NATURAL BEAUTY OF ARTIFICIALLY TEXTURED SURFACES: MORPHO-BUTTERFLY COLORING WITH PARTICLE ARRAYS

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Is there any minimum unit in the nature's beauty? Let us first think about jewels such as ruby or diamond. Owing to the historic studies of optics and optical properties of crystals, now we understand the origin of the beauty generated by these jewels. The knowledge combined with the high-pressure and high-temperature technologies, now enable us to fabricate and deliver various jewels at a reasonable cost without loosing their fascination. There is another type of beauty in jewels which is not yet fully understood and artificially reproduced. That is iridescent coloring observed in opal or cat's eye. The opal-like coloring is also observed in the surfaces of creatures such as insects.

We can remember that in our childhood we were completely enthralled by strange insects, such as beetles and butterflies. The fascination of their colorful surfaces is now revealed to arises from their fine surface textures which are microscopically difined and then difficult to be mimicked by our current technologies. But we can again raise the question, as in the past we put to the jewels, whether our science and technology can break the code and artificially reproduce fine textures of creatures surface. A study to imitate the textured surface and reproduce the beauty of a kind of butterfly, morpho, made famous by its fascinating iridescent colors has been thus boosted. Morpho has very brilliant wings able to catch our eyes from as far away as 1 km. There are people who believe its beauty is beyond that of the black opal. The natural wing of a morpho-butterfly has a periodic structure, as determined by optical and electron microscopy. Each 100-μm continuous parallel gratings. This structure could be closely duplicated using fine particles and their regular arrays.

Ordered arrays of colloidal particles coated on surfaces are usable in industry either as a diffraction grating, an optical storage medium or an interference layer. Formation of ordered colloidal particle arrays has been studied and fabricated by spin coating [Deckman et al., 1983, 1988], or mechanical or chemical packing of colloidal particles at the air-water interface [Dunsmuir et al., 1989]. Here we propose a novel fabrication method for preparation of colloidal particle arrays with crystalline order. The essence of our fabrication of two-dimensional (2D) assembly of particles lies in the use of stable wetting film that is made on the substrate surface as shown in Figure 1 [Nagayama, 1993]. This wetting film plays two important roles here; 1) 2D liquid medium where particles can be carried by water flow to the crystal boundary for growth (convective self-assembly, Figure 1C) [Denkov, et al., 1992, 1993; Dushkin, et al., 1993[a], 1993[b]; Dimitrov, et al., 1994], and 2) interparticle attractive force induced by the surface tension for the particle packing (lateral capillary force, Figure 1D) [Kralchevsky, et al., 1992, 1994; Velev, et al., 1993]. First, particles undergo the Brownian motion in the thick film (Figure 1A). When the wetting film becomes as thin as the particle size by the removal of water, an ordered 2D domain starts to grow on the surface (Figure 1B).

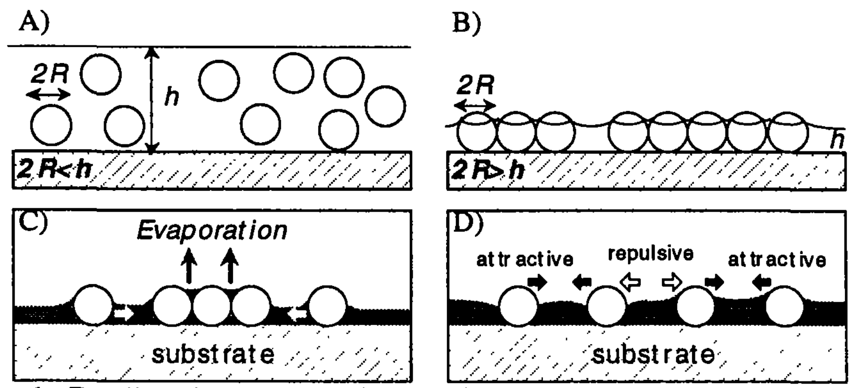

Figure 1 Two-dimensional assembly of particles in the wetting film [Nagayama, 1993].

A) Particles undergo the Brownian motion in the liquid layer of which the thickness is much larger than the particle size.

B) Particles start to assemble in the wetting film as the thickness of the film becomes comparable to or slightly smaller than the particle size.

C) Convective flow responsible for the assembling of particles stimulated by the liquid evaporation.

D) Lateral capillary forces responsible for the hexagonally closed packing of particles.

For a wettable solid plate vertically dipped in a suspension of colloidal particles, monolayers and successive multilayers of particle arrays spontaneously start to form near the three-phase contact line on the plate surface (Figure 2) [Dimitrov & Nagayama, 1995]. The formation of particle array films can be explained again by the mechanism mentioned above. This procedure was applied to different suspensions of polystyrene particles with diameters from 0.079 to 2.106 μm. Wetting films were formed due to the capillary rise along the plates. When the plates were fixed, mono-, bi-, trilayers, etc., started to form in the vicinity of the plate-suspension-air contact line. We controlled the growth of particle arrays that have multiple layers, and especially of monolayer arrays, by withdrawing the substrate plates from the suspensions with an adequate rate.

Regular structure of textured surfaces and the colors of our 953-nm particle array films was compared to those of the wings of a Morpho butterfly, *sulkowsky* (Figure 2) [Dimitrov & Nagayama, 1995]. Our experiments showed that for the same incidence angle of illumination, the dispersed light coloring of the textured surfaces mainly depends on the texture periodicity, and on the orientation of the surface domains. When illuminated by white light, the particle arrays we produced mimic the iridescent coloring of Morpho-butterfly wings. Microscopic observations showed that the similarities in the coloring of both particle arrays and butterfly wings are due to the same special periodicity of the surface texture, which is on the order of or slightly above the wavelength of visual light. Our film fabrication using colloidal particles and the film iridescent coloring will open a new avenue for the additive color processing nowadays, which are used in a wide range of arts and technologies.

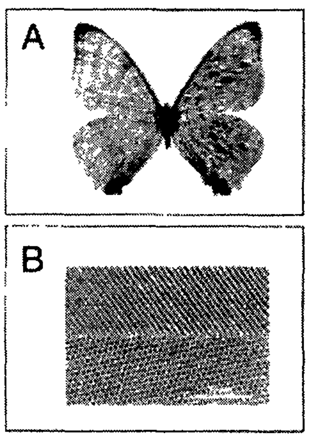

Figure 2 Coloring of textured surfaces with μm-scale periodicity

A) Morpho butterfly (*sulkowsky*) with original (left) and artificial wing (right).

B) Scanning electron microscope image of the grating on a scale from the Morpho butterfly wing (top) and monolayer particle arrays mimicking the wing grating (bottom).

References:

Deckman, J. A.; Dunsmuir, J. H. "Applications of Surface Textures Produced with Natural Lithography", J. Vac. Sci. Technol., 1983, B1, 1109.

Deckman, H. W.; Dunsmuir, J. H.; Garoff, S.; McHenry, J. A.; Peiffer, D. G. " Macromolecular Self-organized Assemblies", J. Vac. Sci. Technol., 1988, B6, 333.

Denkov, N. D.; Velev, O. D.; Kralchevsky, P. A.; Ivanov, I. B.; Yoshimura, H.; Nagayama, K. "Mechanisms of Formation of Two-Dimensional Crystals form Latex Particles on Substrate", Langmuir, 1992, 8, 3183.

Denkov, N. D.; Velev, O. D.; Kralchevsky, P. A.; Ivanov, I. B.; Yoshimura, H.; Nagayama, K. "Two-Dimensional Crystallization", Nature, 1993, 361, 26.

Dimitrov, A. S.; Dushkin, C. D.; Ivanov, I. B.; Yoshimura, H.; Nagayama,K. " Observation of Latex Particles Two-Dimensional Crystal Nucleation in Wetting Films on Mercury, Glass, and Mica", Langmuir, 1994, 10, 432.

Dimitrov, A. S.; Nagayama, K., Lungmuir, submitted.

Dunsmuir, J. H.; Deckman, H. W.; McHenry, 1989, J. A. U. S. Pat. No. 4,801,476.

Dushkin, C. D.; Nagayama, K.; Miwa, T; Kralchevsky, P. A. "Colored Multilayers from Transparent Submicrometer Spheres", Langmuir, 1993[a], 9, 3695.

Dushkin, C. D.; Yoshimura, H.; Nagayama, K. "Nucleation and Growth of Two-Dimensional Colloidal Crystals", Chem. Phys. Lett., 1993[b], 204, 455.

Kralchevsky, P. A.; Paunov, V. N.; Ivanov, I. B.; Nagayama, K. "Capillary Meniscus Interaction between Colloidal Particles Attached to a Liquid-Fluid Interface", J. Coll. Interface Sci., 1992, 151, 79.

Kralchevsky, P. A.; Nagayama, K. "Capillary Forces between Colloidal Particles", Langmuir, 1994, 10, 23.

Nagayama, K. "Fabrication of Two-Dimensional Colloidal Arrays", Phase Transitions, 1993, 45, 185.

Velev, O. D.; Denkov, N. D.; Paunov, V. N.; Kralchevsky, P. A.; Nagayama, K. "Direct Measurement of Lateral Capillary Forces", Langmuir, 1993, 9, 3702.