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NanoTurf: Nano-engineered Low Flow Friction Surfaces

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Flow friction on solid surfaces, whether it is inside small pipes or over large vessel surfaces, is determined by the shear at the wall. For all the practical purposes, the flow velocity at the wall surface is considered zero—the so-called "non-slip" condition. There have been efforts to defy the non-slip and reduce drag of liquid flow, for example, by generating bubbles on the surface. Our breakthrough is to use surfaces covered with nanometer-scale hydrophobic (i.e., non-wetting) posts, coined "NanoTurf". Skidding over the posts and mostly levitated from the wall, the liquid is expected to in effect "slip" over the solid surface. The concept can be demonstrated with micrometer-scale posts, made by conventional lithographic techniques (Fig. 1a). However, it is critical that the posts are of nanometer scale (Fig. 1b), because otherwise the liquid would lose levitation under a slight pressure. Nanotechnology makes the idea practical for the first time.

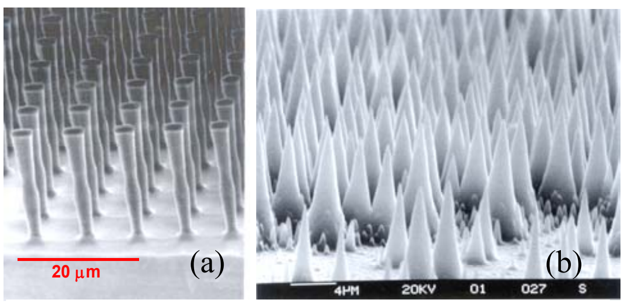

Fig. 1. SEM pictures of nano-structured silicon surfaces. (a) Micro-posts, (b) Nano-posts(Turf)

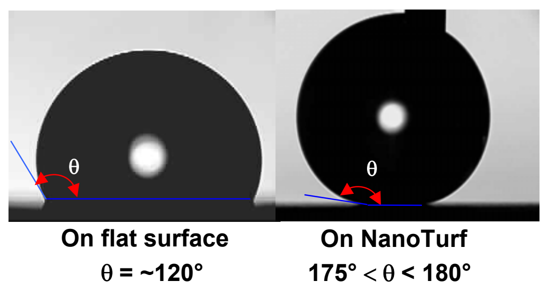

Fig. 2. Contact angles on flat surface and NanoTurf, both coated with very thin Teflon.

In Fig. 2, NanoTurf shows off its super-hydrophobicity, compared with a flat surface. Experiments with our current NanoTurf surfaces revealed that the resistance of *droplet flow* on open surfaces is less than 1% (i.e., over 99% reduction) and droplet flow inside channels is less than 5% (i.e., over 95% reduction) of the resistances of flat surfaces [1].

In addition to the initial NanoTurf in Fig. 1(b), we have been exploring other fabrication methods in collaboration with several other groups to test the feasibility for our application. By using self-assembled synthetic materials (e.g., Fig. 3: nanospheres and block copolymers), organic materials (e.g., S-layer proteins – *in collaboration with Dr. J. S. Tabb in Agave Biosystems*), or nanospheres as templates, we have tested to transfer the nano-patterns onto silicon substrate. However, control of pattern sizes and processing over a large area remain as the challenge. Yet another method to make nanoposts is vertically aligned carbon nanostructures, as shown in Fig. 4. No etching is necessary in this case. We are further testing anodized aluminum and interference lithography for a better control of nano-pattern sizes and periods.

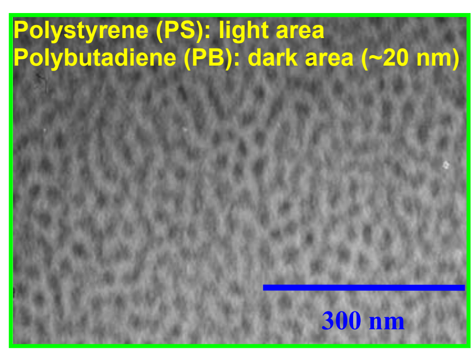

Fig. 3. TEM picture of diblock copolymers (*In collaboration with Prof. S. Tolbert, UCLA*)

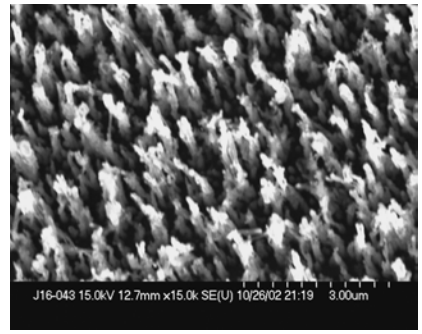

Fig. 4. SEM picture of carbon nanostructures (*In collaboration with Dr. M. L. Simpson, ORNL*)

To prove the advantage of using NanoTurf surfaces for applications involving *continuous flow*, we have also directed our effort to investigate the boundary condition for continuous liquid flow on a flat hydrophobic surface. Despite the effort of several authors on this topic, the data available to date are still inconclusive, the main limitation being the accuracy of the experimental apparatus. Paying extreme attention to eliminate or mitigate all the possible sources of uncertainty, we have devised an experimental setup that allows high accuracy for channel flow down to sub-micron scale. The apparatus is insensitive to thermal disturbances since the temperature of the test section is controlled to within 0.02°C. Flowrates of the order of nanoliters per second are accurately measured with an analytical balance (microgram resolution) placed on a shielded isolation table. Extreme care is used in the determination of the physical dimensions of the channel, since the resolved data (wall friction) are sensitive to the third power of the channel depth.

A combination of surface profilometry, interferometry, SEM, AFM and FESEM techniques have been employed to carefully characterize the surface roughness and the geometrical dimensions of the test channels, which span in depth from 10 microns down to 100 nanometers. The use of channels in the nanometer size range, which exacerbates the experimental difficulties, is mandated by the fact that slip phenomena can be experimentally detected only when the channels are in sub-micron scale. In our extensive study with fluids and boundaries of different nature (i.e. hydrophobic vs. hydrophilic) we have observed with great reproducibility the existence of slip on a solid surface for continuous flow. In addition, the slip increases with the wall shear rate or, in other words, with the flow velocity. The downside is that the measured slip length is at the best around 50 nanometers, which means that wall slip has no practical influence in non-nanostructured (flat surface) channels larger than 1 micron. On the contrary, NanoTurf surfaces are expected to offer a slip length at least a couple of orders of magnitude larger, with the result that they are a practical means of effectively reducing drag in sub-millimeter channels.

A problem that was identified in the first phase of the project was the questionable performance of NanoTurf surfaces prepared by spin-coating Telfon AF (an amorphous fluoropolymer) onto silicon posts. Several alternative methods to increase the hydrophobicity of the surface are being evaluated. First, the feasibility of depositing Teflon from the vapor phase is being assessed. It is not clear whether this method will result primarily in the tips of the asperities being coated, or whether the coating will be uniform and contiguous over all the surface peaks and valleys. Second, we are using conventional approaches for forming self-assembled monolayers to modify the surface. Octadecyltrichlorosilane and octadecyltrimethoxysilane are being used to modify silicon dioxide surfaces, while octadecanethiol is being used to modify gold-coated NanoTurf.

Because we are interested in using NanoTurf to manipulate solutions, not just solvents, we are evaluating the extent to which surface fouling is a problem. Contact angle, AFM and optical methods are being used to determine the extent and distribution of surface residue left behind by fluids in contact with the NanoTurf surface. Of particular interest are biological molecules, which may tend to adsorb on both un-modified silicon dioxide, as well as on substrates modified by hydrophobic monolayers and films.

Drag reduction of liquid flows is fundamental in nature and has far-reaching consequences in numerous application areas from microfluidic devices all the way to chemical plants or marine transportation. Low flow resistance is a critical advantage in microfluidic systems, as liquid flows become exponentially lossy with size reduction. By addressing case-specific issues like surface scaling, NanoTurf can be further developed for large-scale applications as well. An extension of our project will involve exploiting the levitation of the liquid above the NanoTurf floor to selectively modify the tips of the NanoTurf. The long-range goal is to fabricate sensing patches that can be used to incorporate chemical analysis functions into NanoTurf-based devices.

References

[1] J. Kim and C.-J. Kim, "Nanostructured Surfaces for Dramatic Reduction of Flow Resistance in Droplet-based Microfluidics," *Technical Digest, IEEE Conference on MEMS,* Las Vegas, NV, Jan. 2002, pp. 479-482.