Supershear cracks in Tensile Fracture: How fast can materials break?

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Brittle materials fail by means of rapid cracks. At their tips, tensile cracks dissipate elastic energy stored in the surrounding material to create newly fractured surfaces, precisely maintaining `energy balance' by exactly equating the energy flux with dissipation. Using energy balance, fracture mechanics perfectly describes crack motions; accelerating from nucleation to their maximal speed of c_R the Rayleigh wave speed. Beyond c_R , tensile fracture is generally considered to be impossible [1], [2].

Recently, the potential emergence of an entirely *new* branch of fracture *not* incorporated in classical fracture mechanics has been predicted in lattice models to occur at high applied stretch [3]–[5]. This theory predicts Mode I cracks that are able to exceed the shear wave velocity, c_s, and potentially even the dilatation waves speed, c_P [6], [7]. Moreover, these new fracture states are not expected to be governed by the principle of energy balance, the cornerstone of the classical theory of fracture.

Experiments have observed marginal supershear propagation in rubber [8] under extreme (200-300%) strains, however unequivocal experimental evidence for supershear tensile fracture has long been lacking. Here, by the use of brittle hydrogels, we experimentally demonstrate that such a wholly new and different class of tensile cracks indeed exists. We demonstrate that the principle of energy balance no longer dictates their dynamics; this new branch of cracks smoothly surpasses c_R to reach unprecedented speeds that approach the speed of dilatation waves. The transition from `classical' cracks to these `supershear' cracks takes place at critical values of applied strains. We, furthermore, show that the values of these, rather moderate (12-14%), critical strains are intimately related to the microscopic material structure.

While it is still unclear whether this intriguing fracture mode is indeed that predicted theoretically by Marder [4], [9]. It is clear that these extreme tensile cracks have never before been clearly observed in experiments. This new mode of tensile fracture represents a fundamental paradigm shift in our understanding of 'how things break'.

References

[1] K. B. Broberg, Cracks and Fracture. Academic Press, 1999. doi: 10.1007/s13398-014-0173-7.2.
[2] L. B. Freund, Dynamic fracture mechanics. Cambridge university press, 1998.
[3] Y. Jia, W. Zhu, T. Li, and B. Liu, Study on the mechanisms and quantitative law of mode I supersonic crack propagation, Journal of the Mechanics and Physics of Solids, vol. 60, no. 8, pp. 1447–1461, 2012.
[4] M. Marder, Supersonic Rupture of Rubber, Journal of the Mechanics and Physics of Solids, vol. 54, pp. 491–532, 2006.
[5] L. I. Slepyan, Models and Phenomena in Fracture Mechanics. Springer, 2002.
[6] C. Behn and M. Marder, The transition from subsonic to supersonic cracks, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 373, no. 2038, p. 20140122, 2015.
[7] T. M. Guozden, E. A. Jagla, and M. Marder, Supersonic cracks in lattice models, International journal of fracture, vol. 162, no. 1, pp. 107–125, 2010.
[8] P. J. Petersan, R. D. Deegan, M. Marder, and H. L. Swinney, Cracks in rubber under tension exceed the shear wave speed, Physical Review Letters, vol. 93, no. 1, p. 015504, 2004.
[9] P. Petersan, R. Deegan, M. Marder, and H. Swinney, Cracks in rubber under tension exceed the shear wave speed, Physical Review Letters, vol. 93, no. 1, Jul. 2004, doi: 10.1103/PhysRevLett.93.015504.