ADVANCED MATERIAL FOR ENERGY EFFICIENCY

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PROJECT TITLE: Slippery Liquid-Infused Porous Surfaces (SLIPS)
PROGRAM: OPEN 2012
AWARD: $1,999,998
PROJECT TEAM: *Harvard University (Lead)*; Pennsylvania State University
PROJECT TERM: April 2013 – June 2016

TECHNICAL CHALLENGE

A significant portion U.S. energy use is wasted due to fluid flow problems at the surfaces of machines and conduits. The energy is lost through friction, drag and wear compounded by contamination, build-up of microorganisms, and corrosion. In fact, at least 5% of the world's energy is wasted due to frictional losses. To address these problems, innovations in materials design are needed to create stable and robust surface coatings that can work in harsh operating environments.

TECHNICAL OPPORTUNITY

Advances in materials science including nanotechnology, computational methods, powerful characterization tools, and biologically-inspired materials design have opened new pathways for technical innovation and the creation of high-performance materials and coatings.

INNOVATION DEMONSTRATION

The project team adapted the strategy that a carnivorous plant uses for creating robust low-friction surfaces. The approach is to create a surface layer that is porous at the nanometer scale, and then fill the pores with a low-friction fluid. To manufacture such coatings economically, the Harvard team developed methods to create low cost nano-structured coatings on a variety of surfaces.

The team has combined different structured coatings with different fluid fillers, creating a wide range of designed surface properties. The liquid-filled structures repair themselves if scratched or damaged, resulting in stable coatings with the potential to significantly outperform conventional technologies, such as Teflon, in friction and drag reduction and in repelling a broad range of contaminants.

Their robust surface modification and coating process can be adapted for a variety of applications to improve energy efficiency. These applications include refrigeration, shipping, wastewater treatment, industrial cooling systems, and moving materials through pipelines.

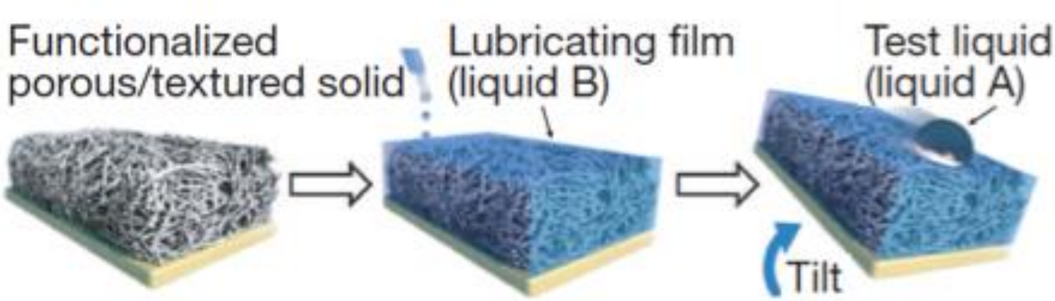

Figure 1: Schematic illustration of the formation of bio inspired low-friction coatings

PATHWAY TO ECONOMIC IMPACT

The Harvard team formed a new company, SLIPS Technologies Inc, which launched in October 2014 after securing venture capital financing. The company is commercializing SLIPS for use in various industrial, consumer, and medical applications. One important energy-focused applications they are pursuing is in refrigeration, where SLIPS coatings can significantly reduce energy needed for defrost cycles. The company is engaged with commercial partners to further develop this application.

In parallel, the Harvard team and the company are jointly evaluating a second possible application to create anti-fouling coatings for ships and other marine structures. These coating will improve fuel efficiency through reduced drag and displace the toxic contaminants that are released from present anti-fouling products.

LONG-TERM IMPACTS

The commercial demonstration of this innovative materials approach to high-performing coatings has reduced the long-term and high-risk technological barriers in the development of an important class of energy-efficient technologies.

The Harvard team's defrosting application is on a promising track to develop viable commercial products and grow in market penetration. This application could save over 2,650 GWh of the annual energy consumed in the United States for residential and commercial refrigeration, with a corresponding annual reduction in CO_2 emissions of more than 1.4 million metric tons.

Additional energy applications, which may be commercialized by the Harvard team, or may be developed by other companies who are inspired to create similar approaches, have the potential to economically reduce energy inefficiency in many other applications. Ultimately, this new class of materials is well positioned to support advanced energy technologies that will strengthen U.S. economic and energy security.

INTELLECTUAL PROPERTY & PUBLICATIONS

As of February 2016, the Harvard team's project has generated nine invention disclosures to ARPA-E and four U.S. PTO patent applications. The team has also published scientific underpinnings of the technology extensively in the open literature. A list of publications is provided below:

Cui, J.; Daniel, D.; Grinthal, A.; Lin, K.; Aizenberg, J., "Dynamic polymer systems with self-regulated secretion for the control of surface properties and material healing", *Nat. Mater.* 2015, *14* (8), 790-795.

Daniel, D.; Mankin, M. N.; Belisle, R. A.; Wong, T. S.; Aizenberg, J., "Lubricant-infused micro/nano-structured surfaces with tunable dynamic omniphobicity at high temperatures", *Appl. Phys. Lett.* 2013, *102* (23), 231603-1-4.

Epstein, A. K.; Wong, T. S.; Belisle, R. A. ; Boggs, E. M.; Aizenberg, J., "Liquid-infused structured surfaces with exceptional anti-biofouling performance", *P. Natl. Acad. Sci. USA* 2012, *109* (33), 13182-13187.

Grinthal, A.; Aizenberg, J., "Mobile Interfaces: Liquids as a Perfect Structural Material for Multifunctional, Antifouling Surfaces", *Chem. Mater.* 2014, *26* (1), 698-708.

Hou, X.; Hu, Y.; Grinthal, A.; Khan, M.; Aizenberg, J., "Liquid-based gating mechanism with tunable multiphase selectivity and antifouling behavior", *Nature* 2015, *519* (7541), 70-73.

Howell, C.; Vu, T. L.; Johnson, C. P.; Hou, X.; Ahanotu, O.; Alvarenga, J.; Leslie, D.; Uzun, O.; Waterhouse, A.; Kim, P.; Super, M.; Aizenberg, M.; Ingber, D. E.; Aizenberg, J., "Stability of Surface-Immobilized Lubricant Interfaces under Flow", *Chem. Mater.* 2015, *27* (5), 1792-1800.

Howell, C.; Vu, T. L.; Lin, J. J.; Kolle, S.; Juthani, N.; Watson, E.; Weaver, J. C.; Alvarenga, J.; Aizenberg, J., "Self-Replenishing Vascularized Fouling-Release Surfaces", *ACS Appl. Mater. Interfaces* 2014, *6* (15), 13299-13307.

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Kim, P.; Wong, T. S.; Alvarenga, J.; Kreder, M. J.; Adorno-Martinez, W. E.; Aizenberg, J., "Liquid-Infused Nanostructured Surfaces with Extreme Anti-Ice and Anti-Frost Performance", *ACS Nano* 2012, *6* (8), 6569-6577.

Leslie, D. C.; Waterhouse, A.; Berthet, J. B.; Valentin, T. M.; Watters, A. L.; Jain, A.; Kim, P.; Hatton, B. D.; Nedder, A.; Donovan, K.; Super, E. H.; Howell, C.; Johnson, C. P.; Vu, T. L.; Bolgen, D. E.; Rifai, S.; Hansen, A. R.; Aizenberg, M.; Super, M.; Aizenberg, J. Ingber, D. E., "A bioinspired omniphobic surface coating on medical devices prevents thrombosis and biofouling", *Nat. Biotechnol.* 2014, *32* (11), 1134-1140.

MacCallum, N.; Howell, C.; Kim, P.; Sun, D.; Friedlander, R.; Ranisau, J.; Ahanotu, O.; Lin, J. J.; Vena, A.; Hatton, B.; Wong, T. S.; Aizenberg, J., "Liquid-Infused Silicone As a Biofouling-Free Medical Material", *ACS Biomater. Sci. Eng.* 2015, *1* (1), 43-51.

Shillingford, C.; MacCallum, N.; Wong, T.-S.; Kim, P.; Aizenberg, J., "Fabrics coated with lubricated nanostructures display robust omniphobicity", *Nanotechnology* 2014, *25* (1), 014019-1-12.

Sunny, S.; Vogel, N.; Howell, C.; Vu, T. L.; Aizenberg, J., "Lubricant-Infused Nanoparticulate Coatings Assembled by Layer-by-Layer Deposition", *Adv. Funct. Mater.* 2014, *24* (42), 6658–6667.

Tesler, A. B.; Kim, P.; Kolle, S.; Howell, C.; Ahanotu, O.; Aizenberg, J., "Extremely durable biofouling-resistant metallic surfaces based on electrodeposited nanoporous tungstite films on steel", Nat. Commun. 2015, 6, 8649-1-10.

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Wilson, P. W.; Lu, W.; Xu, H.; Kim, P.; Kreder, M. J.; Alvarenga, J.; Aizenberg, J., "Inhibition of ice nucleation by slippery liquid-infused porous surfaces (SLIPS)", *Phys. Chem. Chem. Phys.* 2013, *15* (2), 581-585.

Wong, T. S.; Kang, S. H.; Tang, S. K. Y.; Smythe, E. J.; Hatton, B. D.; Grinthal, A.; Aizenberg, J., "Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity", *Nature* 2011, *477* (7365), 443-447.

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Yao, X.; Hu, Y.; Grinthal, A.; Wong, T. S.; Mahadevan, L.; Aizenberg, J., "Adaptive fluid-infused porous films with tunable transparency and wettability", *Nat. Mater.* 2013, *12* (6), 529-534.