Study of dynamics at a soft interface: the role of geometry, friction, and surface energy

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Abstract

Interfaces, formed when two or more phases come together, display interesting properties and are ubiquitous in nature. A unique property of interfaces is the existence of interfacial stresses. While interfacial stresses are usually negligible in rigid solids, they play a significant role in soft and biological systems. The relative importance of interfacial stresses and elasticity in soft solids depends on the length scale being probed. Many interesting previous works have studied the interplay between surface stresses and elasticity at a static soft interface and how it gives rise to a diverse range of patterns at the interface. In this thesis, we examine the nature of dynamics at a soft interface and the phenomena that emerge from the coupling of dynamics with elasticity and interfacial stresses. We design a model interface consisting of a highly bendable thin polymer sheet that is weakly adhered to a water-swollen hydrogel substrate to study the dynamics and discover some interesting new phenomenology.

An important feature of dynamics at an interface is the nature and role of friction. Conventional techniques for measuring friction typically involve point or planar contacts. However, real soft and biological systems come in a variety of shapes and geometries. We develop an experimental system that enables us to measure friction between two soft surfaces of different intrinsic shapes moving relative to each other- thereby functioning as a sensitive tribometer. We examine how geometry affects friction at this thin sheet-hydrogel interface. We find a strong dependence of friction on the relative geometry of the two surfaces: a flat sheet experiences significantly larger friction on a spherical substrate than on a flat or cylindrical substrate. We show that the stress developed in the sheet due to its geometrically incompatible confinement is responsible for the enhanced friction. This mechanism also shows a size-dependent friction with a transition in the nature of friction as the sheet radius is increased beyond a critical value. Our finding reveals a

hitherto unnoticed mechanism based on an interplay between geometry and elasticity that may influence friction significantly in soft, biological, and nanoscale systems. In particular, it provokes us to reexamine our understanding of phenomena such as the curvature dependence of the mobility of biological cells.

We use the compressive stress arising from the frictional interaction between the sheet and the hydrogel substrate in the above-described experimental system to slowly and controllably crumple extremely thin sheets and study their crumpling dynamics. Through these controlled crumpling experiments on thin sheets, we find a new class of elastocapillary phenomenon, which we refer to as the capillary crumpling transition. We find that as we begin to compress the sheet, initially it becomes increasingly difficult to compress the sheet further; however, after a well-defined critical compression, the sheet transitions into a self-crumpling state. The transition observed by us reminds one of the crumpling transition that has been theoretically predicted in thermalized sheets at temperatures above a critical threshold, but has never been convincingly observed experimentally. We show that the capillary crumpling transition we observed is driven by the sheet's surface energy. A comparison of the relative importance of surface and elastic energy in a typical crumpling process allows us to introduce a dimensionless parameter, the capillary crumpling number, that measures the sheet's tendency to undergo the capillary crumpling transition. We found that many-layered biological tissues and two-dimensional nanomaterials fall within the regime of a large capillary crumpling number. The transition is characterized by the percolation of a fold network and a power-law increase in fold density, typical signatures of a critical phenomenon.

In our experiments, the crumpled state of the sheet displays a tunable order of folds, establishing the phenomenon's potential as a simple and scalable technique to do origami with extremely thin sheets. We can tune the symmetry of the fold pattern in the sheet using the substrate geometry. We also use a pattern of grooves engraved on a flat hydrogel substrate to imprint desired fold pattern in the sheet. The technique further allows us to mold a 2D flat sheet into a 3D shape. The 3D shape is maintained even after the sheet is released from the substrate. We also show the ability to uncrumple and retrieve the flat sheet by using the force of surface tension of water. The resulting flat sheet preserves the pattern of creases reminiscent of the fold patterns that were imprinted on it, which are expected to modulate the mechanical response of the sheet.