Dynamic failure precursors in soft matter

S. Aime, L. Ramos, L. Cipelletti

Abstract

Material failure is ubiquitous, with implications from geology to everyday life and material science. It often involves sudden, unpredictable events, with little or no macroscopically detectable precursors. A deeper understanding of the microscopic mechanisms eventually leading to failure is clearly required, but experiments remain scarce. The detection of microscopic dynamics in samples under shear is experimentally very challenging, because it requires to combine the highest mechanical sensitivity to strict requirements on the geometry of the whole setup and on the quality of the optical interfaces. In this work we present one of the first successful attempts to measure microscopic failure precursors in model soft solids. Here, microscopic plasticity under shear is observed using a novel setup, coupling a custom-made stress controlled shear cell to small angle static and dynamic light scattering (DLS).

DLS is a very powerful technique, but its application to materials under shear is not trivial. In a first step we show a theoretical, numerical and experimental investigation of how DLS may be used as a tool to measure the microscopic dynamics in soft systems under shear. In ideal solids and simple viscous fluids, the displacement field resulting from an applied shear deformation is purely affine. Additional non-affine displacements arise in many situations of great interest, for example in elastically heterogeneous materials or due to plastic rearrangements. We show how affine and non-affine displacements can be separately resolved by DLS, and discuss the effect of several non-idealities in typical experiments.

As a model system, this work mainly focuses on a fractal colloidal gel. We thoroughly characterize the linear power-law rheology of the gel, we show that it is very accurately described by the phenomenological Fractional Maxwell (FM) model, and we discuss the possible relationship between the FM model and the microscopic structure of the gel.

Under a constant shear stress (creep experiment), the colloidal gel exhibits a fast, elastic deformation followed by a slow sublinear power-law creep, which is eventually interrupted after several hours by an upturn in the shear rate, leading to the delayed failure of the material. Our experiments show that the first power-law regime, nicely described by linear viscoelasticity, corresponds at the microscopic scale to partially nonaffine, yet fully reversible dynamics. Upon deviation from the linear viscoelasticity, a sharp acceleration, localized in time of the nonaffine dynamics is observed. These faster rearrangements precede the macroscopic failure of the gel by thousands of seconds: they thus are dynamic precursors of failure that allow one to predict the fate of the gel well before any rheological measurement.

To obtain a more comprehensive picture of material failure, we next address the onset of irreversibility under a cyclic perturbation repeated many times (fatigue experiment). By following the stroboscopic evolution of the system as a function of the cumulated deformation, we observe that as soon as the shear amplitude is increased beyond the linear regime the relaxation rate increases abruptly, indicating that irreversible plasticity is at play. If a large enough stress amplitude is applied, the system on the long run displays delayed fatigue failure, with reminiscences of the one observed in creep. Differences and similarities between the two failure mechanisms are discussed.

Finally, the generality of the results obtained on colloidal gels is checked by investigating as second model system a soft colloidal glass. In this case, our experiments indicate that oscillatory yielding is a gradual process, where two relaxation modes contribute to the observed dynamics. Qualitative analogies found with similar systems (e.g. concentrated emulsions) suggest that a general picture might be obtained with our study, which motivates ongoing and future investigations.