Simulation and experiments of contact with soft materials having a gradient of stiffness

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High-water-content hydrogels have a more compliant skin layer when they are molded against bulk polymer material. Since pressure is a guiding parameter in hydrogel friction and wear, we aim to assess how a softer skin layer affects the contact mechanics. We use finite element analysis to find the force-displacement behavior of various case studies of gradient-stiffness surfaces including linear, exponential, and step changes in stiffness. We find that contact areas are under-predicted by classical contact models in all cases, and that accurate descriptions follow a power-law relation between force and displacement, though a higher power than anticipated.

Keywords: hydrogels, biomimetics, contact mechanics

1. Introduction

Hydrogels are known for their low friction and similarity to biological tissues; as such they are an obvious candidate for load-bearing biomedical applications. However, predicting their behavior under pressure is not yet accurate due to their compliance, stress relaxation, and complex structural organization [1, 2].

In this work we take two approaches to study the outer surfaces of polyacrylamide hydrogels where the bulk meets a submerging water bath. First, we present experimental work confirming the presence of a softer outside layer that arises naturally due to swelling [3]. Next, we simulate the contact of a hydrogel that has a gradient of stiffness at its surface. From these two approaches, we provide proof that the bulk properties of the hydrogel are insufficient to predict the contact mechanics, and that the less compliant outer layer is prominent enough to control contact.

2. Methods

2.1. Experimental Methods

For the experimental work, we use instrumented microindentation of a hard hemisphere into a polyacrylamide slab ~9mm thick, with a polymer content of ~8%, leaving 92% water by mass. The force is applied through a piezoelectric stage and monitored by continuous measurement of the deflection of a known-stiffness 4-bar flexure through capacitive sensors. The contact area is simultaneously visualized by a fluorescence microscope as bright particles diluted into the supernatant water are excluded from the contacting surfaces (Figure 1).

2.2. Simulation method

A composite hydrogel was simulated in Abaqus as a half space indented with a hard probe, in a 2-D axisymmetric cross-section. The nodes were assigned a gradient of modulus from E=5 kPa at the top surface to E=20 kPa at depths of 1, 2.7 .7.4, and 20% of the thickness (Figure 2). Each sample was progressively indented with a hard probe until the indentation depth approached the probe radius.

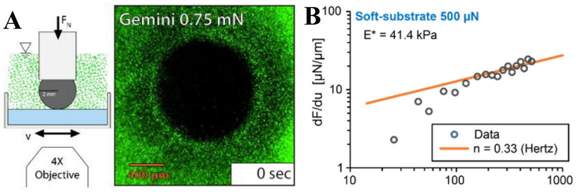

Figure 1: (A) Experimental setup of instrumented indentation with fluorescence microsopy in situ. (B) data showing 2 regimes: sub-Hertz and Hertz (orange line) on a plot of dF/du (load/depth) versus F (load).

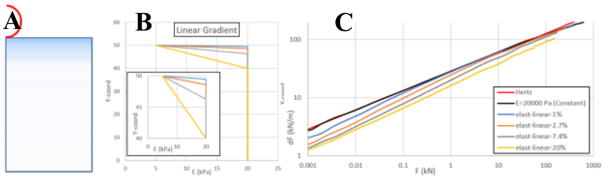

Figure 2: (A) Simulation schematic. (B) Profiles of gradient-stiffness surface as model inputs. (C) Results curves of dF/du vs F showing multiple contact regimes.

3. Discussion

The experiments confirm a sub-Hertz contact regime where the load does not increase as Hertz would predict; that means the outer layer is softer at the lowest forces and smallest depths. That regime is typically where classical contact mechanics are the most accurate. The simulation with a gradient stiffness layer confirmed a power law contact trend with a power less than that of the Hertz model. The error is largest as the gradient layer extends deeper into the hydrogel. This confirms that a soft outer layer controls the contact.

4. References

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