Journal of Mechanical Science and Technology 21 (2007) 624~629

Journal of
Mechanical
Science and
Technology

A Biomimetic Approach for Effective Reduction in Micro-Scale Friction by Direct Replication of Topography of Natural Water-Repellent Surfaces

R. Arvind Singh[a], Hong Joon Kim[a], Jinseok Kim[a], Sungwook Yang[a], Hoon Eui Jeong[b], Kahp Y. Suh[b], Eui-Sung Yoon[a,*]

[a]*Nanobio Research Center, Korea Institute of Science and Technology, Seoul 130-650, Korea*
[b]*School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Korea*

(Manuscript Received September 5, 2006; Revised February 1, 2007; Accepted February 14, 2007)

Abstract

In this paper, we report on the replication of surface topographies of natural leaves of water-repellent plants of Lotus and Colocasia onto thin polymeric films using a capillarity-directed soft lithographic technique. The replication was carried out on poly(methyl methacrylate) (PMMA) film spin coated on silicon wafer using poly(dimethyl siloxane) (PDMS) molds. The friction properties of the replicated surfaces were investigated at micro-scale in comparison with those of PMMA thin film and silicon wafer. The replicated surfaces exhibited superior friction property when compared to those of PMMA thin film and silicon wafer. The superior friction behaviour of the replicated surfaces was attributed to the reduced real area of contact projected by them.

Keywords: Lithography, Biomimetic, Polymer, Micro, Friction, Tribology

---

1. Introduction

Nature offers a variety of surfaces, which exhibit evolutionarily optimized functional properties. In recent years, Biomimetics - an approach that involves the transformation of the underlying principles discovered in nature into man-made technology (Thieme et al., 2001) in gaining popularity in newly emerging fields such as micro/nano-electronics to structural engineering (Gould, 2003; Naik et al., 2005). As an example, the unique ability of Lotus leaf surface to avoid getting wet by the surrounding water, popularly known as the "Lotus effect" (Neinhuis et al., 1997) has motivated scientists world wide to modify/ fabricate surfaces for creating artificial superhydrophobic surfaces (Gould, 2003; Naik et al., 2005). Superhydrophobic surfaces have also been created by the direct replication of Lotus leaf using the process of nanocasting (Sun et al., 2005). Motivated by the surface topography of Lotus leaf, tribologists have modified/fabricated surfaces by means of ion-beam roughening of polymeric surfaces (Yoon et al., 2003) and fabrication of bio-mimetic nano-patterns (Burton et al., 2005; Singh et al., 2005; Yoon et al., 2006) in order to enhance the tribological performance at micro/nano-scales through the reduction of contact area. These investigations (Burton et al., 2005; Singh et al., 2005; Yoon et al., 2006) were directed towards enhancing the tribological performance of elements of microelectromechanical systems (MEMS), which are small in size and operate at nano/micro-scales. At these scales of operation, the large surface-to-volume ratio results in high surface forces such as adhesion

---

[*]Corresponding author. Tel.: +82 2 958 5651, Fax.: +82 2 958 6910
E-mail address: esyoon@kist.re.kr

and friction, which decrease the performance of MEMS devices (Nikhil et al., 2004). In this paper, we report on a simple biomimetic approach to obtain enhanced micro-tribological property, which involves the direct replication of natural leaves of water-repellent plants using a capillarity-directed soft lithographic technique.

2. Experimental details

The replication of the surfaces of natural leaves of Lotus (*Nelumbo nucifera*) and Colocasia (*Colocasia esculenta*) was carried out on poly (methyl methacrylate) (PMMA, M_w = 120,000 g/mol, T_g = 105°C, Aldrich) film coated on silicon wafer, using a simple capillarity-directed soft lithography technique, which principally utilizes the competition between capillary and hydrodynamic forces in the course of pattern formation (Suh et al., 2001). The replicated surfaces so fabricated were investigated for their micro-friction property. Friction tests were performed using Soda lime glass balls of radius 0.5 mm as counterface sliders (normal load 3 mN, sliding speed 1 mm/s, scan length 3 mm) in a ball-on-flat type micro-tribotester (Yoon et al., 2005) under reciprocating motion. All experiments were conducted at controlled conditions of temperature (24±1°C) and relative humidity (45±5%). Tests were repeated more than five times and the average values were plotted.

Figure 1 shows a schematic of the replication procedure of the surface of a fresh Lotus leaf. The same sequence was followed to replicate the surface of Colocasia leaf. In the first step, a PDMS mold was made using a real Lotus leaf as the natural template. The PDMS mold was prepared by casting PDMS (10% curing agent) against the surface of a Lotus leaf, which was followed by removing bubbles in ambient conditions for 30 min and then heating in a convection oven at 70°C for duration of 1 hour. This treatment was done to crosslink the heat-curable PDMS mold. Following this treatment, the mold was peeled off from the leaf surface. Next, PMMA dissolved in toluene (15 wt%) was spin-coated onto a cleaned silicon wafer. Finally, the PDMS mold was placed on the PMMA surface under a slight pressure of about ~ 0.2 to 0.3 MPa for conformal contact with the polymer. For a uniform pressure distribution, a thin PDMS block was placed as a buffer on top of the PDMS mold prior to the application of pressure. The sample was thus annealed at 140~150°C, well above the glass transition temperature (T_g = 105°C) for 30 minutes on a hot stage, after which the PDMS mold was removed.

3. Results and discussion

Figure 2 (a) and (b) show the scanning electron microscope (SEM) images of the morphology of real

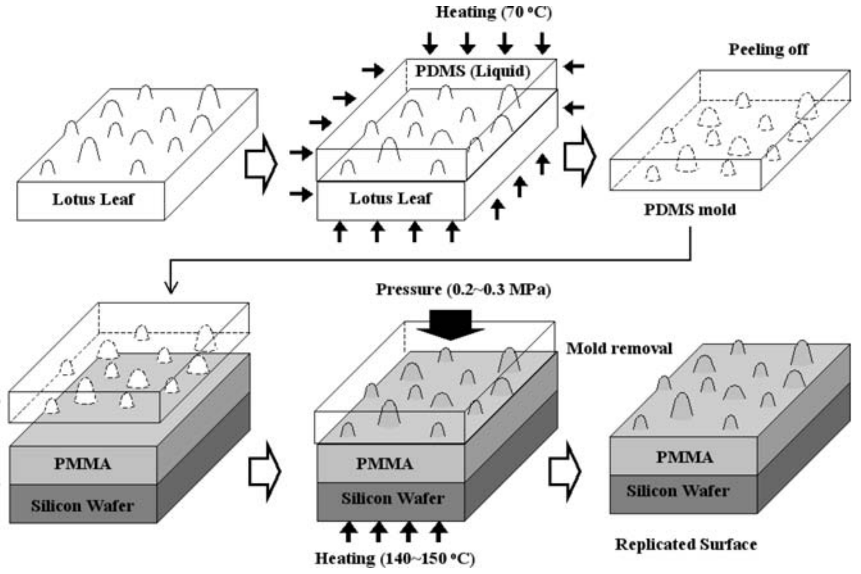

Fig. 1. The processing sequence of replication of the surface of a fresh Lotus leaf. The same sequence was followed to replicate the surface of Colocasia leaf.

Lotus and Colocasia leaves in their fresh conditions respectively. It could be observed from this figure that the morphologies of these leaves are different. Lotus leaf has randomly distributed protuberances and Colocasia has protuberances that are 'bumpy' in shape and appear to be closely arranged (Neinhuis et al., 1997). These leaves of real Lotus and Colocasia are superhydrophobic in nature and have water contact angles of about 162° and 164° respectively, which is due to the combination of the protuberances and the wax on them (Neinhuis et al., 1997).

Figure 2 (c) and (d) show the SEM images of the surface morphology of replicated Lotus-like and Colocasia-like surfaces, respectively. It can be seen that the surfaces of the real leaves have been replicated on a smoother scale. The replicated surfaces were characterized for their static contact angle of water using the sessile-drop method. When compared to the water contact angle of silicon wafer and PMMA thin film, it was found that the replicated surfaces had higher values of water contact angles (Fig. 3).

The replicated surfaces were investigated for their micro-friction property and were compared with that of the silicon wafer and PMMA thin film. In micro/nano-scale devices such as micro/nanoelectromechanical systems (MEMS/NEMS), silicon (Si (100)) is a traditionally used material and PMMA is a polymer often found in these devices (Nikhil et al., 2004). Hence, from the tribological point of view, a comparison of the friction behaviour of the replicated surfaces with those of silicon wafer and PMMA thin film becomes important. Figure 4 shows the results of the micro-friction tests. From this figure, it could be observed that the replicated surfaces exhibit superior micro-friction property than the silicon wafer and PMMA thin film. The coefficients of friction of the replicated surfaces were almost five times lower than that of the PMMA thin film and four times lower than that of the uncoated silicon wafer. The superior friction behaviour of the replicated surfaces is attributed to the reduced real area of contact projected by them. The reduction in the real area of contact leads to lowering of friction in accordance with the fundamental law of friction given by Bowden and Tabor (Bowden et al., 1950). According to this law, friction force is directly proportional to the real area of contact. Equation (1) gives the expression for the

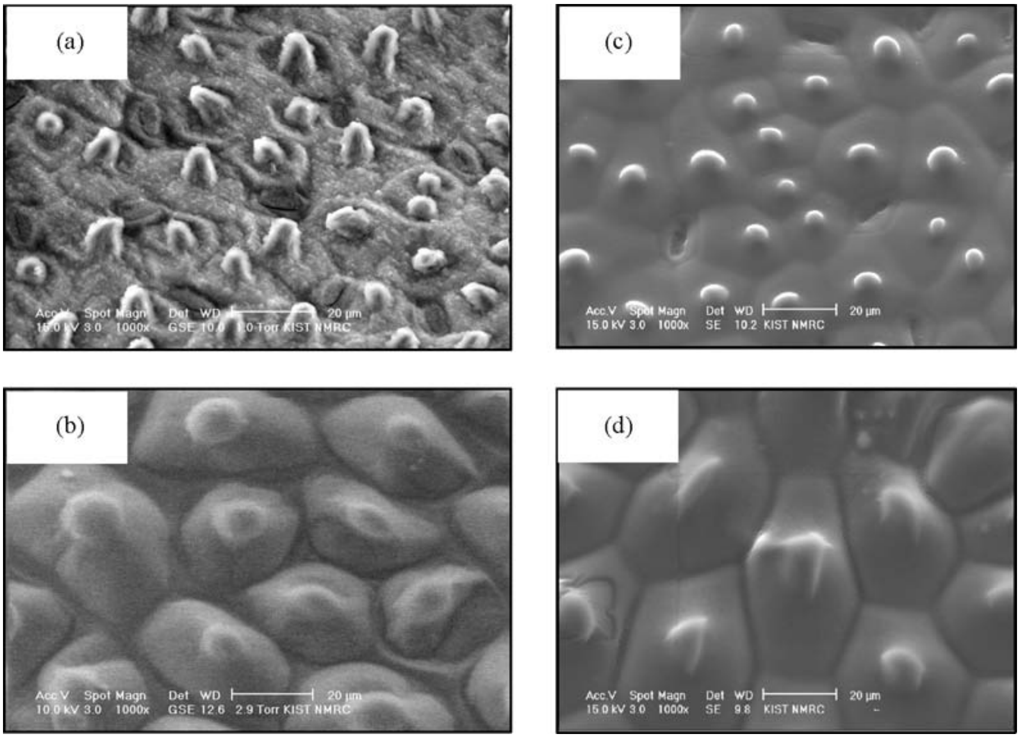

Fig. 2. SEM images of real surfaces: (a) Lotus leaf (fresh) and (b) Colocasia leaf (fresh). SEM images of replicated surfaces: (c) Lotus-like and (d) Colocasia-like surfaces.

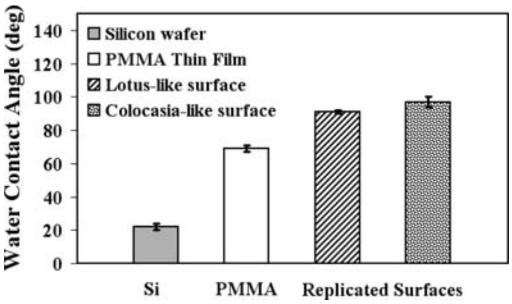

Fig. 3. Water contact angles of the test samples. The replicated surfaces have higher water contact angles than silicon wafer and PMMA thin film.

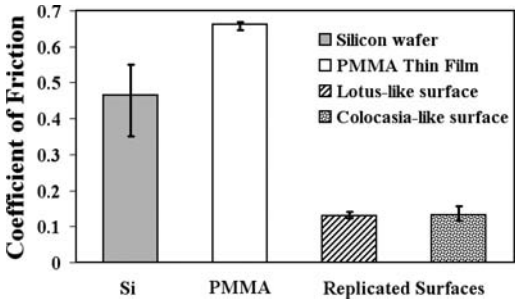

Fig. 4. Coefficient of friction of test materials. The replicated surfaces exhibit superior micro-friction property than silicon wafer and PMMA thin film.

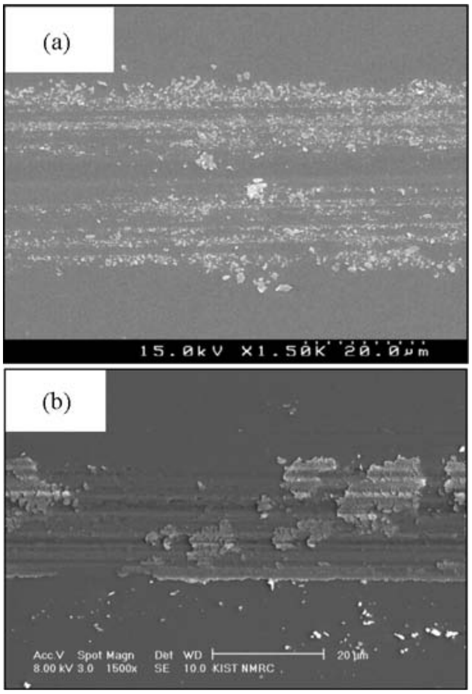

Fig. 5. Worn surfaces of the (a) silicon wafer and (b) PMMA thin film.

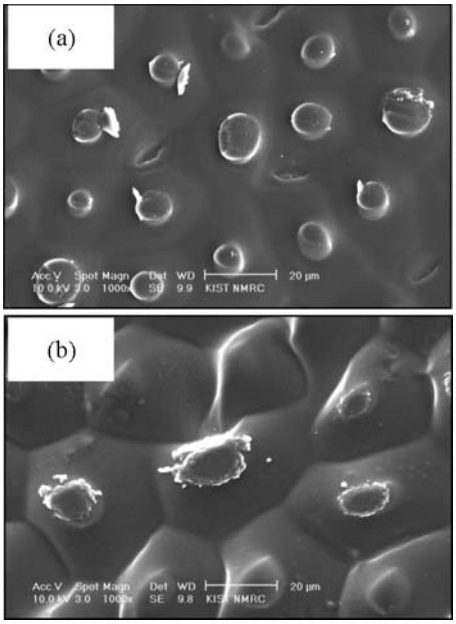

Fig. 6. SEM images of replicated surfaces taken after the friction tests: (a) Lotus-like and (b) Colocasia-like surfaces.

friction force.

$$F_f = \tau A_r \tag{1}$$

where, τ is the shear strength, an interfacial property and A_r the real area of contact.

In the present case, the replicated surfaces exhibit reduced real area of contact owing to the fact that patterning of surfaces causes a reduction in the real area of contact when the size of the asperities (protuberances) is considerably smaller than that of the counterface slider (glass ball in the present case) (Burton et al., 2005; Zou et al., 2005). Further, considering the JKR theory (Johnson et al., 1971), the contact area not only depends on the applied normal load and the radius of the ball, but also on the interfacial energy. According to this theory, the contact area is related to the applied normal load, the ball size and the interfacial energy of a material as given in Eq. (2).

$$A_r=\pi[R/K(F_n+6\pi\gamma R+[12\pi\gamma RF_n+(6\pi\gamma R)^2]^{1/2})]^{2/3} \tag{2}$$

where, R is the size of the ball, K the effective elastic modulus, F_n the applied normal load and γ the interfacial energy of the material.

When compared to the silicon wafer and PMMA thin film, the replicated surfaces have lower surface energies indicated by their higher values of water contact angle (cosine of water contact angle is a measure of surface energy [Beake et al., 2000]). Thus, the lower surface energies of the replicated surfaces in addition contribute towards reducing the real area of contact thereby lowering their friction values.

Figure 5 (a) and (b) shows the representative surfaces of silicon wafer and PMMA thin film after the friction tests. The silicon wafer and PMMA thin film undergo wear, whereas the patterned surfaces show roughening and deformation at the tip of their asperities (protuberances) as shown in Fig. 6. In our earlier work, we investigated on micro-scale friction property of nano-patterned surfaces with various geometrical parameters (size and shape) fabricated using an artificial template by the same soft lithographic method (under the same experimental conditions as those in the present investigation) (Singh et al., 2005; Yoon et al., 2006). Results showed that the lowest possible value of coefficient of friction was about one third of the PMMA thin film (Singh et al., 2005; Yoon et al., 2006), while in the present case the coefficient of friction reduced almost by five times. This finding indicates that the surfaces of these leaves appear to be highly optimized in terms of friction despite the fact that one might be able to create low-friction surfaces using artificial templates with carefully designed parameters.

The soft lithographic method used in the present work to replicate the natural surfaces on a smoother scale is simple, cost effective, and less time consuming. Although the method of nanocasting (Sun et al., 2005) has the ability to reproduce the surface topography of a Lotus leaf with high accuracy, the process is comparatively time consuming and in addition requires a chemical treatment (coating of an antistick monolayer). An intricate replication of the surface topography becomes necessary in order to achieve superhydrophobic nature (Sun et al., 2005), whereas to considerably enhance a micro-tribological property such as micro-scale friction, replication of the topography on a smoother scale in a fast and efficient route would suffice, as is seen from the present work. As a part of our ongoing research work, we are exploring the replication of natural surfaces with different polymeric materials to ensure flexibility of the fabrication method and which would provide wide range of surfaces with superior tribological properties.

4. Conclusion

In conclusion, we have presented a novel method to enhance micro-scale tribological property by the replication of natural surfaces and have emphasized on the potential of nature-based solutions for superior tribological performance. Looking at the enhanced tribological properties exhibited by these surfaces, we believe that in the future, these kinds of surfaces would have potential application in small-scale devices like MEMS.

Acknowledgments

This research work was supported by a grant (06K1401-00930) from Center for Nanoscale Mechatronics and Manufacturing of 21st Century Frontier Research Program. This work was also supported in part by the Micro Thermal System Research Center of Seoul National University.

References

Beake, B. D., Leggett, G.. J., 2000, "Variation of Frictional Forces in Air with the Compositions of Heterogeneous Organic Surfaces," *Langmuir*, Vol, 16, pp. 735~739.

Bowden, F. P., Tabor, D., 1950, "The Friction and Lubrication of Solids," *Clarendon Press*, Oxford, pp. 90~121.

Burton, Z., Bhushan B., 2005, "Hydrophobicity, Adhesion, and Friction Properties of Nanopatterned Polymers and Scale Dependence for Micro- and Nanoelectromechanical Systems," *Nano Letters*, Vol, 5, pp. 1607~1613.

Gould, P., November 2003, "Smart, Clean Surfaces," *Materials Today*, pp. 44~48.

Johnson, K. L, Kendall, K., Roberts, A. D., 1971, "Surface Energy and Contact of Elastic Solid," *Proceedings of the Royal Society of London A*, Vol, 324, pp. 301~313.

Naik, R. R., Stone, M. O., September 2005, "Integrating Biomimetics," *Materials Today*, pp.18~26.

Neinhuis, C., Barthlott, W., 1997, "Characterization and Distribution of Water-Repellent, Self-Cleaning Plant Surfaces," *Annals of Botany*, Vol, 79, pp. 667~677.

Nikhil, S. T., Bhushan, B., 2004, "Scale Dependence of Micro/Nano-Friction and Adhesion of MEMS/NEMS Materials, Coatings and Lubricants," *Nanotechnology*, Vol, 15, pp. 1561~1570.

Singh, R. A., Yoon, E. S., Kim, H. J., Kong, H, Suh, K.

Y., Jeong, H. E., 2005, "Submicron-Scale Polymeric Patterns for Tribological Applications in MEMS/NEMS," *KSTLE International Journal*, Vol, 6, No. 2, pp. 33~38.

Suh, K. Y., Kim, Y. S., Lee, H. H., 2001, "Capillary Force Lithography," *Advanced Materials*, Vol, 13, pp. 1386~1389.

Sun, M., Luo, C., Xu, L., Ji, H., Ouyang, Q., Yu, D., Chen, Y., 2005, "Artificial Lotus leaf by Nanocasting," *Langmuir*, Vol, 21, pp. 8978~8981.

Thieme, M., Frenzel, R., Schmidt, S., Simon, F., Hennig, A, Worch, H, Lunkwitz, K. and Scharnweber, D., 2001, "Generation of Ultrahydrophobic Properties of Aluminium – A First Step to Self-Cleaning Transparently Coated Metal Surfaces," *Advanced Engineering Materials*, Vol, 3, pp. 691~695.

Yoon, E. S., Singh, R. A., Kong, H., Kim, B., Kim, D. H., Suh, K. Y., Jeong, H. E., 2006, "Tribological Properties of Bio-Mimetic Nano-Patterned Polymeric Surfaces on Silicon Wafer," *Tribology Letters*, Vol, 21, No. 1, pp. 31~37.

Yoon, E. S., Singh, R. A., Oh, H. J., Kong, H., 2005, "The Effect of Contact Area on Nano/Micro-Scale Friction," *Wear*, Vol, 259, pp. 1424~1431.

Yoon, E. S., Yang, S. H., Kong, H., Kim, K. H., 2003, "The Effect of Topography on Water Wetting and Micro/Nanotribological Characteristics of Polymeric Surfaces," *Tribology Letters*, Vol, 15, pp. 145~154.

Zou, M., Cai, L., Wang, H., Yang, D., Wyrobek, T., 2005, "Adhesion and Friction Studies of a Selectively Micro/Nano-Textured Surface Produced by UV Assisted Crystallization of Amorphous Silicon," *Tribology Letters*, 20, pp. 43~52.