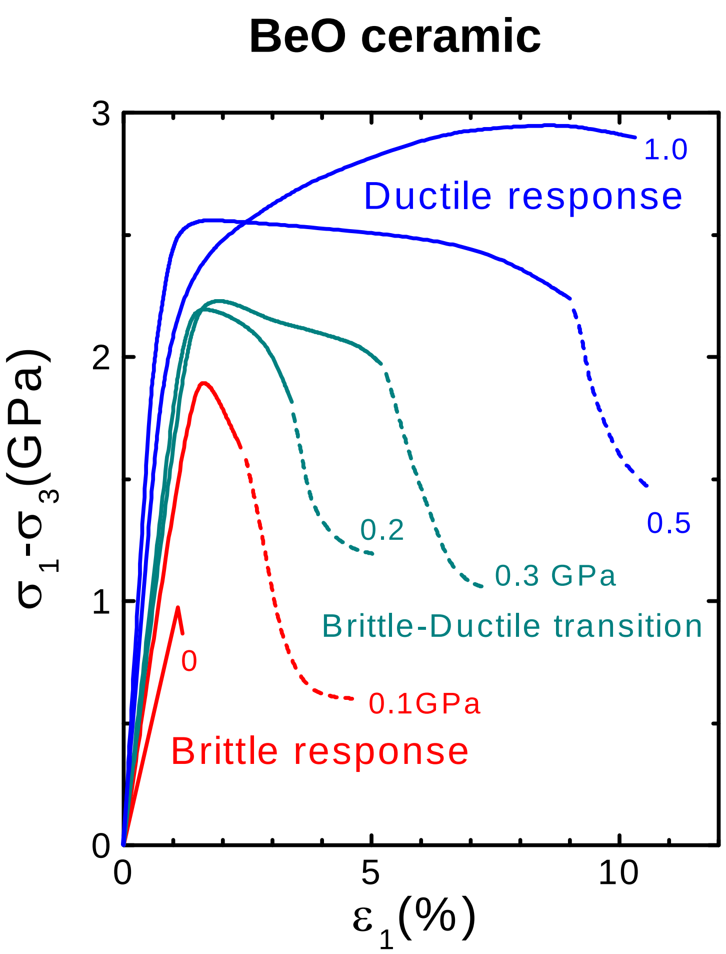
Griffith's fracture criterion: the fracture occurs when the highest local tensile stress at the longest crack of the most dangerous orientation reaches a critical value.

SHOCK COMPRESSION AND SPALL FRACTURE OF ALUMINA CERAMIC



- Ceramic demonstrates remarkable spall strength when the spallation occurs after elastic compression or after compression at insignificant plastic deformation.
- The waveforms do not indicate any signature of compressive fracture

BRITTLE-DUCTILE TRANSITION AT HIGH PRESSURE

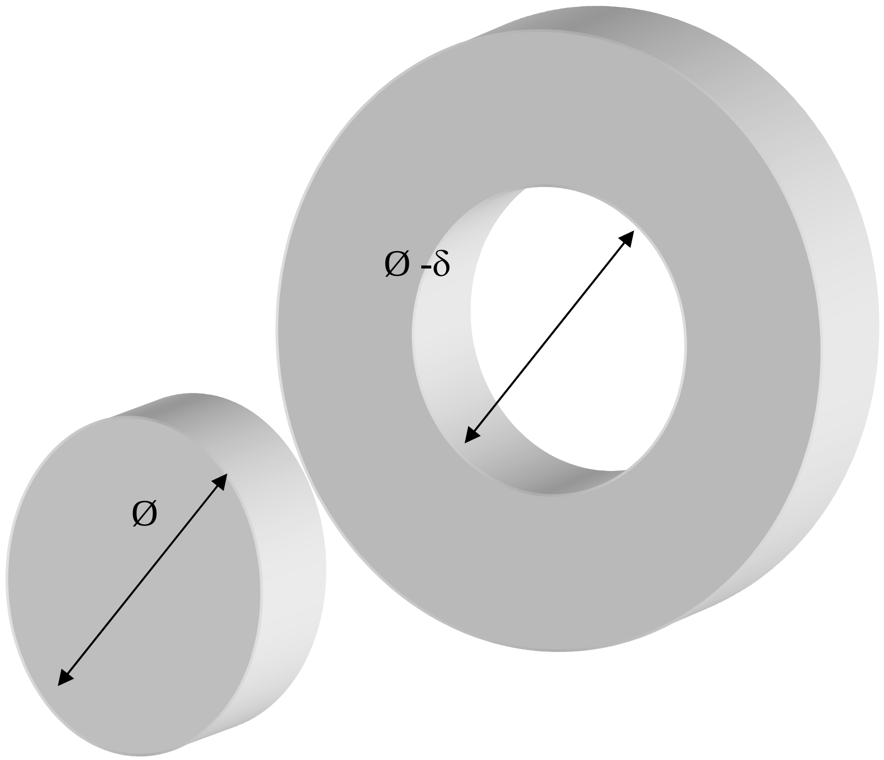


H.C. Heard, C.F. Cline, *J. Mat. Sc.*, **15**, 1889 (1980)

- Below 0.2 GPa of the confining pressure the ultimate compressive strength increases rapidly with pressure growth.
- The brittle-ductile transition occurs within 0.2–0.3 GPa pressure range.
- Above 0.3 GPa the ultimate strength is growing much slower.

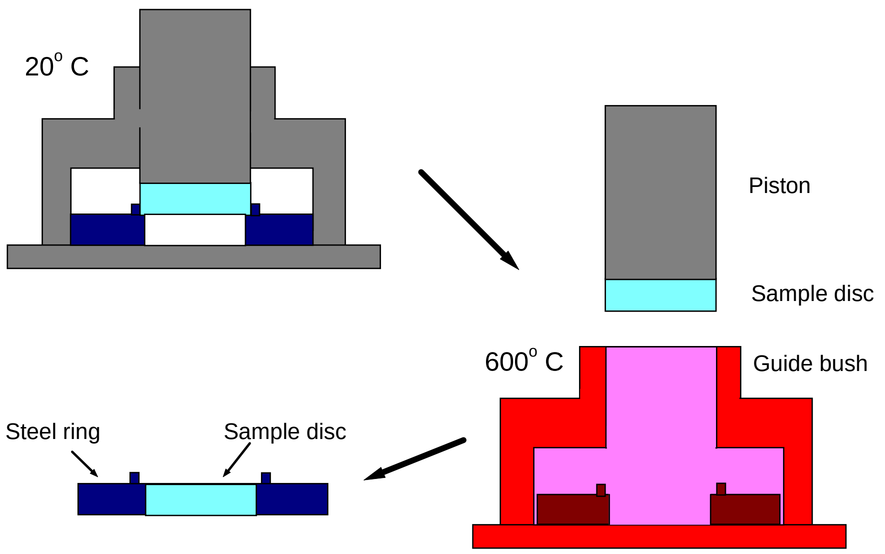
- Ceramic exhibits an increasing ductility when the confining pressure arises above the brittle-ductile transition.
- At a low confining pressure, the failure occurred by macroscopic shear on fault planes, while the rest material contained numerous axial microcracks.
- At a confining pressure > 0.5 Gpa, the dominant deformation mechanism became intracrystalline slip by dislocation motion.

EXPERIMENTS WITH SPECIMENS CONFINED BY SHRINK-FIT SLEEVE



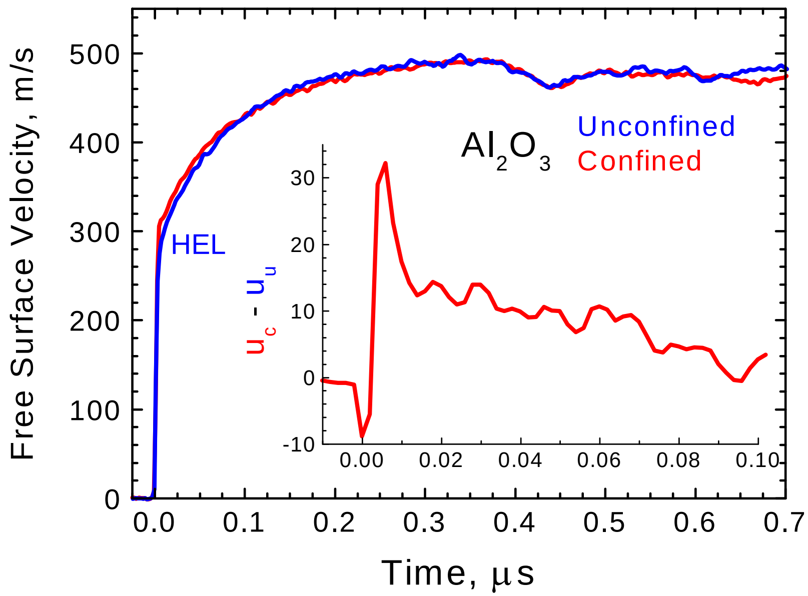
FITTING OF THE DISK SAMPLE INTO THE COMPRESSIVE RING

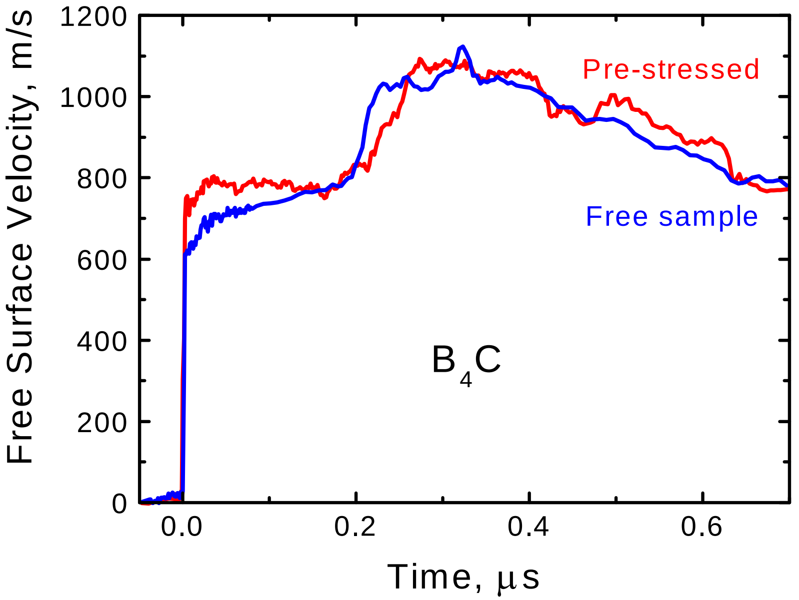
(Zaretsky et al., 2002)



The confining stress produced by the sleeve is controlled by the misfit δ value and the yield stress of the sleeve material.

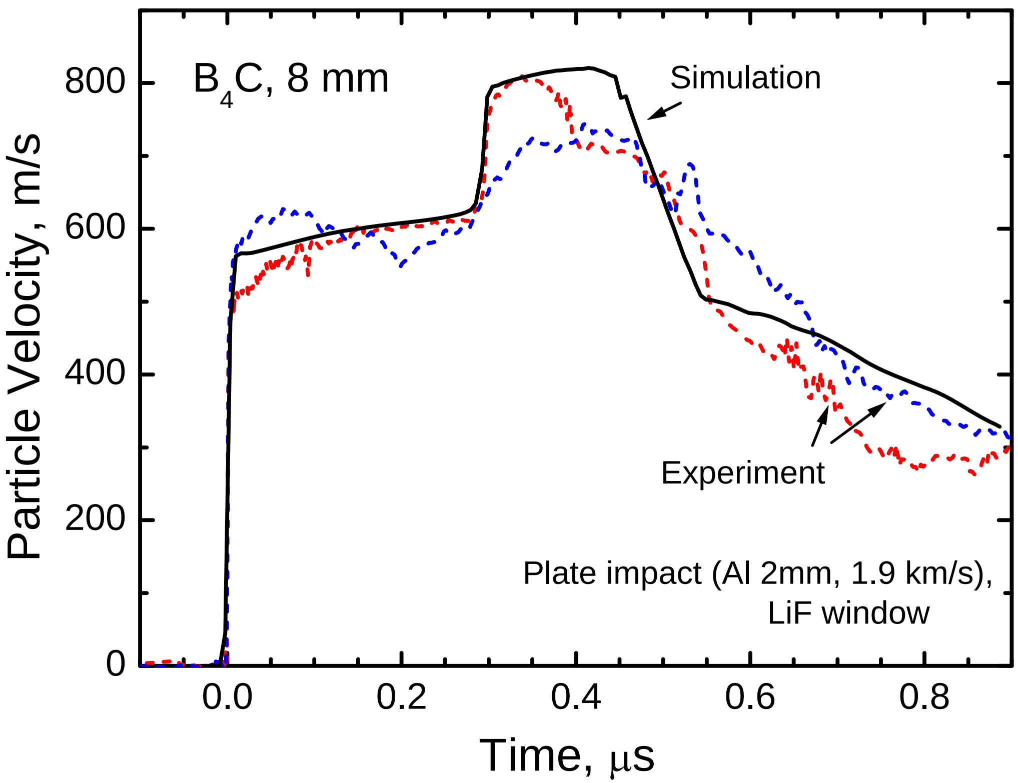
DUCTILE AND BRITTLE RESPONSE OF CERAMICS UNDER UNIAXIAL SHOCK COMPRESSION

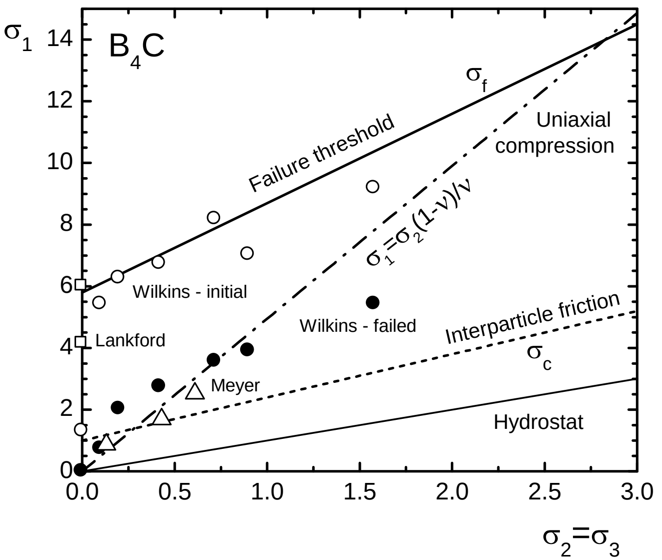


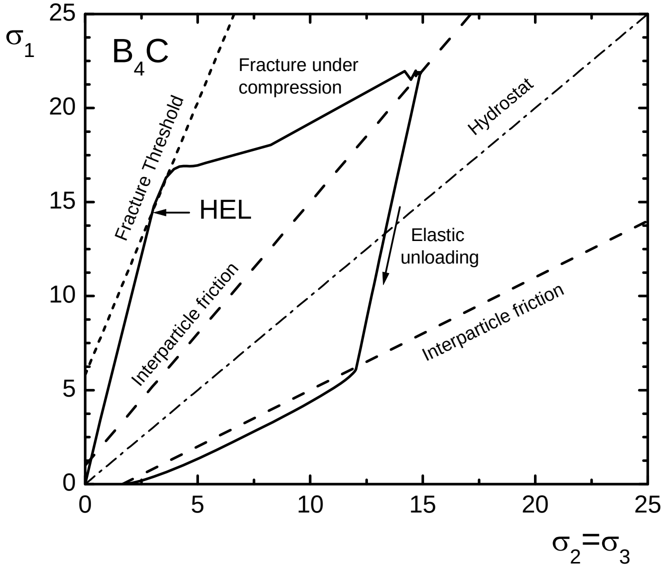


Boron carbide exhibit brittle response whereas the behavior of alumina is ductile

Compressive fracture of the B_4C ceramic
Computer simulations



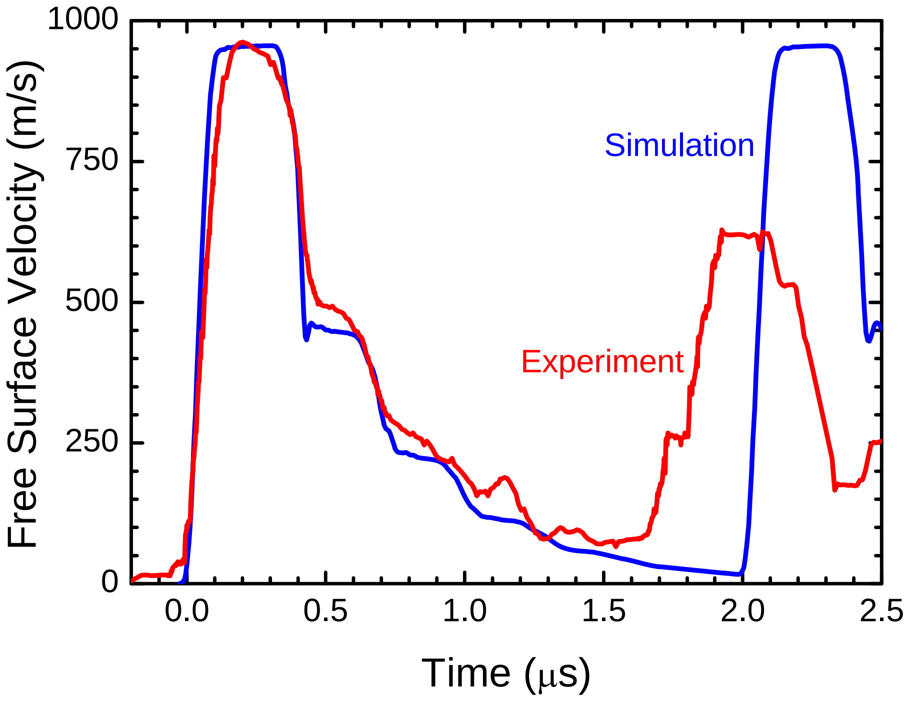


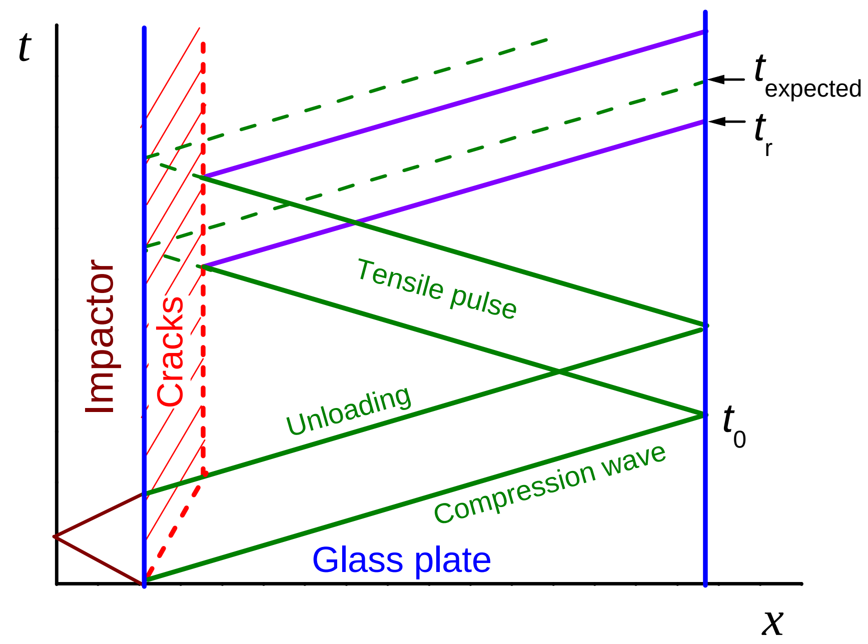


FAILURE WAVES
IN SHOCK-COMPRESSED GLASSES

MEASUREMENTS OF DYNAMIC TENSILE STRENGTH OF A GLASS

Kanel, G.I., Molodets, A.M., and Dremin, A.N., *Fizika Goren. Vzriva*, **13**(6), p. 905 (1977)

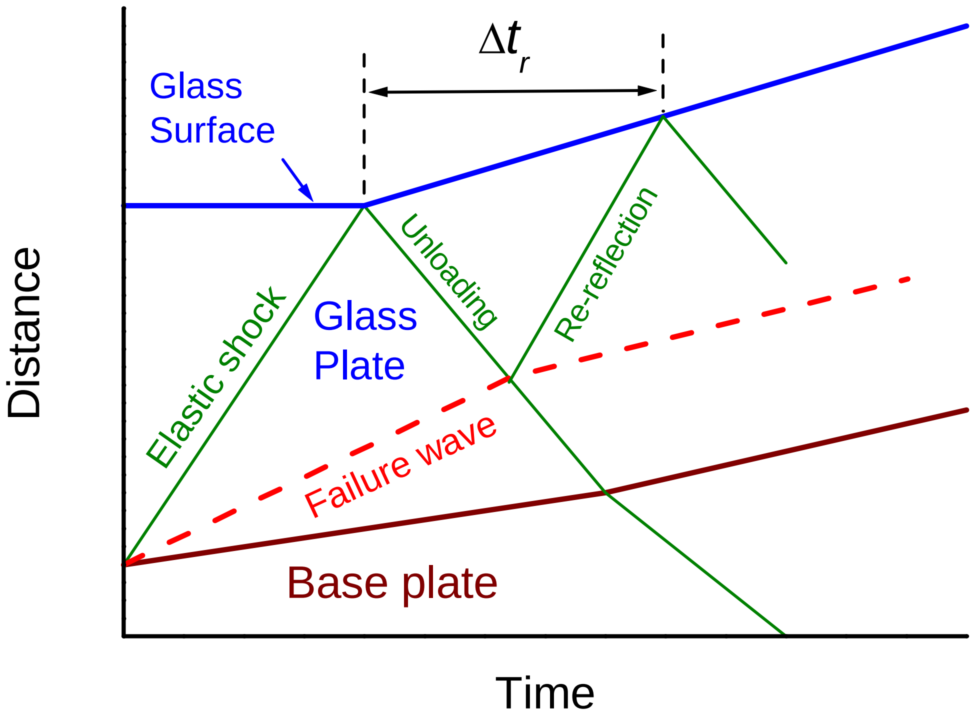




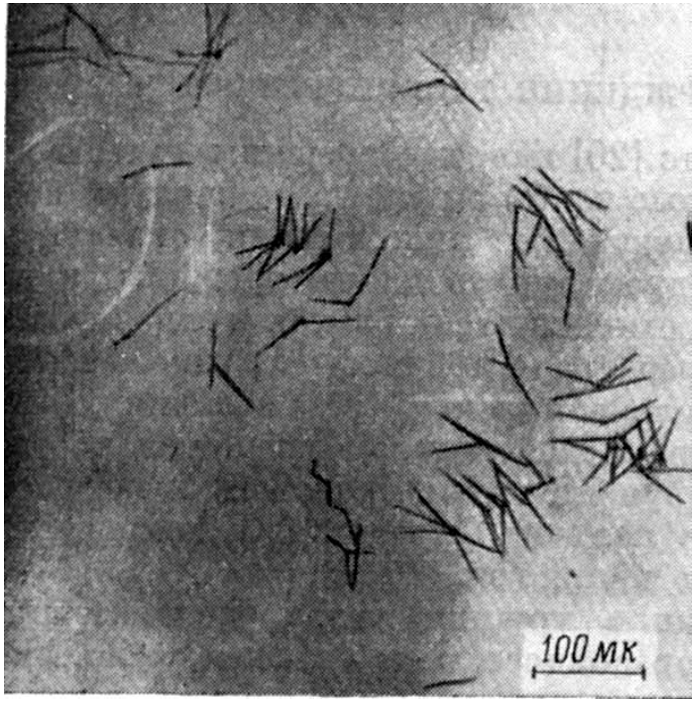
The reverberation time t_{rev} of an elastic compression pulse is less than the expected one.

The surface layer obviously has been damaged by cracks.

FAILURE WAVE IN SHOCK-COMPRESSED GLASS

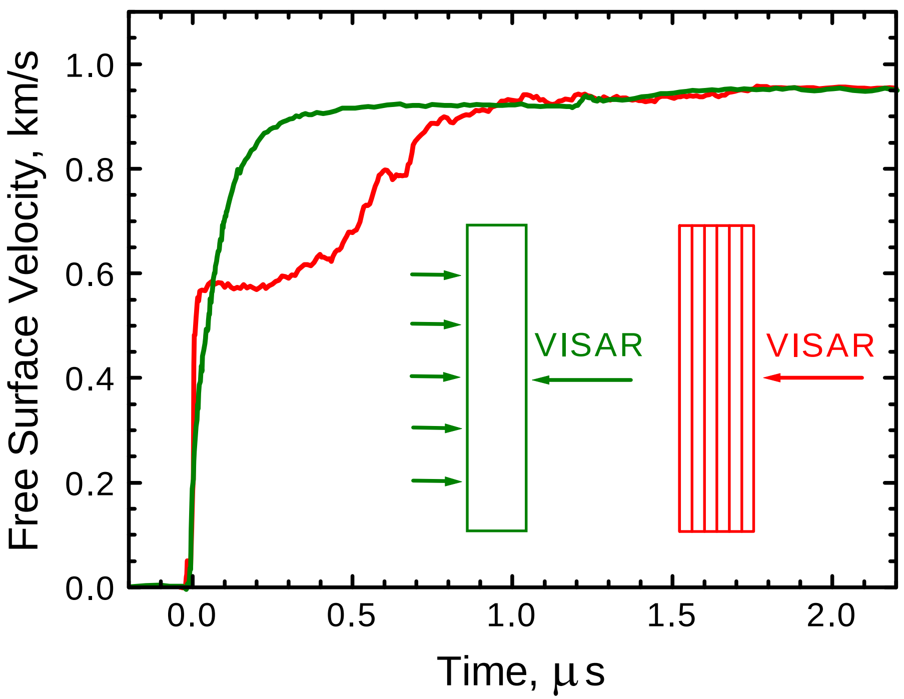


Incipient microcracks always exist on the glass surface.



- **The failure wave is a network of cracks that are nucleated on the surface and propagate with subsonic speed into the stressed body;**
- **Investigation of failure wave in shock-compressed glasses may provide information about the mechanisms and general rules of nucleation, growth and interactions of multiple cracks and lead to a better understanding of experiments on brittle ceramics and rocks.**

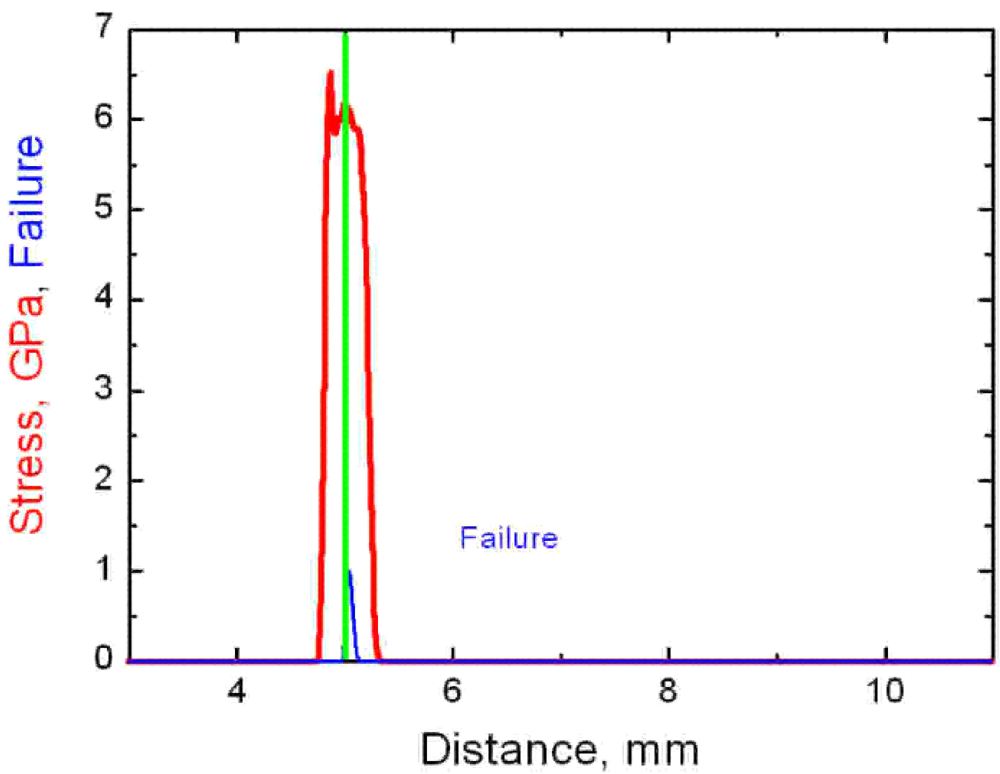
TRANSFORMATION OF SHOCK COMPRESSION PULSES IN A PILE OF SODA-LIME GLASS PLATES

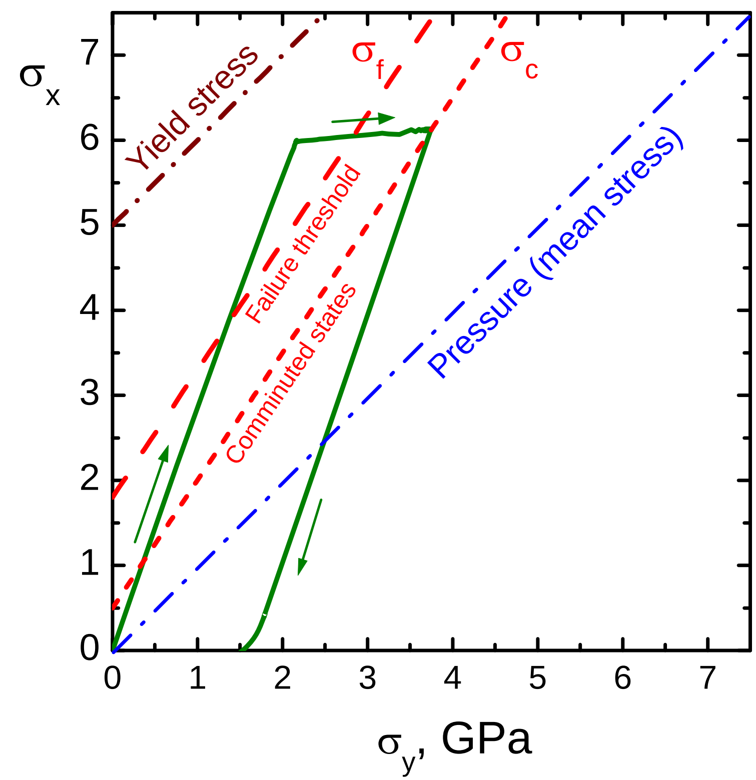


- Superposition of failure waves forms the compaction wave: elastic wave transforms into an elastic-plastic wave;
- Magnitude of the precursor wave is the failure threshold;
- The pile may be considered as a model of polycrystalline brittle material.

COMPUTER SIMULATION OF THE FAILURE WAVE:
COMBUSTION-LIKE MODEL

Copper impactor | Glass plate



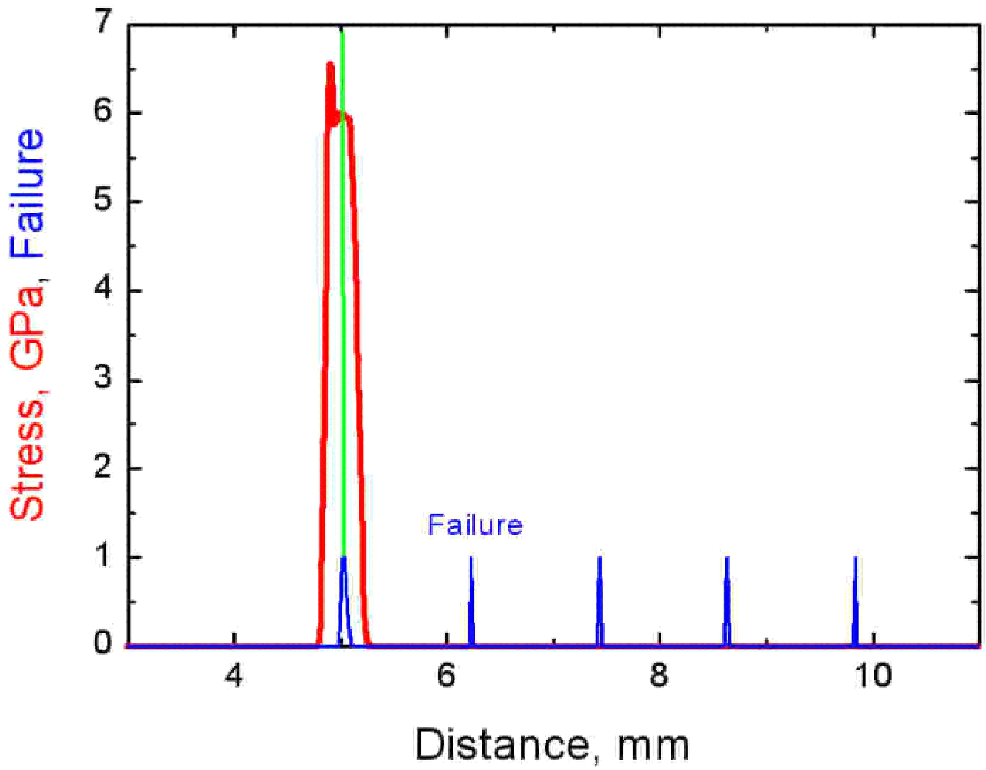


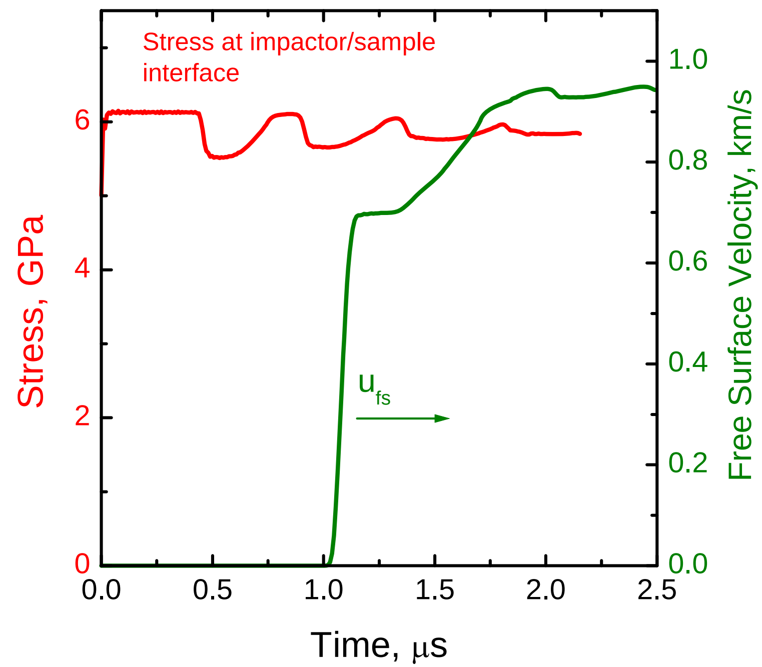
Propagation of fracture: $$\left(\frac{\partial D}{\partial t}\right)_h = c_f \left|\frac{\partial D}{\partial h}\right|_t$$

(Y. Partom. *Int. J. Impact Engng*. **21**(9), 791, 1998)

When the material becomes failed the stress deviator relaxes to σ_c

COMPUTER SIMULATION OF THE FAILURE WAVE:
COMBUSTION-LIKE MODEL

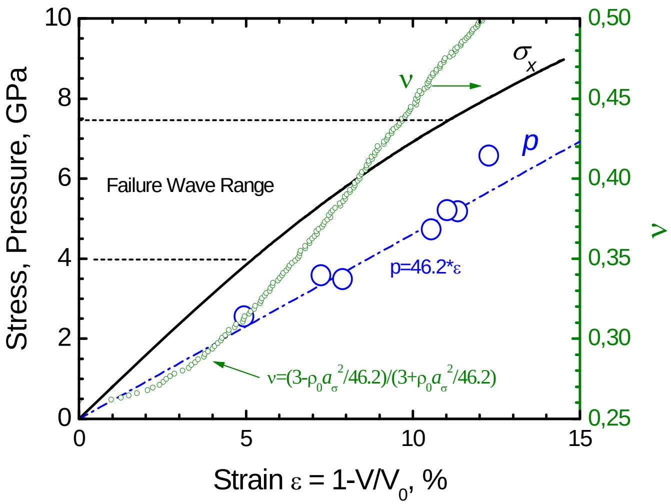


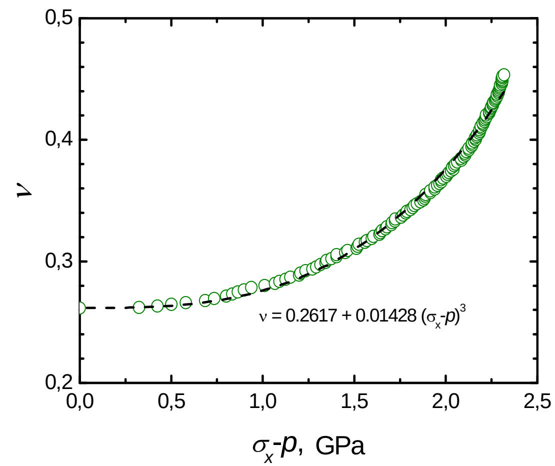


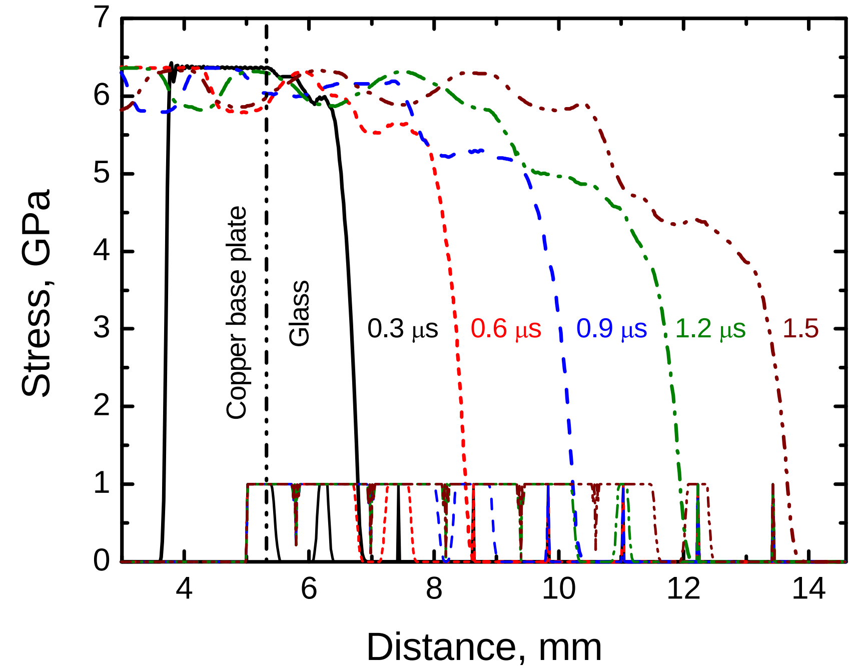
Each surface is a fracture nucleation site.

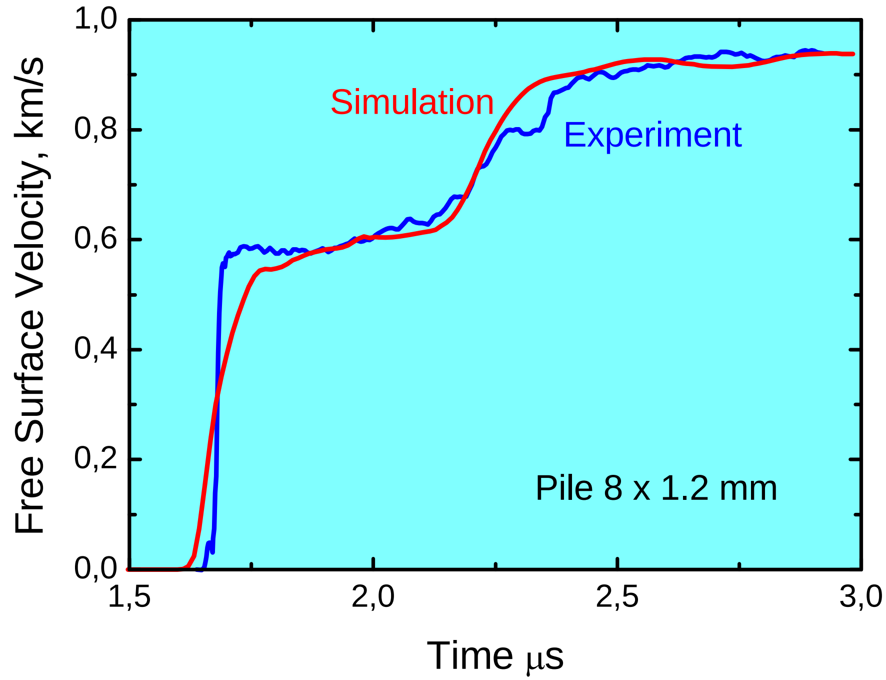
The model reproduces the decrease of magnitude of leading elastic wave at each interface, the free surface velocity history, and the stress oscillations on input glass surface.

Computer simulations with accounting for anomalous growth of the Poisson's ratio

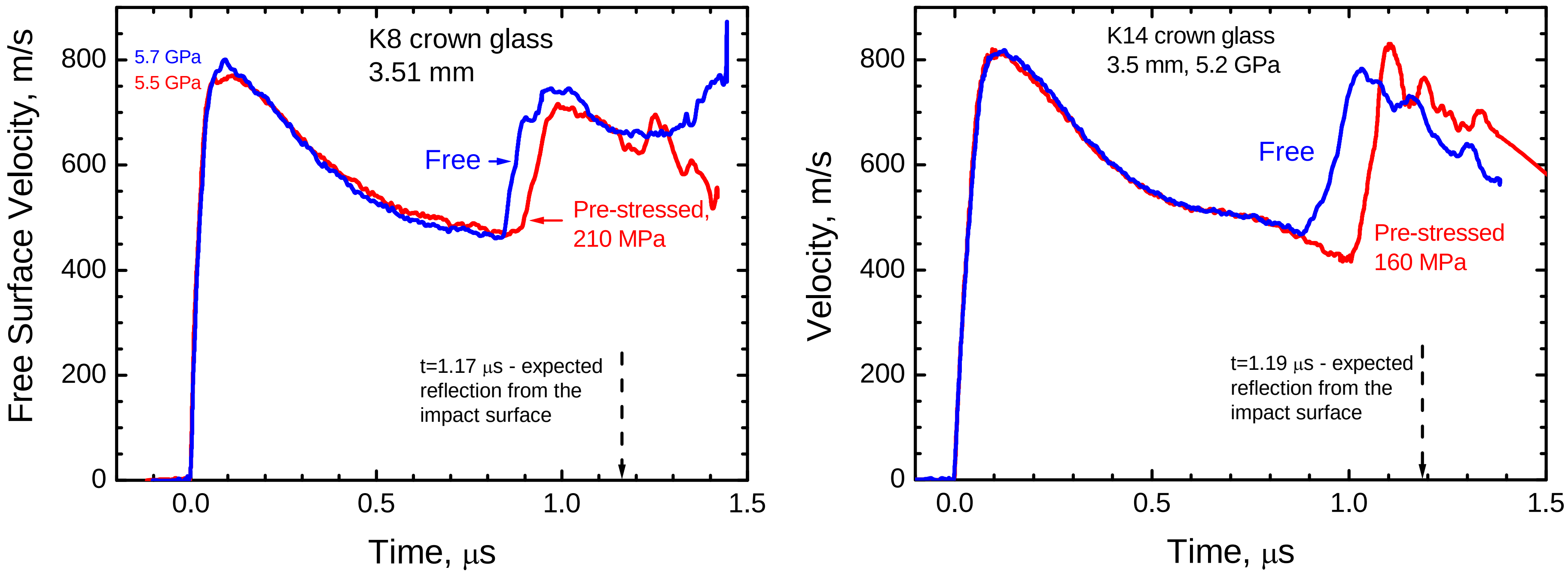








PRE-STRESS EFFECT ON THE FAILURE WAVE

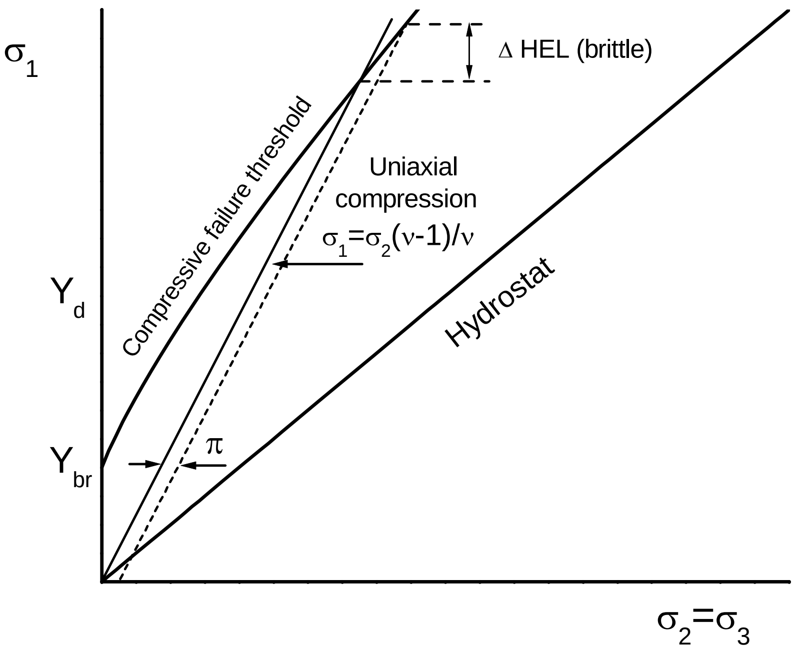


Failure wave is stopped by unloading when the stress decreases down to the failure threshold

The measurements clearly demonstrate the influence of pre-stressing on the distance of the failure propagation which appears in increased reverberation time.

The effect is larger in the case of K14 glass which is characterized higher failure threshold.

Influence of a lateral pre-stressing on the compressive failure threshold



Sensitivity of the threshold value to small variations of transversal stress (Zaretsky et al., 2002):

$$\frac{d\sigma_f}{d\pi} = \frac{(1-\nu)(3-2\nu)}{(1-2\nu)}$$

For glasses expected $d\sigma_f / d\pi \approx 3.5$

Upper estimation of real pre-stress effect $\Delta\sigma_f$ on the failure threshold σ_f

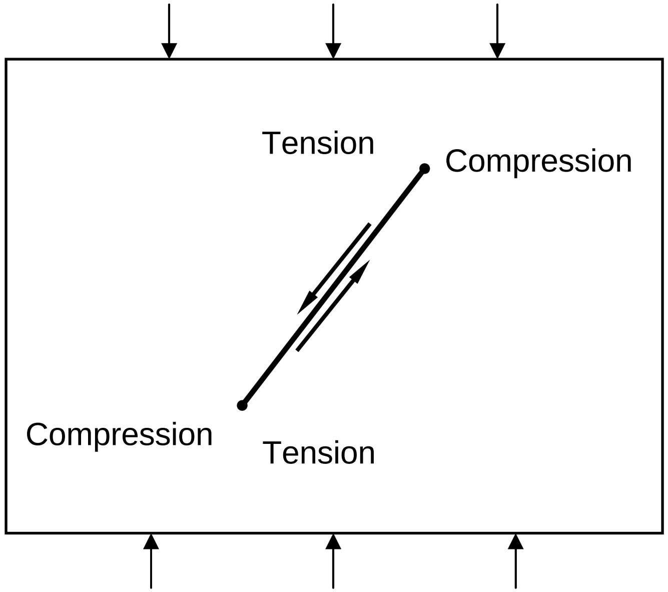
$$\Delta\sigma_f = \rho c_l \frac{\dot{u}_{fs}}{2} \frac{\Delta t_f - \Delta t_s}{2}$$

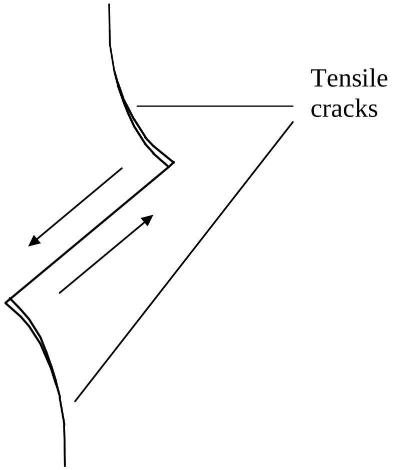
For K8 crown glass at 215 MPa radial confinement stress $\Delta\sigma_f$ = 140 MPa, $\Delta\sigma_f / \pi$ = 0.65

For K14 crown glass at 160 MPa radial confinement stress $\Delta\sigma_f$ = 400 MPa, $\Delta\sigma_f / \pi$ = 2.5

Obviously, there are some physical phenomena which we did not account for our analysis.

NUCLEATION OF CRACKS UNDER COMPRESSION



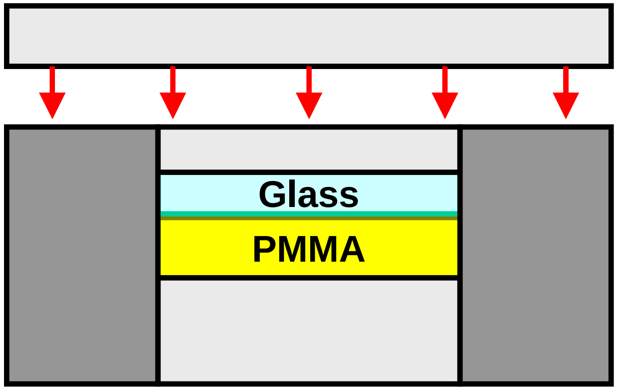


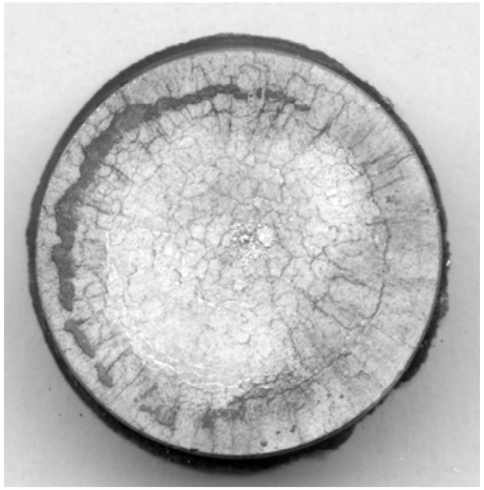
Wing crack

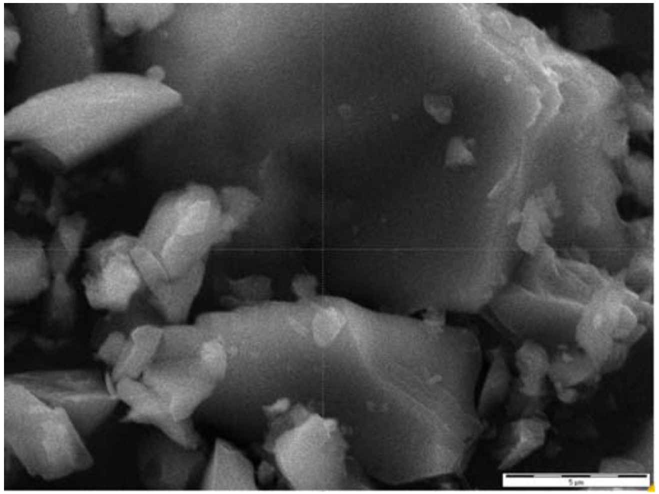
In the "wing crack" model, generation of local areas of tension is accompanied with appearance of local areas of excess compression.

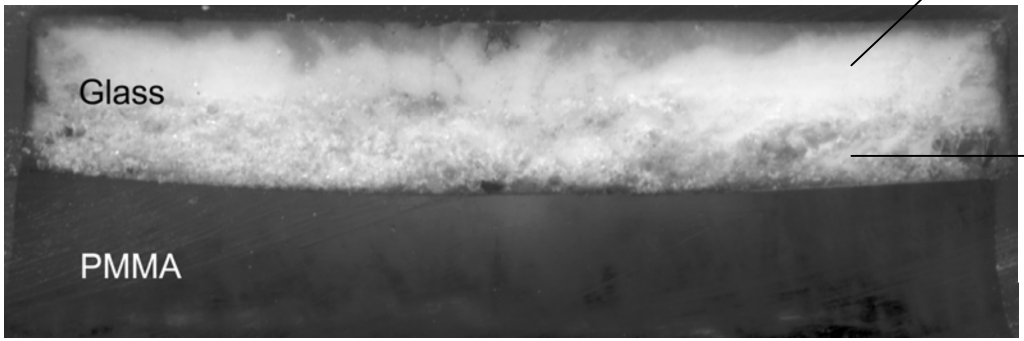
As a result, conditions for the irreversible densification are created.

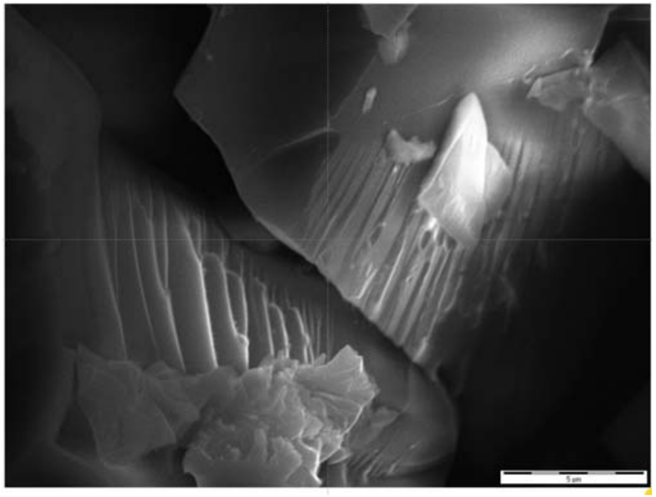
GLASS AFTER SHOCK COMPRESSION





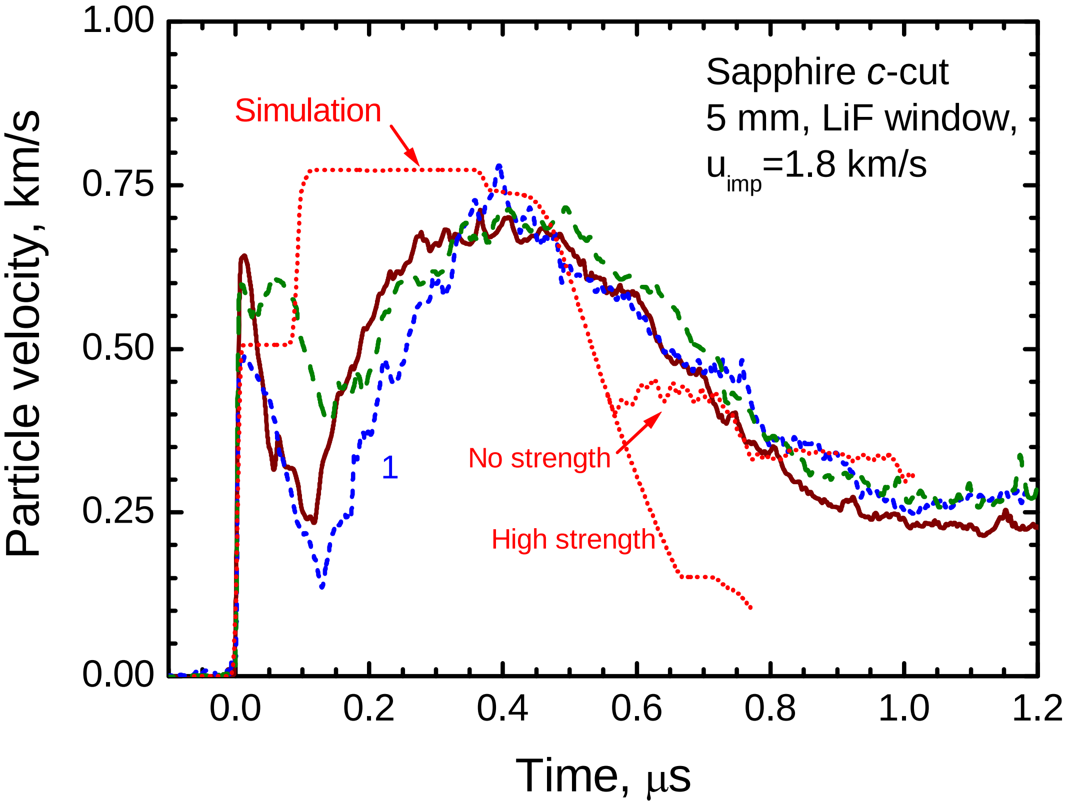


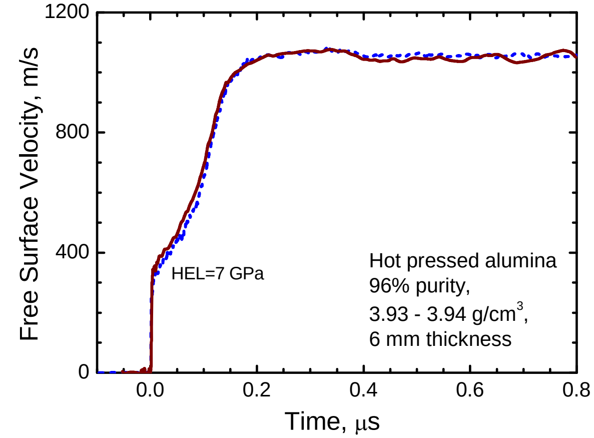


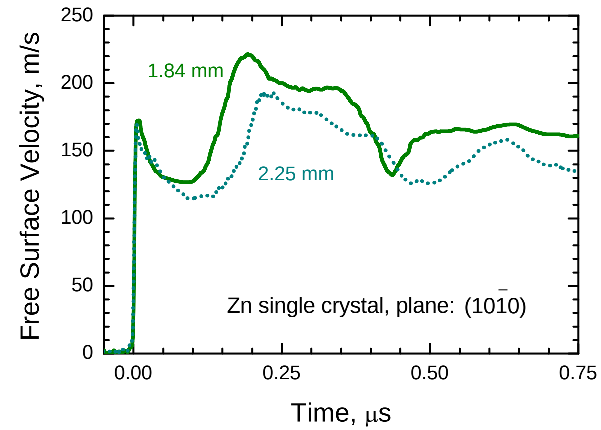


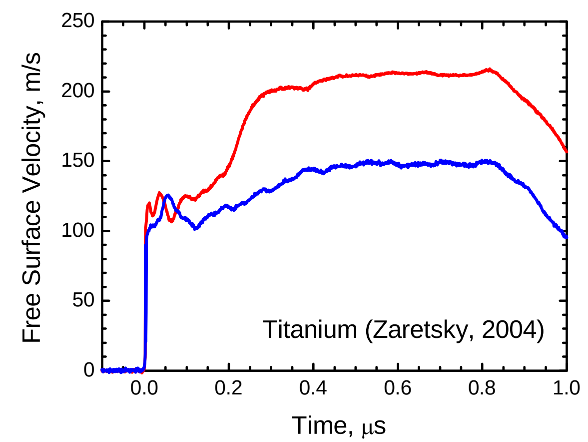
Sapphire

c-cut sapphire at intermediate impact stress





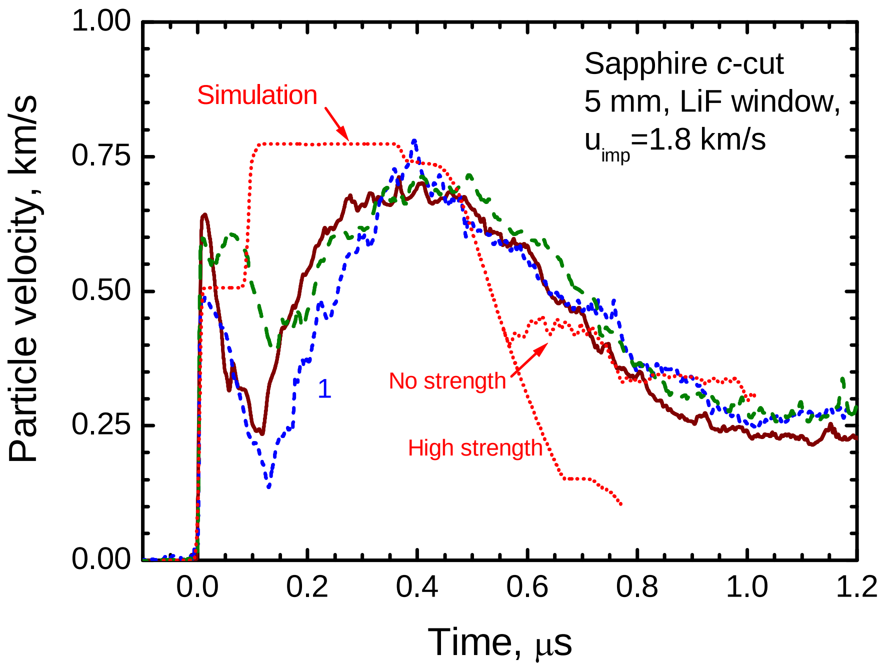


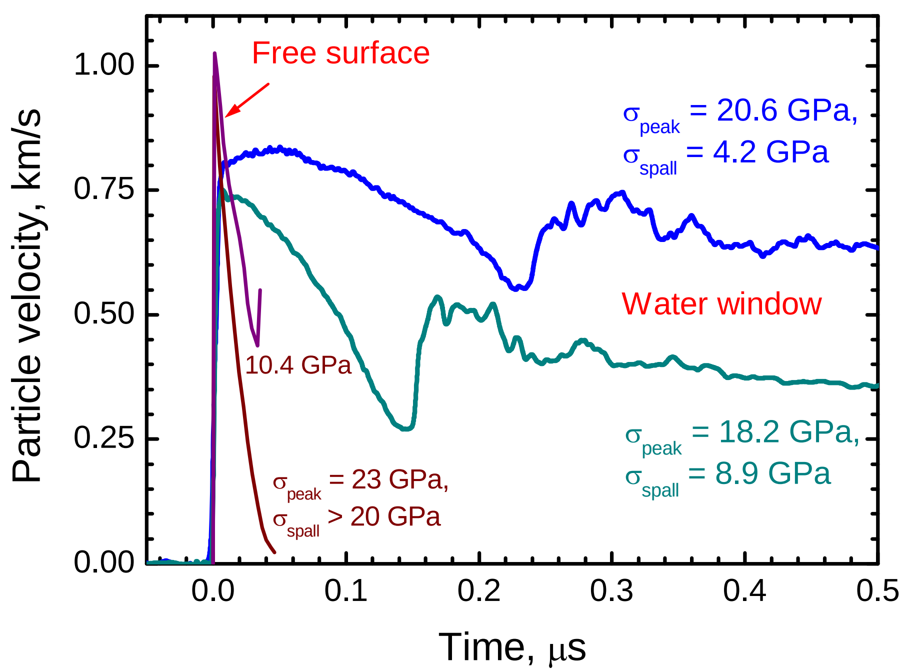


The strong irregular oscillations and low reproducibility of the waveforms are a consequence of intrinsic heterogeneity of its inelastic deformation.

The precursor waveforms with spikes are associated with accelerating stress relaxation behind the precursor front.

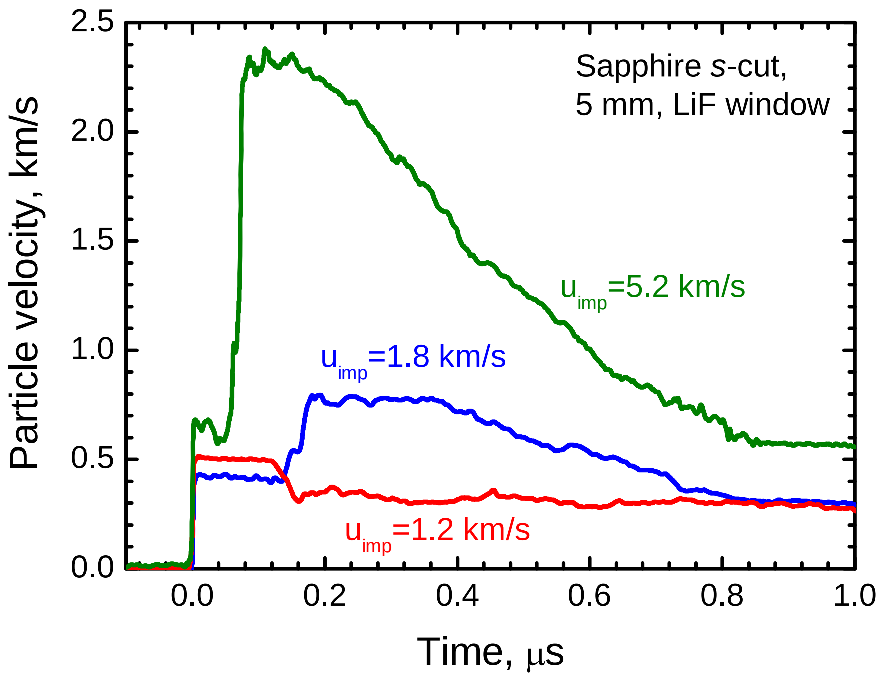
Spall strength of *c*-cut sapphire

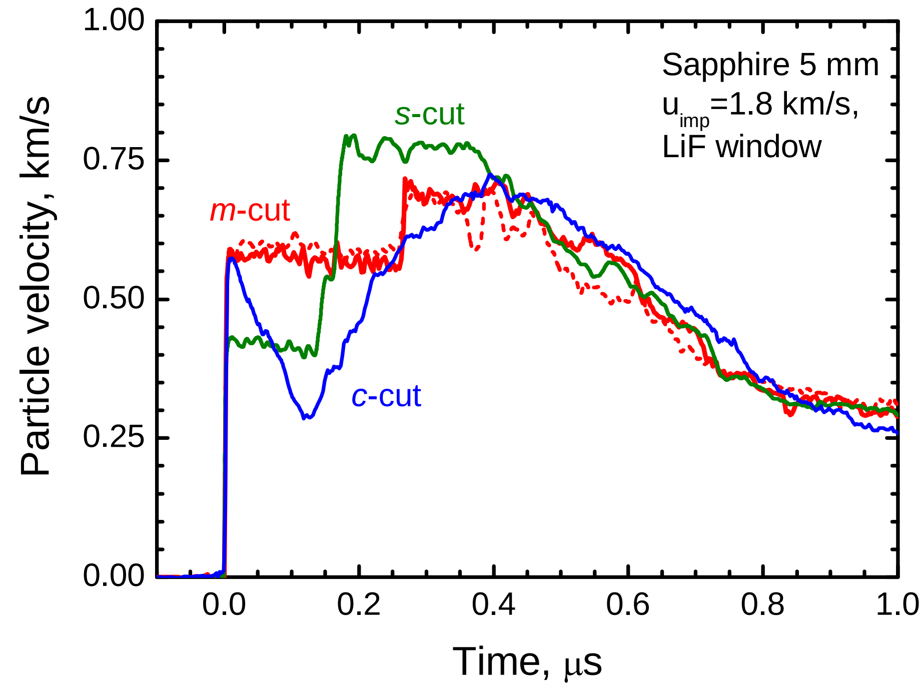




- **Comparison of the measured and simulated waveforms indicates negligible tensile strength after deformation in the plastic wave.**
- **At shock compression below the HEL, sapphire demonstrates the highest values of spall strength, which grow with shortening of the load duration.**
- **There is also a trend for the spall strength to decrease with increasing peak stress.**

s-cut and *m*-cut sapphire





- **Irregular oscillations in the waveforms are of higher frequencies and lower amplitudes than those recorded for other orientations.**
- **The data are very reproducible and much less noisy than the waveforms of most other orientations.**
- **The rise time of the plastic wave at the intermediate peak stress is about 5 ns.**
- **The stress at the front of the elastic precursor at intermediate impact velocity is less than for a lower impact velocity.**


Thank you for your attention!
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