# HYPERVELOCITY IMPACT

# Dynamic Fracture Behavior of Brittle Polymers

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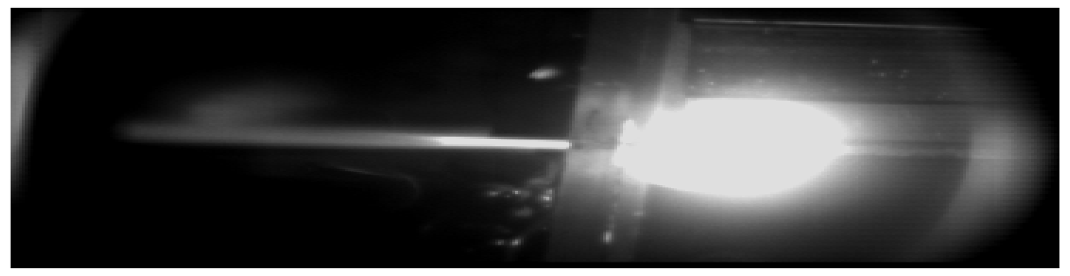
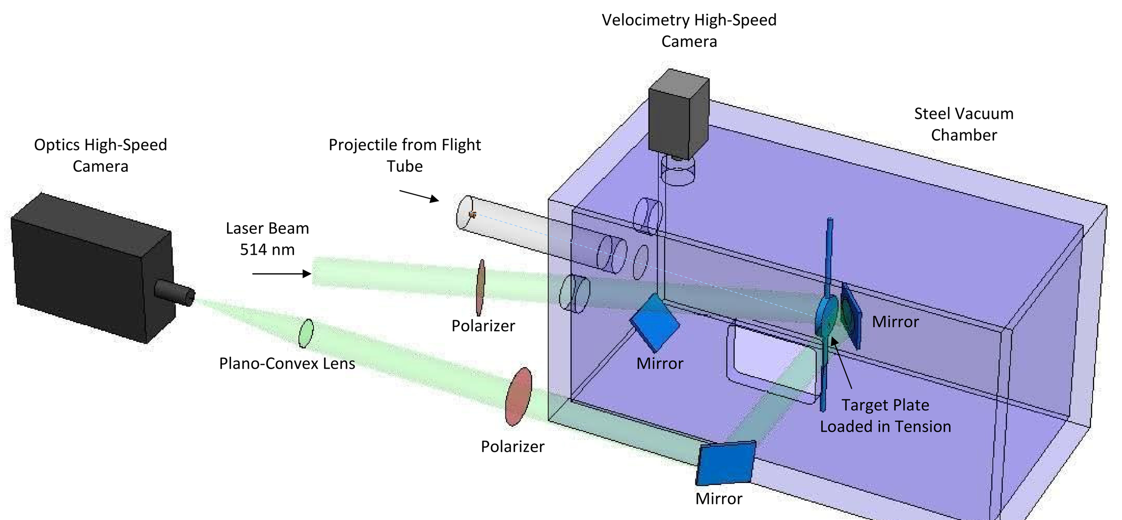
## Introduction

### How do things break when hit by a shooting star? . . .



Hypervelocity impact induced fracture behavior of brittle polymers was experimentally investigated using a unique two-stage light-gas gun at speeds averaging 6 km/s (13,4000 mph). Resulting mode I or opening mode crack tip stress intensity and energy release rates were analyzed using the optical techniques of caustics and dynamic photoelasticity.



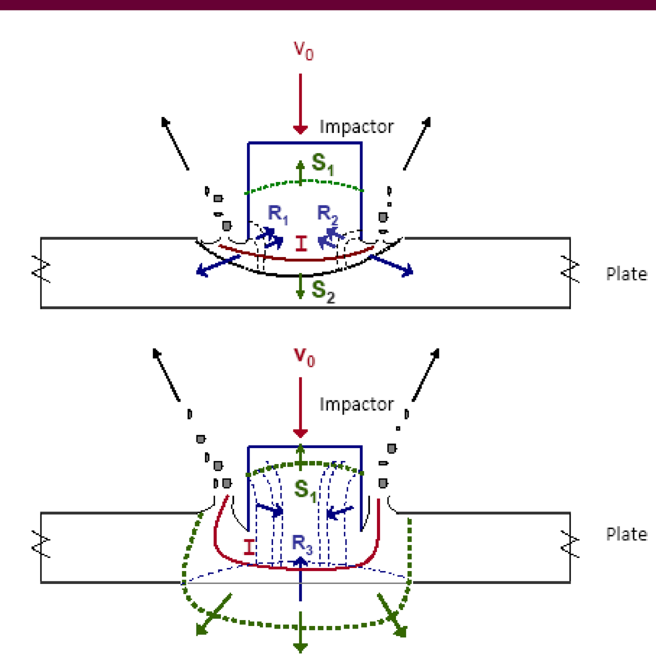

*(Above)*
*Nylon right cylindrical slug, L = 1.8 mm, L/D = 1, m = 5 mg, impacting Mylar film, 12.7 microns thick, at 5.5 km/s.*

*(Left)*
*Experimental configuration of light-gas gun impact on brittle targets in tension utilizing dynamic photoelasticity and caustics [1].*

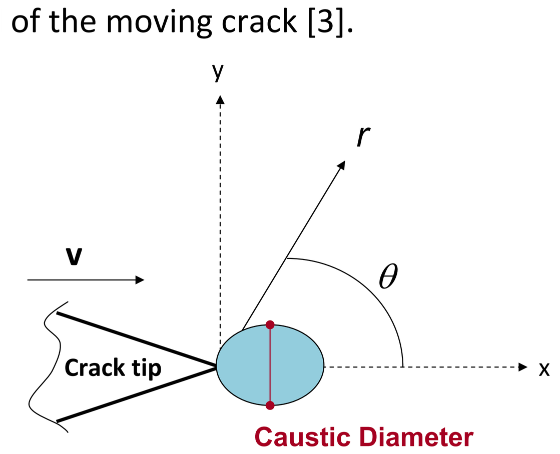
## Dynamic Fracture & Impact Physics

The process of hypervelocity fracture at the impact site can be regarded as a multiple-spalling phenomenon initiated at the free surfaces.

Upon impact at $v_0$ two shock waves propagate away from the interface, I, one towards the end of the impactor, $S_1$, and one towards the rear side of the plate, $S_2$. Rarefaction waves are then transmitted toward the axis of symmetry of the impactor, and later at the ends of the impactor and plate causing ejecta to form at the impact site and cracks to propagate in the plane of the plate *(figures right)* [2].




The mode-I or crack opening dynamic stress intensity factor can described by the singular stress solution and is directly related to the energy release rate ahead of the moving crack [3].




**Stress Intensity**

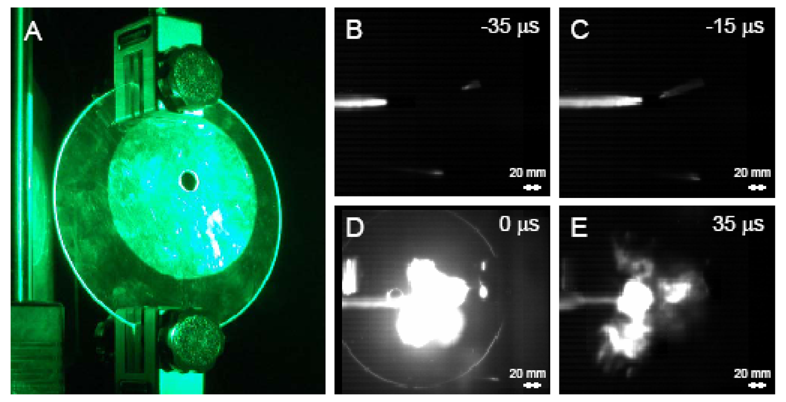
$$K_{ID}(t) \propto \sigma_{ij}\sqrt{2\pi r}\cdot f(v,\theta)$$

**Energy Release Rate**

$$G_{ID}(t) \propto \frac{A_I}{E}K_{ID}^2$$

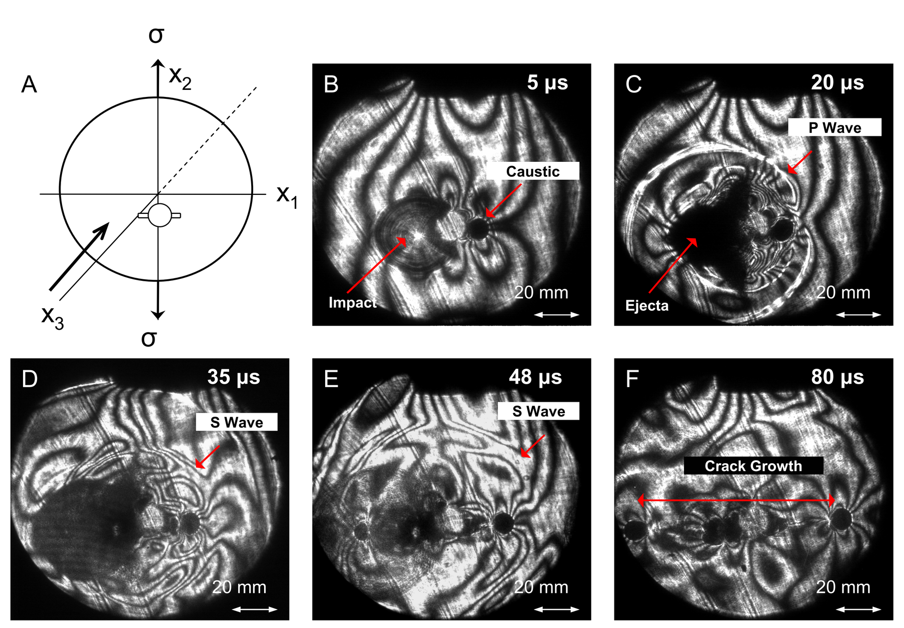
where t is time, v is crack speed, E is the plate Young's Modulus, $\sigma_{ij}$ is the stress tensor and $A_I$ is a universal function which includes plate material properties and wave speeds

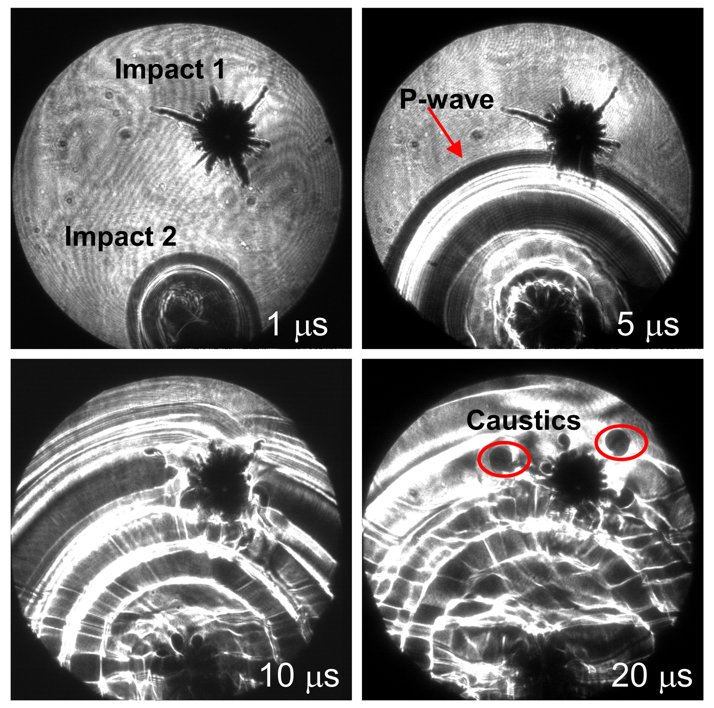
## Optical Methods & High-Speed Photography




***(A)*** *Photograph of 150 mm diameter, 1.6 mm thick polymer plate held in load frame inside two-stage light-gas gun with collimated laser beam illumination around a 20 mm hole with pre-cracks.* ***(B)*** *High-speed photography (1 million frames per second) is used to capture the hypervelocity impact, self-illuminated, as it files through the field of view from left to right, creating a streak of ionized gas in its path 35 µs before impact.* ***(C)*** *At 15 µs before impact the projectile is closer to the polymer plate and has an impact velocity of 5.2 km/s.* ***(D)*** *Spectral flash and plasma formation upon impact with polymer plate.* ***(E)*** *Ejecta 35 µs after impact with considerable localized heating present.*

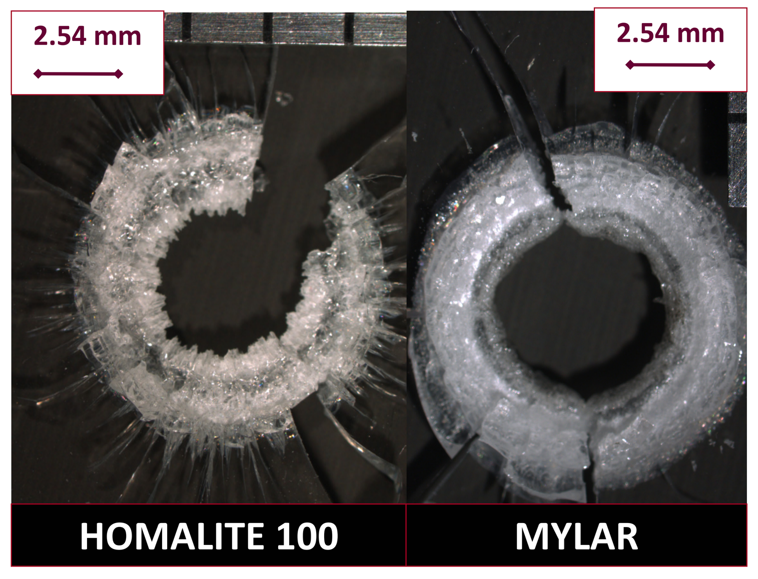
*High-speed photography (100 million frames per second) is used to capture the isochromatic fringe pattern and caustics generated during crack growth resulting from a nylon 6/6 cylindrical slug impact at 4.5 km/s on Mylar.* ***(A)*** *Configuration of plate for hypervelocity impact.* ***(B)*** *Upon impact the caustic from the right pre-crack has not yet felt the impact shock.* ***(C)*** *The fastest stress wave, the longitudinal wave, travels radially outward from the impact site at 2447 km/s and disturbs the caustic, but there is no crack growth. Eject is thrown from the plate and clouds the field of view.* ***(D)*** *The crack begins to grow, ejecta is starting to disperse and the shear wave is seen moving radially outwards from the impact site at 1185 m/s.* ***(E)*** *The crack appears to growth just behind the shear wave.* ***(F)*** *After 80 µs the polymer plate has almost completely failed, cracks speeds averaged 360 m/s.*



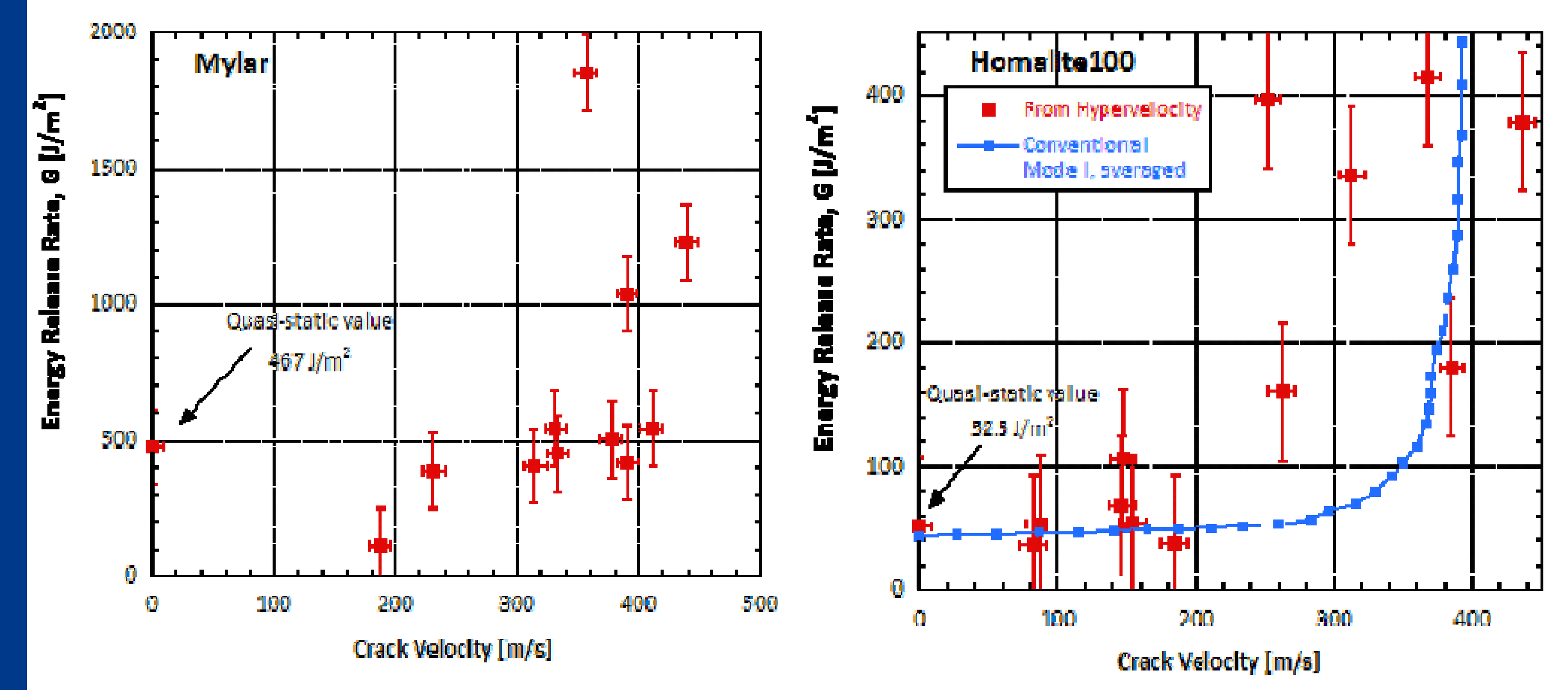



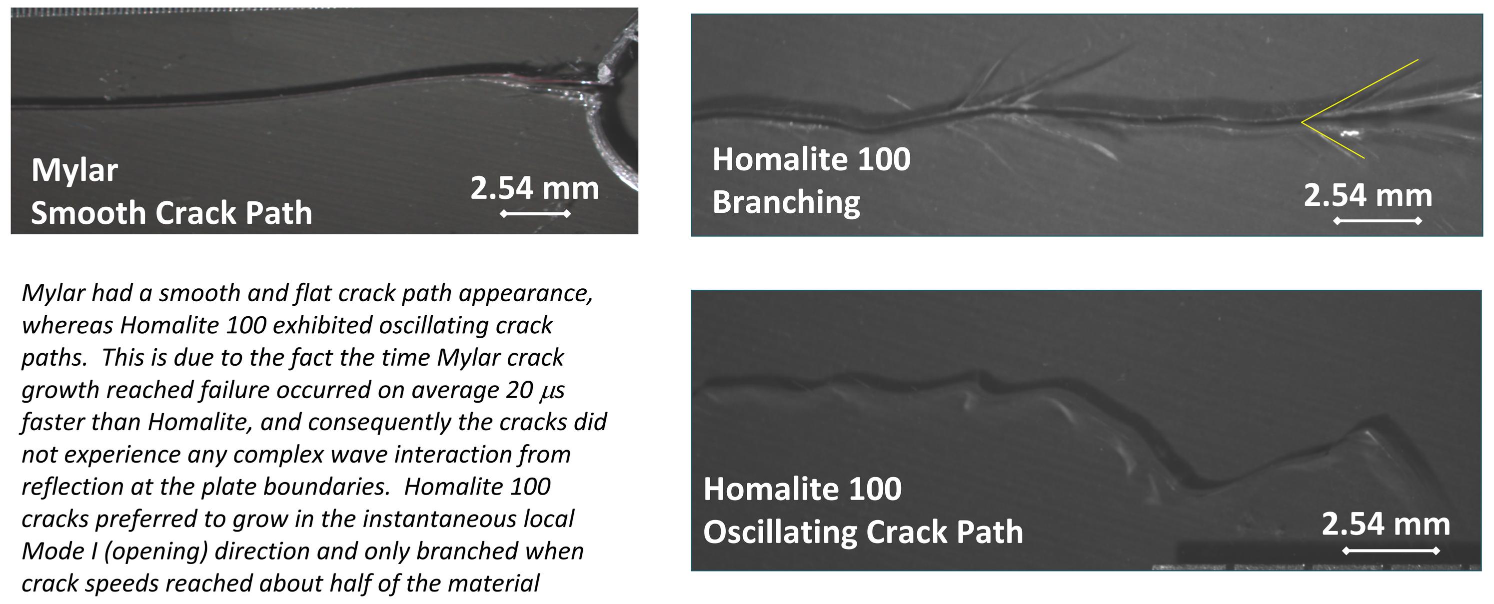

*A nylon 6/6 right cylindrical slug, L = 1.8 mm, L/D = 1 and mass of 5 mg, impacts a Homalite 100 plate 6.5 mm thick that has existing hypervelocity impact damage. The second hypervelocity impact collided with the plate at 5 km/s and the wave phenomena and interaction with the existing damage site is captured with high-speed photography and optical diagnostics. Imaging laser power is at 2 Watts with the beam expanded to a 100 mm diameter field of view, and exposure times are around 70 ns. After 5 µs the P wave from the second impact has reached the first impact site and soon after caustics from crack growth can be seen at both impact sites. Complex wave interaction and reflections from free surfaces is seen after 10 µs.*

*Impact sites of Homalite 100 and Mylar are compared side-by-side. Each was hit with a nylon 6/6 right cylindrical slug 1.8 mm in length and diameter at approximately 5 km/s. Notice that the Homalite 100 site has extensive dynamic branching, whereas the Mylar site has a glassy like appearance of melt fronts. This could be due to the fact that the thermal conductivity of Mylar is about 30% lower than Homalite 100. Additionally the size of the impact holes in both materials are greater than the diameter of the hypervelocity projectile.*




## Crack Tip Fracture Behavior




*Mylar had a smooth and flat crack path appearance, whereas Homalite 100 exhibited oscillating crack paths. This is due to the fact the time Mylar crack growth reached failure occurred on average 20 µs faster than Homalite, and consequently the cracks did not experience any complex wave interaction from reflection at the plate boundaries. Homalite 100 cracks preferred to grow in the instantaneous local Mode I (opening) direction and only branched when crack speeds reached about half of the material Rayleigh wave speed. Average branching angle was approximately 30°.*

| | MYLAR | HOMALITE 100 |
|---|---|---|
| †P Wave Speed [m/s] | 2447 | 2145 |
| S Wave Speed [m/s] | 1185 | 1082 |
| Averaged Crack Tip Velocity [m/s] | 330 | 230 |
| *Quasi-Static Fracture Toughness [MPa/√m] | 1.0 | 0.45 |
| Averaged Dynamic Stress Intensity [MPa/√m] | 1.0 | 0.73 |
| Quasi-Static Energy Release Rate [J/m²] | 467 | 52.5 |
| Averaged Dynamic Energy Release Rate [J/m²] | 690 | 208 |
| Crack Path Appearance | Flat | Oscillating |

† Determined by averaging 2 amplitudes from pulse-echo ultrasonic technique, +/- 175 m/s
*from literature (Mylar from Shockey 1981, Homalite from Rosakis 1983)

## Acknowledgements & References

[1] Special thanks to Felipe Figueroa at USC for the SolidWorks facility image.
[2] C.J. Maiden, A.R. McMillan, *AIAA J.*, **2 (11)**, 1992 (1964).
[3] A.J. Rosakis, A.T. Zehnder, *Int. J. Fracture*, **27**, 169 (1985).

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