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Linear stability analysis for the formation of wrinkles on confined swelling hydrogels

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Wrinkling, buckling and creasing instabilities are some of the most familiar phenomena observed in the study of soft materials including hydrogels. They arise when there is mechanical confinement, for example from a fixed base or from hoop stresses in swelling spheres, leading to the preferential formation of wrinkles to relieve shear stresses from the confining strain. These have long been studied as purely elastic instabilities, with a mechanism akin to Biot's classic stability analysis of an elastic half-space under pre-stress. Here, we argue that the swelling process itself is a key part of the mechanism driving these instabilities by carrying out a linear stability analysis of the swelling of a finite layer of gel under horizontal confinement. This stability analysis uses our own linear-elastic-nonlinear-swelling theory for hydrogels that captures the nonlinearities arising from the large isotropic strains when a gel takes on water but allows for an analytically tractable approach through linearising around small deviatoric strains. Under this theory, the physical processes driving the swelling and drying that forms the wrinkles can be easily seen, unlike in fully nonlinear approaches where only a condition for marginal stability can be derived through minimisation of free energy. Furthermore, the growth rate of a given instability is deduced, allowing us to determine the separate influences of wavenumber, layer thickness and material properties on the stability of the water-gel interface. It is observed that the anchoring effect of the fixed base of the gel layer stabilises low-wavenumber (long-wavelength) wrinkles, whilst the growth rate increases unboundedly with the wavenumber, leading to an 'ultraviolet catastrophe' whereby infinitesimally small wavenumbers grow at an infinite rate. We propose solving this by introducing a surface tension at the gel-water interface that serves to stabilise short-wavelength instabilities. The effect of this surface tension is quantified for two different mechanisms; firstly, a surface tension that arises as a bulk elastic discontinuity in stress, and secondly as one arising from a discontinuity in the pore pressure of water between the liquid and gel phases. Quantitative differences between these two mechanisms are discussed, and the evolution of the most unstable wavenumber in time is evaluated and compared to the smoothing and healing of these instabilities seen in experiments, where wrinkles are known to coarsen and, in some cases, disappear entirely as the gel layer imbibes more water. We show that our theory, with the addition of surface tension, can describe all these observations and postulate how further experimentation could determine the true physical origin of the surface tension at the interface.

Participation

In-Person

References

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