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Anisotropy in Soft Sliding Friction from Chemical Heterogeneities: Impact on Tactile Interfaces*

Kayla A. Hepler[1] , Leanne Ton[1], Pushpita Bhattacharyya[2], Jared Medina[2] and Charles B. Dhong[1,3]

Abstract— **Touch perception of chemical heterogeneities was studied using silane-based surface coatings to create a chemical 'edge' on silicon wafers on otherwise low roughness (< 0.8 nm) surfaces. Participants were able to reliably find and mark the chemical heterogeneity when sliding their fingers from a region of C4 into a region of APTMS, and equivalently successful when in the reverse sliding direction of APTMS into C4. However, participants could only accurately locate the 'edge' when sliding their finger from a region of C6 into C4 and not in the reverse direction of C4 into C6. Mechanisms to explain this anisotropy were explored based on soft sliding friction phenomena.**

I. Introduction

Physical heterogeneities in the form of bumps, textures, or surface roughness are well known to contribute to the tactile feel of an object [1]–[3]. Consider a square of paper sitting on a table: as the finger encounters a physical ridge of the paper, mechanical forces generated by this physical heterogeneity give rise the sensation of the 'edge' of the paper [4], [5]. However, in addition to physical heterogeneities, objects also contain chemical heterogeneities: differences in the degree of fiber alignment in the pulp of the paper, presentation of different surface moieties, the varying degrees of uniformity in any coating process on the paper and leather [6], [7]. While the role of physical heterogeneities on tactile sensations has been studied often [8]–[10], it is unclear how chemical heterogeneities may impact the tactile feel of objects or how chemical heterogeneities may be leveraged to improve tactile interfaces [11]–[15].

II. Human Psychophysical Testing

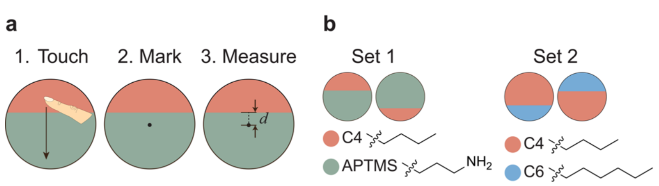

Figure 1. Human psychophysical testing setup. a) Schematic showing participants sliding their fingers from the first silane into the second, marking the hypothesized location of the chemical heterogeneity, and measuring the distance *(d)* to the real location. b) Schematic showing reversal of sliding direction, variation of 'edge' location, and silane chemistries for Sets 1 and 2.

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[1]Department of Materials Science and Engineering, University of Delaware, Newark, DE, USA. E-mail: cdhong@udel.edu
[2]Department of Psychological & Brain Sciences, University of Delaware, Newark, DE, USA
[3]Department of Biomedical Engineering, University of Delaware, Newark, DE, USA

A. Method

Silicon wafers were coated with two different silanes to generate an 'edge' (Fig. 1b), Set 1 was comprised of n-butyltrichlorosilane (C4) and n-aminopropyltrimethoxysilane (APTMS) whereas Set 2 was comprised of n-butyltrichlorosilane (C4) and n-hexyltrichlorosilane (C6).

This study was conducted and approved by the Institutional Review Board of the University of Delaware (Project #1484385-7). Once familiarized, subjects were given 12 samples from set one (6 of each sliding direction) and asked to touch and mark where they thought the 'edge' was on each wafer within 30 seconds (Fig. 1a). This was then repeated with the second set for each of the six participants. Counterbalancing was used to eliminate order effects when testing both sliding directions within a set. Additionally, the set presented first was alternated between each participant. Upon completion the performance was evaluated by measuring the distance *(d)* between the actual 'edge' and the participant's mark.

B. Results

The apparent contact area of the fingertip (≥ 10 mm^2) is much larger than the size of chemical heterogeneity [16], [17]. Thus, if a subject's mark was less than 10 mm from the true location the trial was marked as a "success". Fig. 2 shows the average success rates for sets 1 and 2. In Set 1, participants on average passed similarly regardless of sliding direction. The pass rate when sliding from C4 into APTMS was 77.8% and 75.0% in the reverse, APTMS into C4. However, in Set 2, directional anisotropy was observed. The pass rate was significantly decreased when sliding from C4 into C6 as compared to C6 into C4, 38.9% and 66.7% respectively.

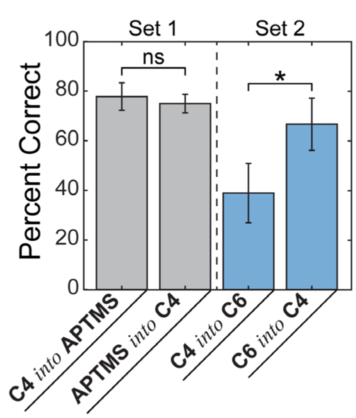

Figure 2. Results of psychophysical testing with human subjects. Error bars indicate standard error of the mean. Asterisks represent significance. Each condition had 6 trials with $n = 6$ subjects.

III. Mechanism for Anisotropy

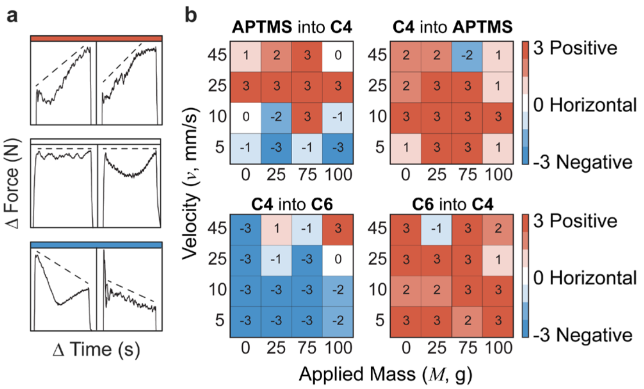

Figure 3. Friction forces across the chemical 'edges'. a) Representative friction traces across a chemical heterogeneity creating positive, horizontal, and negative slopes. b) Friction force trends at the chemical heterogeneity for Set 1 and Set 2 in each sliding direction at M = 0-100 g added to the deadweight of the finger and v = 5-45 mm/s. Each of the 16 mass and velocity conditions were run in triplicate.

To understand the basis of this anisotropy mesoscale friction of each condition was explored using a mock finger. Though we identified many trends, the only trend that identified C4 into C6 as a unique surface was that friction forces tended to decrease across the 'edge', whereas all other surfaces showed a rise.

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