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CORRUGATION ELASTICITY AS A NEW PROPERTY OF NANOSTRUCTURED MATERIAL: HOLOGRAPHIC ANALYSIS OF *APATURA* BUTTERFLY WINGS

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Abstract

The corrugation of the structure is a special property of the material that has a great influence on almost all other characteristics of the same. The connection between materials based on the corrugation of natural structures such as *Apatura* butterfly wings and its examination (the six samples of same species) by the method of holographic interferometry (with four different wavelengths of laser radiation) is presented in this paper. The concept of material's corrugation elasticity is presented as well as the advantages of this concept. The holographic method was implemented as appropriate for monitoring the structure dynamics at the nanoscale. Finally, the important factor that impacts the elasticity of the corrugation of the material lies in the optical factors of the environment is emphasized, i.e., in the light of laser radiation that structure interferes with. A completely non-linear dependence on the wavelengths of light is shown, where for wavelengths of 532 nm and 660 nm the elasticity of the corrugation is observed, while for 450 nm and 980 nm a plastic deformation of the corrugation is observed. These preliminary studies open new possibilities in the synthesis and testing of different materials and monitoring of their dynamics in real time.

Keywords: corrugated materials, structure morphology, holographic monitoring, dynamics monitoring, *Apatura* butterfly.

1. Introduction

When talking about nanostructures, very small deviations in dimensions play a big role. The corrugation of the material - the nanostructure, has numerous advantages and the material itself has different properties due to different types of corrugation [1]. To gain a deeper understanding of the range of complex corrugated structures, the three different types of corrugation of natural structures are presented by Scanning Electron Microscope (SEM) images in Figure 1.

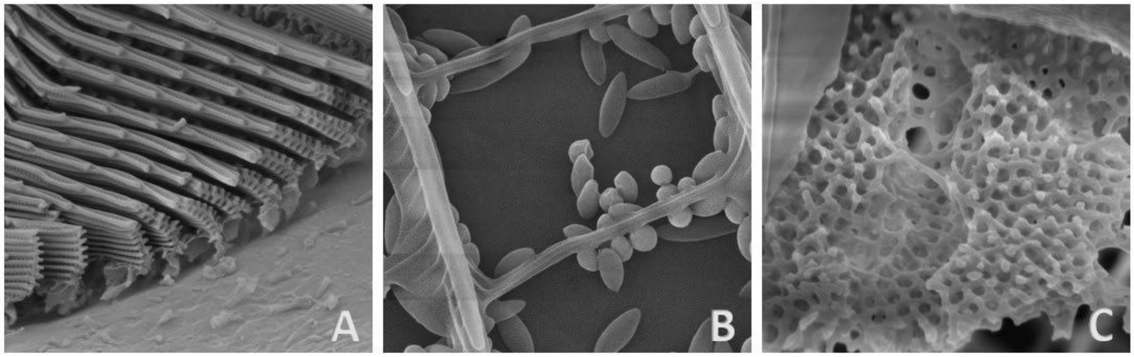

Fig. 1. SEM images of the representatives of various structures: *Morpho didius* butterfly (A), *Pieris rapae* butterfly (B), and *Calophrys rubi* butterfly (C).

In this paper we deal with the corrugation of the surface of nanomaterials of *Apatura* butterfly wings. Generally, surface corrugation can have a huge impact on the performance of the material as well as on the durability of the structure. Measurements of the corrugation could be done in a several different ways [2], such as measuring the average corrugation and the extreme values. However, determining the characteristics of the corrugation itself and its behavior under certain influences is of much greater importance.

The influence of temperature on the material, its deformation, can be examined by different methods [3, 4], easily and visually ascertained, when it comes to obvious tearing of the structure or a change in the chemical composition. [5] When dealing with a change in corrugation property that has the potential to return to its original state after some period of time, microscopic observation is not always the best method. The method itself or the conditions required for the method used can lead to error. For example, a sample holder could speed up the cooling process, more precisely it could lead to an unrealistic degree of heating. In this case, the method of holographic interferometry [6] can be an excellent choice since it has the possibility to follow the deformation over time. Hence, if there is a very small change in the moment of exposure, which changes over time or the object of exposure returns to its original state, holography will record such information. Therefore, the holographic method is ideal when talking about the dynamics of complex corrugations of nanoscale structures.

When we talk about the behavior of the corrugation itself of a nanostructure during and after deformation, more precisely about the plastic or elastic deformation [7] of that corrugation, it can be said that we are aiming for a higher level of behavior of corrugated nanomaterials. The concept of *corrugation elasticity* of the material can be introduced, which would imply the ability of the material to return its damaged corrugation property to the original form. The benefits of corrugated materials are enormous [8], so a detailed examination of their characteristics and the disclosure of their special properties are of great importance.

To test the elasticity of the corrugation the less-understand phenomena at micro-scales called thermophoretic effect was used. [9, 10] When the distance between surfaces which have different temperatures, is in order of the free path of the molecules, thermal forces occur. Due to the mentioned temperature differences, the surrounding gas causes the formation of a force, and the resulting forces are called mechanical displacement. In this specific experiment, the temperature difference is caused by radiation of lasers of different wavelengths. Finally, this mechanical displacement of the corrugation is noticed on the *Apatura* butterfly wing structure, and it is holographically monitored.

2. Materials and methods

2.1 Samples

The structure of butterfly wings proved to be a very characteristic corrugated structure. An example of the mentioned type of structure, precisely "herringbone" type, the structure of the *Apatura* butterfly's wing [11] used to examine the phenomenon presented here, is shown in Figure 2 (A and B).

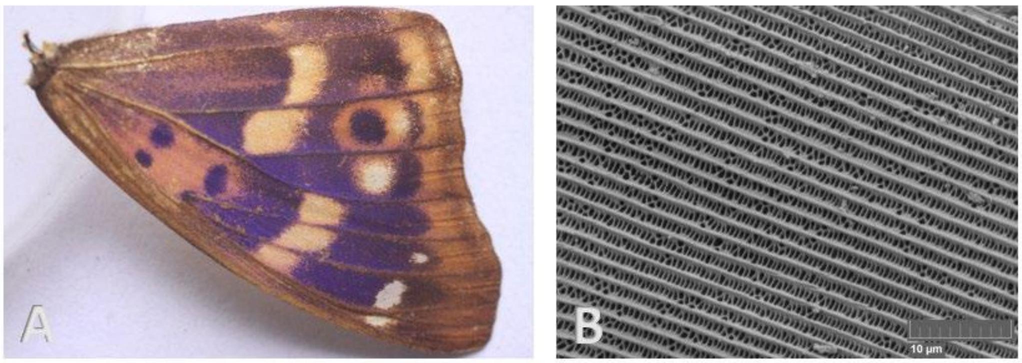

Fig. 2. Apatura butterfly wing: A photographic image (A) and SEM image (B).

2.2 Scanning Electron Microscopy (SEM)

Standard methods were used as auxiliary methods for obtaining the results of this research. Surface morphology of samples was characterized by scanning electron microscope *JEOL JSM 6610 LV (Japan).* Part of the recorded samples before the SEM procedure was not irradiated with laser light, while the other part has been irradiated and passed the holographic recording. This division is important for later analysis. The SEM image of apatura butterfly wing before laser treatment is presented in Figure 2 (B).

2.3 Holography

Holography, or holographic interferometry, is a method that records information about the deformation of an object between two moments of exposure. [12, 13] For this research, a special case of holographic interferometry was used, applied to monitor the mechanical movement of a part of the biophotonic structure that occurred as a result of external heating, that is, interaction with laser radiation. In this sense, this displacement is observed at the nanoscopic level in real time. The whole process is carried out in order to analyze the properties of the corrugated structure, which is deformed due to interaction with electromagnetic radiation. The possibility of a short exposure, i.e. the recording of complete three-dimensional information about the resulting changes, proved to be a very significant property of holographic study. Such an option of subsequent reconstruction is very important for movable objects of small and variable dimensions.

A simplified holographic setup was used in the experiment and the scheme of the here applied holographic setup is given elsewhere. [14]

2.4 Pre-characterization

Before the main part of the experiment, a small number of samples were used to determine the power range of the lasers that play the role of incident light sources. The mentioned samples were first tested for the lowest power to which they react. In the second phase, they were tested for the power at which the samples burn and at which moment they are destroyed. An optimal power of 1mW was determined for performing the main part of the experiment. The total number of tested samples in the main part of the experiment is six.

Each of the samples was heated by external lasers with four different wavelengths of light (450 nm, 532 nm, 660 nm and 980nm). In the following segment, the influence of light of different wavelengths on the elasticity of the corrugation of the examined structure was monitored and analyzed.

3. Results and discussion

Initially several butterfly species with various wing scale types were compared to find the best design for photophoretically sensitive micro-platelets. The selected *Apatura* butterfly belongs to the structure of the herringbone type. Afterwards, these samples were tested for the intensity of photophoretic response [10] in mentioned holographic setup.

When suitable species for examination were determined, the experiments were started after obtaining the SEM images. The goal was to observe the behavior of corrugations in time. Firstly, the deformation of the corrugation would be initiated by heating with light of different wavelengths, and then the cooling process would be observed.

Different wavelength lasers were used to heat the samples (450 nm, 532 nm, 660 nm, and 980 nm). This procedure was holographically monitored. As part of analyses holographic reconstructions were made and showed the thermal imprint [14]. The sample cooling time was the critical point in the analysis (the period after the end of the laser illumination).

Forty frames are created and are arranged so that each one is compared to the first, zero frame, which represents the initial state of the sample. In this way, we checked whether the complete cooling of the sample occurs and in what period. The following panels (Figure 3 and Figure 4) present holographic reconstructions [14] of the *Apatura* wing pattern for two different wavelengths. The reconstructions of all 40 frames were not included, 15 were chosen in order to see more clearly and also not to lose the flow of cooling or non-cooling.

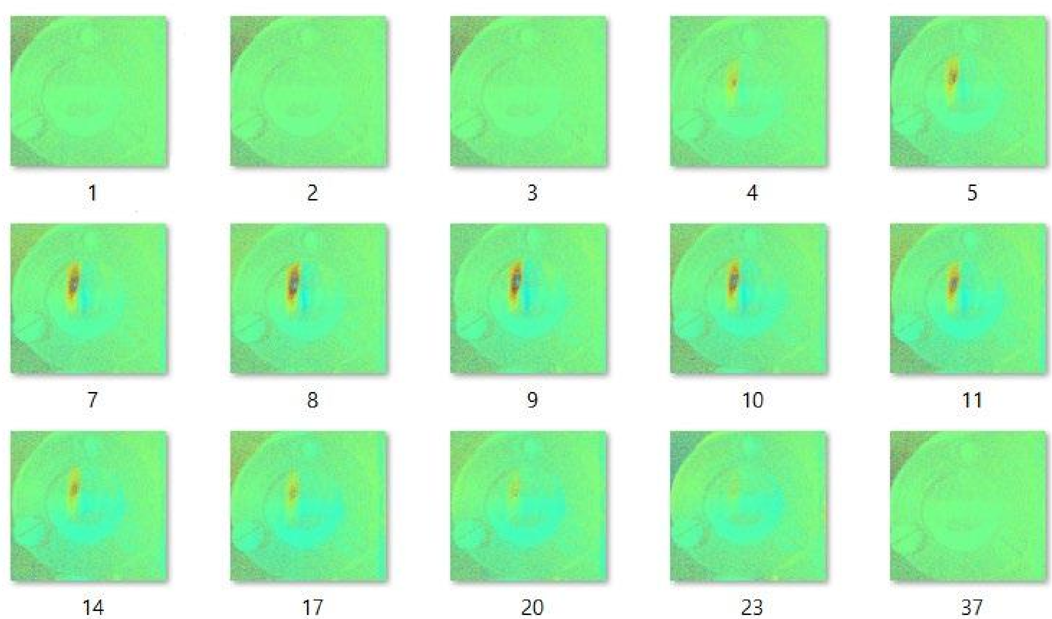

Fig. 3. Holographic reconstructions of the deformation of the corrugation of the wing structure of the *Apatura* butterfly tracked in time and caused by heating with laser light of a wavelength of 532 nm. The elastic deformation of the corrugation is observed, i.e., the return of the structure to its original state in less than 5 minutes.

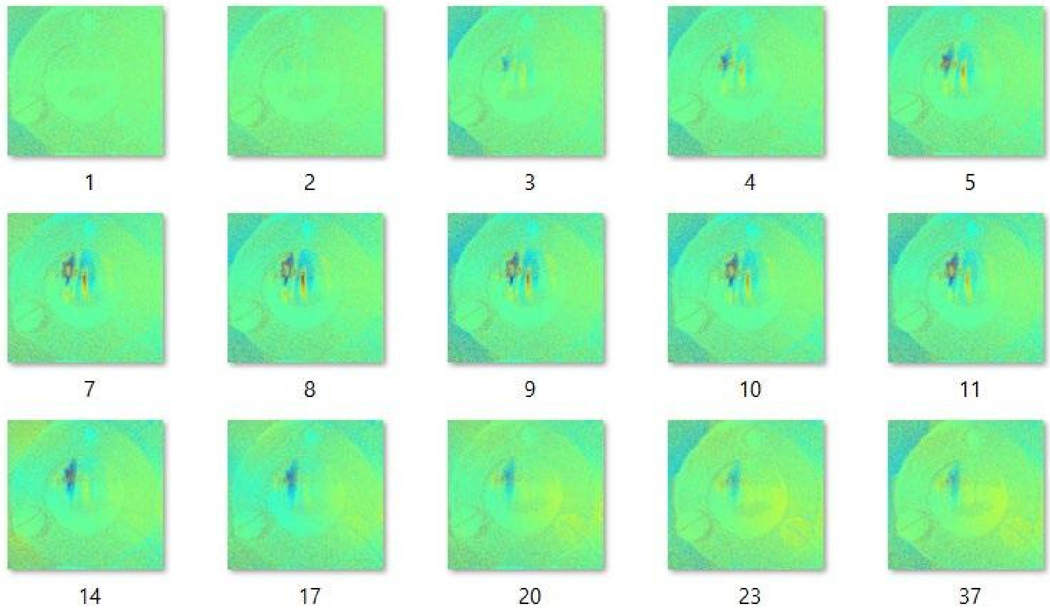

Fig. 4. Holographic reconstructions of the deformation of the corrugation of the wing structure of the *Apatura* butterfly tracked in time and caused by heating with laser light of a wavelength of 980 nm. The plastic deformation of the corrugation is observed, i.e., the structure does not return to its original state after 5 minutes of rest.

Firstly, the difference in temperature absorption due to heating with laser light of different wavelengths was measured. The highest absorption was measured when using wavelengths of 450 nm, and the lowest for the wavelength of 980 nm. This order was not followed in the direction of cooling the sample, that is returning the deformed corrugation to its previous state. For the wavelengths of 532 nm and 660 nm, a complete return to the initial state is observed (Figure 3), while for the wavelengths of 450 nm and 980 nm plastic deformation can be seen (Figure 4). This result is important because it shows the nonlinearity of the dependence on the wavelengths of the laser light used. This data indicates that every wavelength must be examined in this direction and that a linear response cannot be assumed.

As another characterization parameter, SEM images of the samples were taken. Regarding the used samples, those that holographically showed plastic deformation, the SEM image of that sample after use in the holographic setup also showed irreversible deformation of the structure and this is shown in Figure 5.

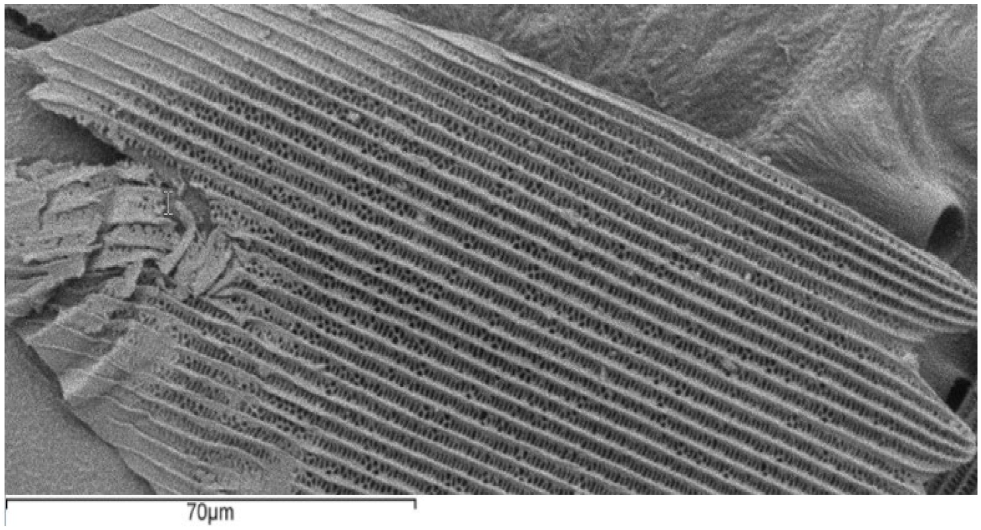

Fig. 5. SEM image of the corrugation of *Apatura* butterfly's wing after the experiment with the observed plastic deformation of the corrugation at wavelength 980 nm of laser radiation.

The elasticity of the corrugation structure is a concept subject to further extensive testing. What is important at this stage is that we have shown that this concept should be included in a separate characteristic of the material.

The property of the elasticity of the material corrugation was examined in this research for deformations caused by incident light of different wavelengths. Regarding laser power, at this moment, the only important thing is the optimal power on which the phenomenon of corrugation elasticity can be observed, because it was done on one type of butterfly wing, that is, on one type of corrugated structure. The powers of the lasers used as sources of incident light could also be an important parameter when this research is directed in the direction of different possible structures. Currently, the main effect being investigated is that of the wavelength of light that heats the structure and causes deformation. As the holographic reconstructions compare the real-time recording with the initial state, the cooling period of the samples was monitored and whether the corrugation of the sample returned to its original state.

It is important to note that the initial tests are described here, and for absolutely accurate information about this phenomenon, it is necessary to perform a very complex analysis (with more different samples representing more different types of structure, as well as for the entire spectrum of wavelengths) of the correlation between the corrugated structure and the wavelengths of the incident light, which will be the subject of further research. From these preliminary tests, it is established that the elasticity of the corrugation of the structure depends on the optical factors of the environment, which is the wavelength of light acting on the structure.

This type of examination gives the characteristics of structured materials in terms of reaction to the interference with light of different wavelengths. Specifically, it can be concluded that the corrugation of the herringbone type structure behaves elastically for two examined wavelengths from the visible spectrum, while it shows plastic deformation for another two wavelengths, in the UV and IR region.

Regarding the possibility of making artificial materials, this kind of material could be especially important for implementing in micro and nano electromechanical systems for different purposes for example as sensors/detectors of infrared radiation. [10, 15]

3. Conclusions

In this work, the innovative concept of the elasticity of the nanostructure corrugation was investigated. Wing samples of *Apatura* butterflies were used as a representative structure. Six samples of the mentioned structure were prepared and all of them were subjected to identical testing. A holographic method was used to monitor the deformation of the corrugation caused by heating with laser light of four different wavelengths (450 nm, 532 nm, 660 nm, 980 nm), as well as the period after the heating stopped. The investigation resulted with the conclusion that the same samples react differently when exposed to different wavelengths: At wavelengths of 532 nm and 660 nm, they show the elasticity of the corrugation, while plastic deformation of the corrugation is observed at wavelengths of 450 nm and 980 nm. The possibility of affecting the physical and thermodynamic function of a material by nano corrugation is an entirely new and exciting feature that unprecedentedly merges photonics with material sciences. Understanding the behavior of the corrugation structure under the influence of the light of different wavelengths can delineate the specific application (thermal, sensory, military) of different materials in different conditions and raise the analysis of material properties to a higher level.

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