AFM STUDY OF STRUCTURE INFLUENCE ON BUTTERFLY WINGS COLORATION

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Abstract. *This study describes the structural coloration of the butterfly Vanessa Atalanta wings and shows how the atomic force microscopy (AFM) can be applied to the study of wings morphology and wings surface behavior under the temperature. The role of the wings morphology in colors was investigated. Different colors of wings have different topology and can be identified by them. AFM in semi-contact mode was used to study the wings surface. The wing surface area, which is close to the butterfly body, has shiny brown color and the peak of surface roughness is about 600 nm. The changing of morphology at different temperatures is shown.*

Keywords

Atomic force microscopy, diffraction, morphology, natural nanostructure, reflection, structural color, temperature influence.

1. Introduction

Even with naked eyes the ancient Greeks observed that minute scales, which cover the wing membrane produced the pattern and coloration. Hence the scientific name of these insects as “lepido-ptera” means “scaled wing” [1].

The Red Admiral (Vanessa Atalanta) is a well-known colorful butterfly, found in temperate zones in Europe, Asia and North America. This large butterfly is identified by its striking dark brown, red, and black wing pattern [2] as shown in Fig. 1. The wings are covered with thousands of chitin laminae (scales) that vary in shape, size, and color. Scale microstructure, usually consisting of longitudinally extending ridges connected by a series of cross-ribs, has been the subject of numerous studies by optical and electron microscopy techniques [3].

The scales of butterflies are divided according to their coloration on pigmental and optical ones. A pigmental color can be very bright, but it is always dull and without shine. There are optical scales alone which provide a metallic lustre of butterfly wings. The light reflected from the wings undergoes repeated reflections. In the scales which form layers, both a diffraction and interference occur. These phenomena are responsible for colors shifting which also depends on a viewing angle. Multiple interference results in a fact that a surface has the shine of glitter polished metal. The scales also protect wings, improve their aerodynamics properties, and control a variation of temperature. In order to increase the temperature of body, butterflies do not change the metabolism, but use different positions of wings in order to absorb light [4]. Either wings absorb the sun irradiation and butterfly´s body is heated, or wings reflect the irradiation onto a body. This is defined by the color of wings which are located in the vicinity of the body because the major meaning for the temperature regulation belongs to these parts. In [5] was also suggested that the solar heat is absorbed and conducted away by the ridges or ribs in the wing.

Fig. 1: Photo of the butterfly Vanessa Atalanta (Red Admiral) [6].

The wings design gives information and impact for scientists to apply these biological structures for the study and construction of micro- and nano-devices (like photonic crystals). Therefore, one of challenges for present days in science is a replication of biomimetic structures over large scales and at an affordable price for industrial applications [7], [8], [9], [10].

The AFM is a useful tool for high-resolution investigation of both inorganic and organic materials and allows study over a range of surface properties. It has a lot of adventures for study of biological materials: nondestructive methods, study of nonconductive materials, measurements in the large range of temperatures.

2. Experimental

AFM NTEGRA Prima (NT-MDT, Russia) was used for a study of the wings surface, working both in non-contact and semi-contact modes. For the noncontact mode, a ultrasharp diamondlike carbon tip (NSG01_DLC, NT-MDT) with typical curvature radius of 1 nm was chosen for measurement. Sometimes a semi-contact mode using whisker type probes (NSC05_10°) is better for a study of biological objects due to the reduction of lateral forces between a probe and a sample. The suitable choice of measuring methods could also be made by the variation of scanning parameters [11]. By lack of available information, the various measuring modes were used in the research. For the evaluation of the AFM data NOVA software by NT-MDT production has been used.

The separate investigated colored areas are presented below. Figure 2 shows the black area of the wing laminae surface.

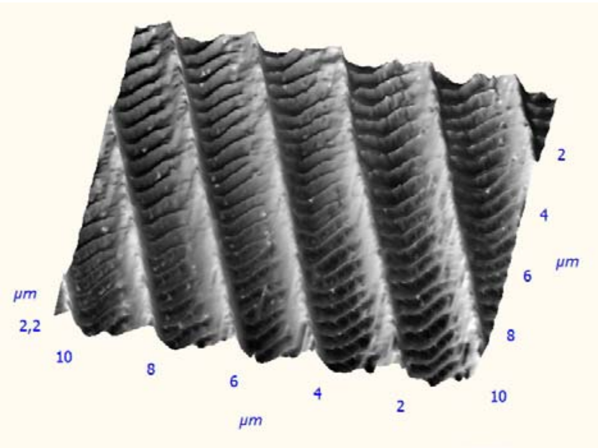

Fig. 2: Morphology of the black area of the wing laminae.

Black pigments give a good contrast because they absorb all frequencies of visible light. However, it is not quite right because some part of the light is reflected. As was reported in [12] on some black spots of butterfly´s wing (Achillides Ulysses), it is possible to observe the cells structure where scales have very small holes (diameter of 1 µm). These scales have high refraction index, therefore a total internal reflection emerges. Due to this reflection we can see the wings of deep black color.

The surface is composed by a multilayered chitin film, and the surface between large ridges is periodically squiggled, and a regular set of cavities is observed. These cavities are elongated. The distances between large ridges are in the range from 1,83 to 1,98 µm, and the distance between small under-ridges varies from 391 to 395 nm. There are also few sub-ridges of several nm in size. By simple comparison of roughness distribution (the amount of histogram points is the same) of the black area (Fig. 3) with the white area (Fig. 4), it is possible to note that a roughness histogram for black area contains much more elements of morphology with lower size. The average roughness of the black surface is 340,266 nm and of white surface is 526,847 nm.

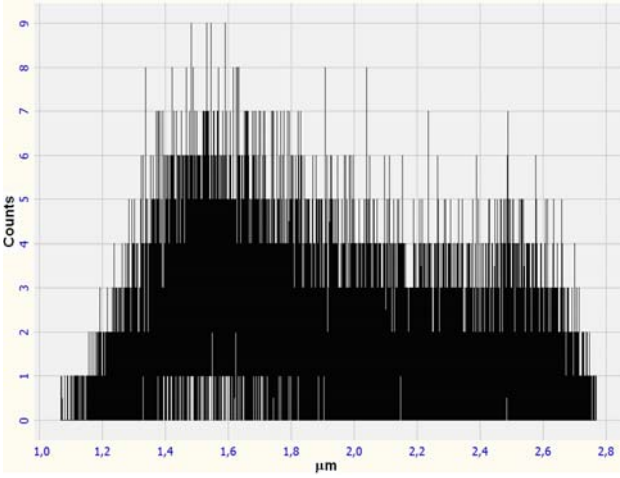

Fig. 3: The roughness distributions function of the wing black area.

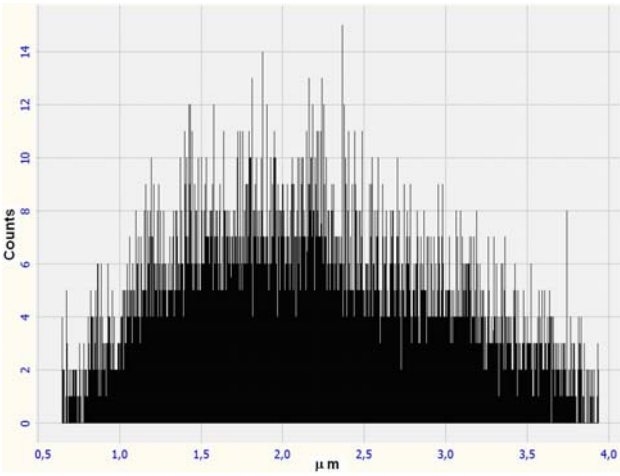

Fig. 4: The roughness distributions function of wing white area.

The morphology of the white area is then presented in Fig. 5. Although a width of the ridges is approximately the same as for the black area, the laminae are visible only with difficulty (due to the multiple reflections inside layers).

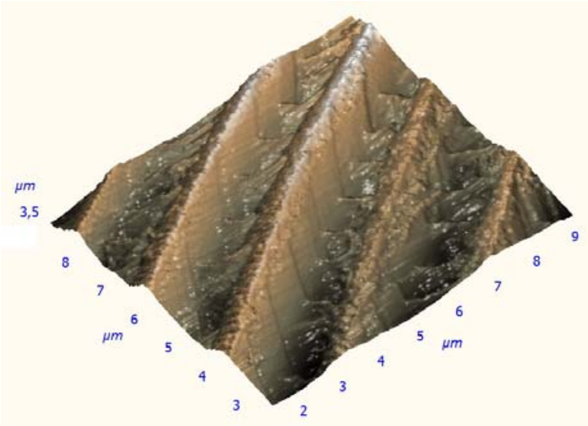

Fig. 5: Morphology of the white area of the wing.

Area with orange color is presented in Fig. 6. The distance between large ridges is 1,15 µm and the distance between small under-ridges varies from 0,561 to 0,777 µm. The average roughness of the orange surface is of 175,266 nm.

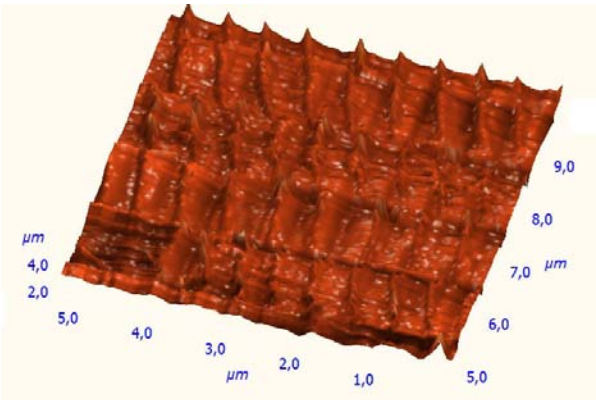

Fig. 6: Morphology of the orange area of the wing.

Morphology of the shining brown color area is shown in Fig. 7. It represents the layers of (1,66-1,71 µm) in breadth. The average roughness of the brown surface is 34,4392 nm. Figure 8 shows a roughness of this area, where the main peak is about 600 nm high. This corresponds to the wavelength of yellow color. So the diffraction on the microstructure of the surface can be a reason of the glitter brown color.

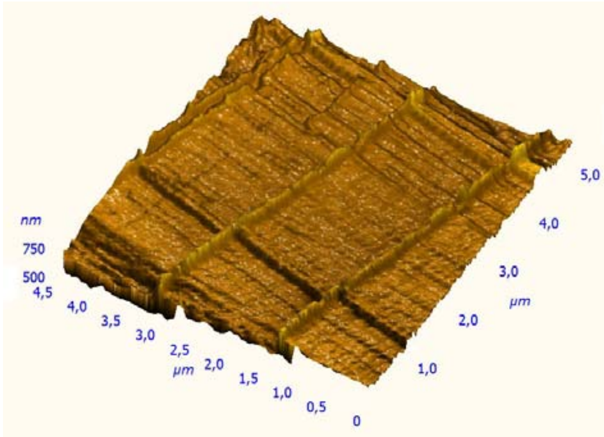

Fig. 7: Morphology of the brown area of the wing.

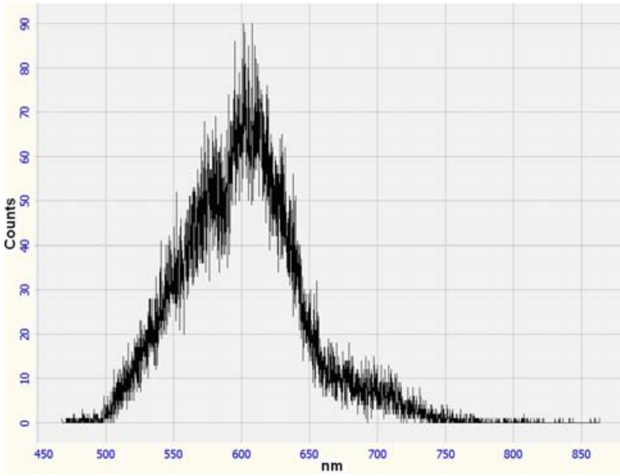

Fig. 8: Roughness distributions function of the brown area of the wing.

Properties of the butterfly wings are of interest because, besides their aerodynamic function, they have a lot of other complex functions. As noted therein before, a surface structure of butterfly wings also provides a regulation of temperature. This feature also was investigated by AFM with thermal table. For this purpose, a probe with tip radius of 10 nm (NSG01 – NT-MDT, resonant frequency 87-230 kHz, and force constant 1,45-15,1 Nm^{-1}) was chosen in order to reduce fluctuations of probe because of temperature gradient.

The performance of barrier interface that controls interaction of the butterfly with neighbor environment is of special importance. The surface sheet of the wings is thermally resistant up to 90 °C due the stability of its main component – chitin.

Very interesting feature is that a wing surface simultaneously exhibits a thermal sensitivity by a simple change of distance between ridges. This behavior was studied at [6] and encouraged a creation of better temperature sensors [13]. The morphology of the same part of wing at 40 °C, 70 °C and 90 °C was measured and results are shown in the Figs. 9-11, correspondingly.

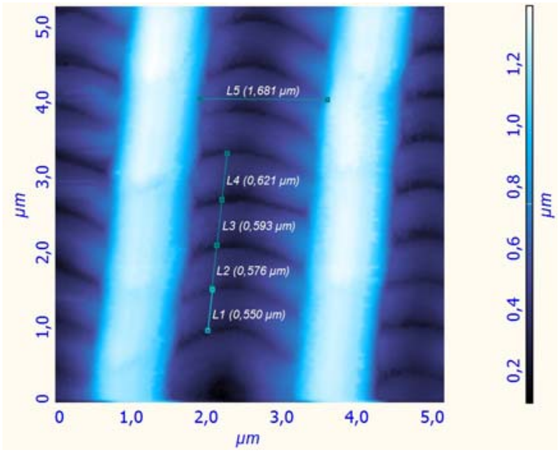

Fig. 9: Morphology of the wing at 40 °C. Average roughness is of 335,513 nm.

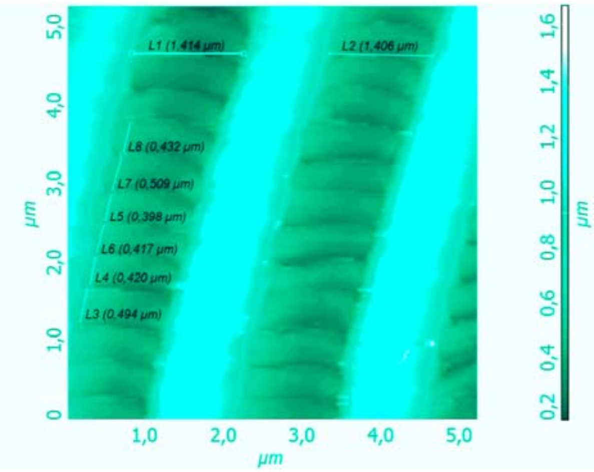

Fig. 10: Morphology of the wing at 70 °C. Average roughness is of 328,742 nm.

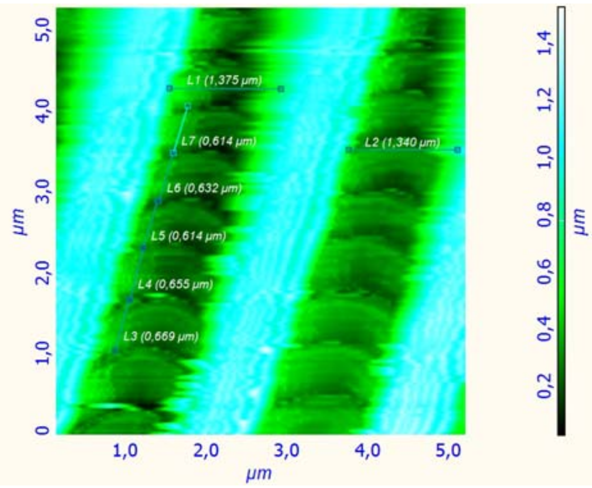

Fig. 11: Morphology of the wing at 90 °C. Average roughness is of 347,079 nm.

The specific colors are due to the fine diffraction grating forming the scales. Unfortunately, because the morphology, as well as thermal behavior, was studied on post-mortem samples, only stationary modifications provided by heated sample were observable. Hence, the dynamic changes inherent with living tissue are not perceptible here.

3. Conclusion

The paper deals with the application of semi-contact mode AFM in a study of structural coloration of the butterfly Vanessa Atalanta wings. By using a combination of thermal table with AFM, it is possible to study the wings surface behavior under temperature variations. The wing surface area which are close to the butterfly body exhibits a fine structure and reflects shine brown color. Consequently, in opposition of the outer part of the wing, the peak of surface roughness is of about 600 nm high. The morphology-temperature dependence is also shown for three different temperatures.

The AFM facilities provide tools for well comprehensive understanding of structural formation of colors. Design of periodical structure is an important optical property of the surface. The structures like butterfly wings are of great interest for creation of photonic crystals, which can find applications in optoelectronics and other fields, where it is necessary to obtain the colors which will not tarnish in time because of light.

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References

[1] BALINT, Z., Z. VERTESY, K. KERTESZ and L.P. BIRO. *Scanning Electron Microscopic Investigations in Butterfly Wings: Detecting Scale Micro- and Nanomorphology and Understanding their Functions*. Current Issues on Multidisciplinary Microscopy Research and Education, 2004, no. 133, pp. 87-92. ISBN 978-84-609-6605-4. [online]. Available at: www.nhmus.hu/users/foldvari/balint_no_133.pdf.

[2] SHALAWAY, S. *Butterflies in the Backyard*. Mechanicsburg, Pennsylvania: Stackpole Books, 2004. ISBN 0-8117-2695-9.

[3] GRUVERMAN, A., B.J. RODRIGUEZ and S.V. KALININ. Nanoscale Electromechanical and Mechanical Imaging of Butterfly Wings by Scanning Probe Microscopy. *Journal of Scanning Probe Microscopy*. 2006, vol. 1, no. 2, pp. 74-78.

ISSN 1557-7937.

[4] KINGSOLVER, J.G. Butterfly Engineering. *Scientific American*. 1985, vol. 253, no. 2, pp. 106-113. ISSN 0036-8733.

[5] ZHANG, W, D. ZHANG, T. FAN, J. GU, J. DING and H. WANG. Novel Photoanode Structure Templated from Butterfly Wing Scales. *Chemical Materials*. 2009, vol. 21, no. 1, pp. 33-40. ISSN 0959-9428. DOI: 10.1021/cm702458p.

[6] Fauna and Flora of the Mid-Atlantic States: Butterflies, Moths and Caterpillars. *MIDATLANTICHIKES.com* [online]. Available at: http://midatlantichikes.com/floraandfauna/butterflies.htm

[7] BIRO, L.P., Z. BALINT, K. KERTESZ, Z. VERTESY, G.i. MARK, Z.E. HORVATH, J. BALAZS, D. MEHN, I. KIRICSI, V. LOUSSE and J.-P. VIGNERON. Role of photonic-crystal-type structures in the thermal regulation of a Lycaenid butterfly sister species pair. *Physical Review E*. 2003, vol. 67, iss. 2, pp. 021907(1-7). ISSN 1550-2376.

[8] SAISON, T., Ch. PEROZ, V. CHAUVEAU, S. BERTHIER, E. SONDERGARD and H. ARRIBART. Replication of butterfly wing and natural lotus leaf structures by nanoimprint on silica sol-gel films. *Bioinspiration biomimetics* [online]. 2008, vol. 3, no. 4, pp. 1-3, ISSN 1748-3190. DOI: 10.1088/1748-3182/3/4/046004. Available at: http://www.ncbi.nlm.nih.gov.

[9] KANG, S.-H., T.-Y. TAI and T.-H. FANG. Replication of butterfly wing microstructures using molding lithography. *Current Applied Physics* [online]. 2010, vol. 10, iss. 2, pp. 625-630, ISSN 1567-1739. DOI: 10.1016/j.cap.2009.08.007. Available at: http://www.ncbi.nlm.nih.gov.

[10] KOVALEV, I. Tubes from butterfly wings. *Science and Life* [online]. 2005, vol. 9, no. 1, pp. 64-67. ISSN 0028-1263. Available at: http://www.nkj.ru/archive/articles/1729/.

[11] AFM study of macromolecules' structure and organization. Application notice [online]. Available at http://www.ntmdt.com/spm-notes/view/afm-study-of-macromolecules-structure-and-organization.

[12] SARFATI, J. Wonderful black and blue butterflies. *Journal of Creation*. 2005, vol. 19, iss. 1, pp. 9-10. ISSN 0819-1530.

[13] PRIS, A.D., Y. UTTURKAR, Ch. SURMAN, W.G. MORRIS, A. VERT, S. ZALYUBOVSKIY, T. DENG, H.T. GHIRADELLA and R.A. POTYRAILO. Towards high-speed imaging of infrared photons with bio-inspired nanoarchitectures. *Nature Photonics*. 2012, vol. 6, iss. 3, pp. 195-200. ISSN 1749-4885.

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