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Hot cracks or cool cracks? A model for the brittle-ductile transition of solids

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The growth of structural micro-cracks and dislocations within a mechanically loaded solid eventually leads to global material damage. When this growth is rather smooth and distributed, it accompanies some important plastic deformations and the solid is considered to be in ductile conditions. Alternatively, an abrupt propagation of localized defects leads to a brittle rupture of the full matrix.
Understanding according to which of these two behaviors a material is prone to break is of paramount importance, notably in engineering, where the brittle rupture of structures can lead to unpredicted disasters. It is also fundamental in Earth science, as the seismicity in the lithosphere is indeed limited to brittle shallow crustal rocks, while the deeper ones are in ductile conditions and hence less prone to generate earthquakes. Such a depth dependency is related to the pressure-temperature conditions and, for specific materials, the transition at higher temperature and confining pressure from brittle to ductile damage is well reported. Nevertheless, the actual physical understanding of this transition is still limited.

We focus here on the thermal effect which are auto-induced by the growth of cracks. During their propagation, part of the system's energy is indeed dissipated by Joule heating, which is arising from the friction in a damaged zone around the cracks fronts. The heat hence generated can in return have a significant impact on the physics of the propagation. For the stability of faults, a lot of attention has been recently set on such thermal effects, with the possibility of thermo-pressurization of fractures due the expansion of in situ fluids.
Independently of this effect, we show, with statistical physics and an Arrhenius law, how the local rise of temperature of the zone which is enduring damage can significantly affect its creep and the global fracturing process. We hence present a dynamical model for the propagation of cracks which holds a dual phase behavior: a [U+FB01]rst phase at low velocity in which the temperature elevation is of little e[U+FB00]ect and the propagation is mainly governed by the mechanical load and by the toughness of the medium, and a second phase in which the crack is thermally weakened and propagates at a greater velocity. We illustrate, with numerical simulations of mode I cracks in thin disordered media, how this dual behavior is compatible with the usual stick-slip in brittle fracturing. We also show how our model compares with experimentally recorded features in the rupture of acrylic based pressure-sensitive glues. Finally, we discuss the existence of a critical ambient temperature above which the cracks propagation is only smooth and mono-phase, without any discontinuity of the rupture velocity as function of the energy release rate when the fracture is loaded or unloaded, thus proposing a novel and physical explanation for the brittle-ductile transition of solids.