ARCHIVES OF METALLURGY AND MATERIALS
Volume 53 2008 Issue 3

K. KONOPKA*

# BIOMIMETICS, ARE WE ABLE TO ACHIEVE THE MASTERY OF THE NATURE?

# BIOMIMETYKA, CZY POTRAFIMY DOŚCIGNĄĆ NATURĘ?

The purpose of this paper is to disseminate the knowledge of the biomimetic domain currently investigated in materials science. An approach of designing and fabricating advanced materials necessarily includes biology because a remarkable properties of nature materials and their capacity to molecular synthesis at very high level of organization. Biomimetics is at the frontier between biological and materials science, chemistry and physics. Materials exist in nature combine many inspiring properties such as miniaturization, hierarchical organizations and sophistication. Nature is a school for, materials science and others associated disciplines such as chemistry, biology and physics. Some examples of biomimetic approach in materials science were presented. Biomimetics is now one of the most rapidly growing area in materials science. The natural templates of constructions, materials and processes are still waiting for use. The presented paper discovered the ideas of biomimetics.

*Keywords*: nature, biomimetics, templates from nature, inspiration from nature

Od samego początku człowiek wspiera się i czerpie z obserwacji natury. Nauka zajmująca się materiałami, strukturami, procesami powstałymi z inspiracji natury nosi nazwę biomimetyka. Biomimetyka stanowi drogę od biologii do inżynierii. Biomimetyka obejmuje również inne dziedzimy życia. Do bardzo ciekawego zakresu biomimetyki należy jej wykorzystanie w naukach społecznych, zarządzaniu zasobami ludzkimi i marketingu.

Celem artykułu jest pokazanie osiągnięć biomimetyki w inżynierii materiałowej na podstawie wybranych przykładów. Omówione przykłady wzorców zaczerpniętych z natury pokazują konieczność łącznego analizowania konstrukcji, materiału i procesów. Potwierdzają konieczność prowadzenia nowoczesnych badań o charakterze interdyscyplinarnym. Wymagają one połączenia wiedzy z zakresu, fizyki, chemii, a w szczególności chemii molekularnej, biologii i inżynierii materiałowej. Biomimetyka jest szybko rozwijającą się dziedziną nauki kreującą nowe rozwiązania materiałowe i technologiczne. Jest ona przez to określana mianem „szkoły myślenia”.

## 1. Introduction

Being an inherent part of nature, has man learned to draw from its ideal solutions? Can he learn from nature? I am sure he can. The motors which drive man to gain from this knowledge are his curiosity and imagination. Albert Einstein said: “Imagination is more important than knowledge”. It is the driving force in searching and developing knowledge and also in seeking how to use it skillfully for creating new things. Nobody can deny such examples as submarines and diving equipment imagined by Julian Verne, which, after years, became real constructions, or various devices and travels into the space, described by Stanislaw Lem, which nowadays are almost available for man.

From the very beginning, man has lent on the nature and drawn knowledge by observing it. It was just nature which, through millions years of evolution, has found ideal solutions, which we try to implement in our doings.

The science which deals with materials, structures and processes that were created through inspiration from nature is known as biomimetics [1]. According to one of the pioneers of biomimetics in Britan, biologist Julian Vincent employed at the Faculty of Mechanics, Bath University, England, “biomimentics is seen as a path from biology to engineering. Biomimetics is the abstraction of good design from nautre” [2]. These definitions have appeared in the publications during the last few years, but this does not mean that earlier the scientists

---

* WARSAW UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIALS SCIENCE AND ENGINERING, WOŁOSKA 141, 02-507 WARSAW, POLAND

were not fascinated by the solutions that existed in nature and did not draw inspiration from it in their work. As an example we may mention the paper of D.W. Thompson "On the Growth and Form" from 1942 [3]. Earlier publications described how to imitate faithfully nature by using available synthetic materials and man-developed techniques of their fabrication. Contemporary publications concerned with biomimetics indicate still other aims. The present paper describes examples that permit us to see this aims.

It is worth considering on what basis materials and technology are transferred from biology into engineering. This basis is energy. Biology knows how to utilize energy in the optimum manner and how to distribute it among the various processes that proceed in the human organism (such as e.g. movement, feeding, reproduction, growth and self-curing). The aim of engineering solutions is to use energy in the optimum way, by adequate design, selection of the material, the method of its fabrication, and production management. Such a basis of transfer from biology to engineering seems to be very clear and is present in many papers [4-6] however, still not enough common for engineering practice. How biomimetics starts to be important can be estimated by the fact that in March 2006 a new journal entitled Bioinspiration and Biomimetics, Learning from Nature published by Institute of Physics in the UK appeared. According to the editorial notes it is an essential new journal which is reserved for publishing research results involving the study and distillation of principles and functions found in biological systems that have been developed through evolution and application of this knowledge to produce novel and exciting materials, technologies and new approaches to solving scientific problems. Biomimetics also includes other domains of science (Fig. 1).

Very interesting branches of biomimetics are social sciences, management of human resources and marketing. Here it may be mentioned investigations of the behaviour of insects, such as e.g. ants or bees, the organization of their common existence in a community, and the disposition of duties among the individual members of the group [7,8]. Humankind adopted some of the rules created by nature but some of that are uncovered or neglected. For all who want to know how important discovering the secrets of nature and the crucial role of the engineering design on the basis for planet Earth are and our quality of life, the book of Janine Benyus Biomimicry [5] is recommended. According to the author of this book "biomimetics is a new way of viewing and valuing nature. It introduces area based not on what we can extract from the nature world, but on what we can learn from it".

The present paper concentrates on the engineering applications of biomimetics, in particular in materials engineering, and thus the examples discussed here will be taken from this field. Engineers are inspired by the construction, materials and "fabrication" processes created by nature. Especially, natural constructions were the first inspiration for the engineers, and hence we can see many architectural and builder's ideas spied on the nature and based on its solutions. There are many perfect constructions existing around of us. Often we are not aware of them. Architects and builders know that load-carrying components in the shape of the double letter T are lighter than those with a square cross-section and at the same time have a higher mechanical strength. Trees, thanks to their strongly developed root system and the thick lower portion of the trunk (Fig. 2), as well as to the structure of wood itself, are splendid natural constructions that live for tens or even hundreds years, often resisting successfully harmful atmospheric conditions, such as e.g. strong winds. Our foundations and supports are imitations of this construction [9].

Leaves have an equally perfect structure, though smaller in scale, (Fig. 3). It is imitated in building roofs, in the construction of greenhouses (Fig. 4) and also in other constructions such as aircraft panels [9,10].

Not many people know that the famous Eiffel tower (Fig. 5) in Paris has been constructed based on a biological model. Its side spans imitate the structure of the spongy bones in the human hip joint [9]. The construction of the new spectacular "skyscraper" (40 floors), commonly known as the 'gherkin', situated in the center of London (Fig. 6) and being the headquarters of a Swiss reinsurance agency, is modeled on a natural marine organism – the Euplecctalla sponge [11]. Thanks to this construction, air is sucked from the bottom of the building into its interior, like water is sucked into a sponge. The sponge anchored at the sea bottom in the vertical position, sucks food-enriched water and transports it upwards through its entire body, and then it ejects the water outside from its top. In the "gherkin" building, the air is transported upwards and heated by a system of helixes. In the case of high buildings, this system of heating and air-conditioning is considered to be the most energy-saving. Another example of utilizing the natural designs in architecture is the temperature-controlling system installed in the Art Center in Singapore, which imitates the way in which polar bears control their temperature [11]. During warm sunny days, the hair of their fur raised letting the sun rays to reach the skin and to worm itself efficiently. In the cooler days, the hairs are lying flat on the skin and retain heat. This effect has been imitated in the building, by constructing the elevation composed of aluminum spines that change their

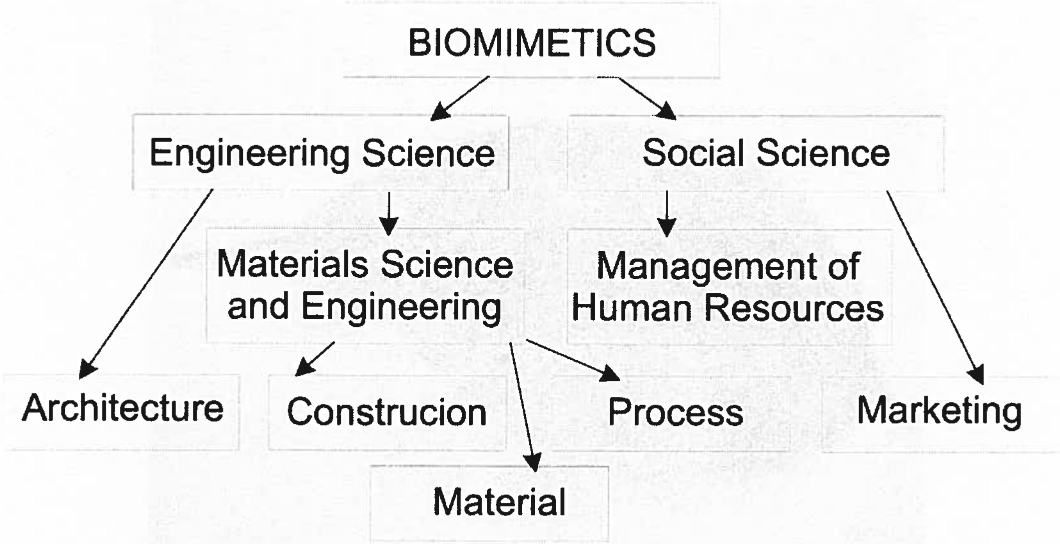

Fig. 1. Biomimetics area

Fig. 2. The sweet chestnut tree in Kew Gardens in London (photo made by Author, November 2006)

position depending on the meteorological conditions. Although we have so many examples of the constructions modeled on natural structures, enough to mention architectural and building structures, we should be aware that the perfect final effect of its compositions has been achieved by selecting, through evolution, the optimum constructions, the optimum materials and the optimum methods of their manufacture. In reality it is difficult to imitate nature. In many cases, we only attempt to analyze and copy a single aspect, such as e.g. the construction, but in erecting it we use materials and techniques available to the constructor nowadays, which often leads to failure. Modern biomimetics tries to take into account all the three aspects, especially in the field of materials engineering (Fig. 7). Although this approach seems to be obvious, to get aware of it took many years and many defeats had to be suffered.

## 2. Animals and flying machines

The first constructor-mimetic may be considered to be Leonardo da Vinci. Like legendary Icarus, he dreamt to be equal to birds and his dreams were to be crowned with a construction of wings modeled on bird's wings. Unfortunately he did not manage to realize his project. Leonardo was a great imitator of nature. He studied the anatomy of animals, in particular birds and bats, and analyzed the way in which they move their wings. Based on his studies, he constructed almost faithful copies of bird's wings and the device for driving them. The wings were built of wood and linen. Leonardo devoted 25 years of his life to construct flying vehicles, known as ornithopters, modeled on birds [12].

Taking inspiration from the anatomy of bats, he designed in 1487 a flying vehicle, in which the pilot lays face down with his feet placed in stirrups. By moving his

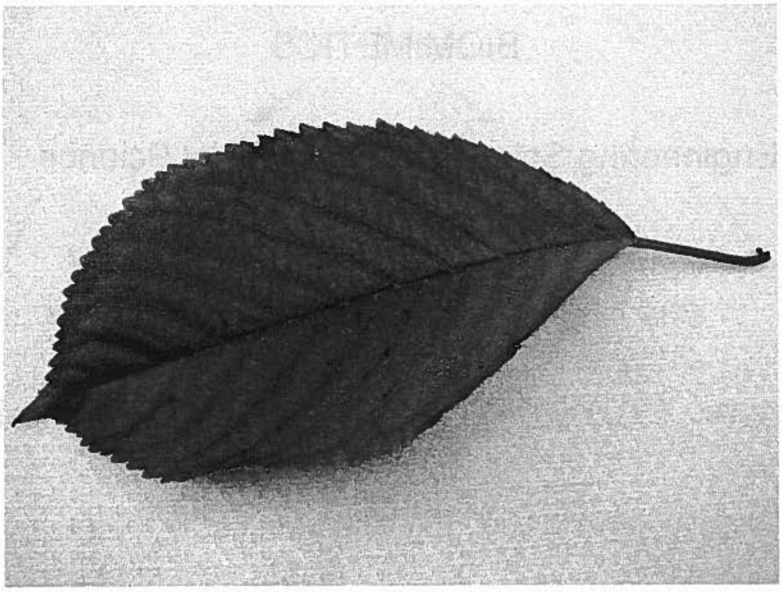

Fig. 3. A leaf showing the corrugations (photo made by Author)

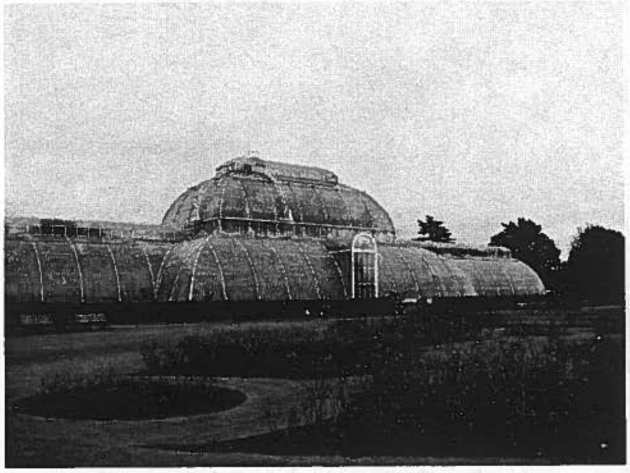

Fig. 4. Green house, Kew Gardens (photo made by Author, November 2006)

Fig. 5. Eiffel Tower, Paris

arms and legs, he drove the wings. Later (1496-1499), Leonardo designed machines with the pilot in the standing position who drove the wings by means of stirrups connected with the wings [12]. However, it appeared

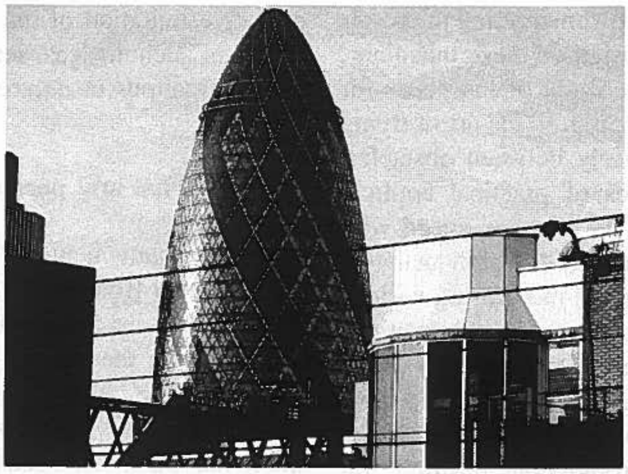

Fig. 6. 30 St Mary Axe-Lord Foster`s 40-storey tower (photo made by Author, London November 2006)

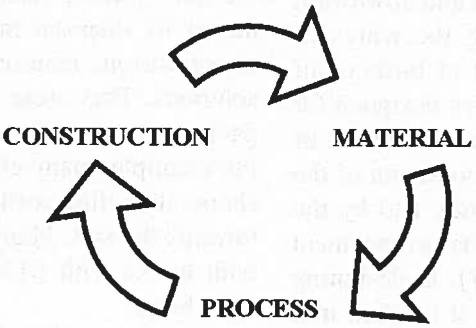

Fig. 7. Schematically presented correlation between construction, material and process in biomimetics

that the force necessary to drive the wings was much greater than the force of the muscles of a single man. In spite of the many years devoted to discovering the secret of flying, Leonardo however rarely tested his machines. The last stage of his studies on the flying machines included constructions with immovable wings, similar to the present-day hang-gliders, which were simpler and easier in use. In the construction of these machines, Leonardo imitated the movement of the falling leaves and the gliding movement of birds. Despite these great efforts to construct flying machines, in particular a machine modeled on the flight of birds, Leonardo achieved no success, and he admitted his being mistaken: “Although human genius through various inventions makes instruments corresponding to the same end, it will never discover an invention more beautiful, nor more ready nor more economical than does nature, because in her inventions nothing is lacking and nothing is superfluous” [13].

The fact that Leonardo failed in his endeavors did not deter other inventors from trying again. We know other attempts at constructing the flying machines modeled on the anatomy of birds or bats, such as e.g. the machine constructed by Clement Ader, with the wings imitating the wings of a bat, driven by an extremely light steam engine. The constructor was successful and in 1892 his machine ran a short-time flight [14]. Another example is the marvelous construction of a glider designed by Otto Lilienthal in 1895. The replicas of both flying machines can be admired in the Science Museum in London.

Despite the efforts of the constructors to reconstruct the bat wings as precisely as possible, the results were unsatisfactory. It appeared that it was not enough to reconstruct faithfully only one of the components of a creation of nature and to neglect the fact that the materials and fabrication mechanisms used by nature are completely different from those available to man. The secret of the wings of a bird or a bat lies not only in their structure or the material of which they are made, but is associated with the fact that the wings are individual manufacturers of energy and, at the same time, constitute inseparable parts of the entire organisms of these animals.

Although the flying machines designed by Leonardo cannot be used by man for flying, Leonardo’s conceptions are still taken into account in constructing micro-air vehicles (MAVs) [15]. In the design of these machines, the inspiration is drawn from the flight of insects as for example dragonfly, which have mastered the art of flying and are able to maneuver precisely between obstacles. There are enormous possibilities of practical applications of the vehicles which can fly at a low speed with a capability of precise maneuvers and a high manageability, for example in surveying and monitoring various spaces, such as tunnels [16]. Aerodynamic examinations of the flight of insects and of the structure of their wings and bodies indicate that their successful flight is possible thanks to deformation of their wings, which take, almost automatically, the optimum aerodynamic position. Insects fly by flapping their wings in an oscillatory manner and twisting them over a wide range of angles. The work cycle of the insect wings includes upward and downward movements. The mechanism of twisting the wings of insects is completely different from that of birds or of bats. Unlike birds, insects have no muscles designed for changing the position of their wings. The movements of the insect wings are due to the dynamic co-action of the forces exerted by the muscles of their body and by the structure of the wings themselves, i.e. the arrangement of their rigid and elastic components [17]. In designing the flying machines modeled on insects, it is taken into account that insects have two pairs of wings often connected one to another so as to form a single plane, and that the ratio of the length to average width of the wings is equal to 7 [17]. The flying micro-vehicles must also be very light in weight, so that they can be supplied from a battery. For example, the flying micro-vehicle known as the 'Entomopter', has been modeled on moths and dragonflies [18]. To construct an MAV is not an easy task, since the physical and mathematical principles of the flight of insects are not known. The progress is rather slow, despite many studies including modeling and physical experiments. There are also designs which imitate other insects and animals, such as lobsters, crickets or scorpions [18]. Studies are also conducted on utilizing our knowledge about fish and other aquatic animals for designing floating units [2].

For getting more knowledge about the world in which we live and better understanding it, we need, apart of our senses, various instruments and sensors. There are many models of them in nature. It is already not surprising, that dauphins have an organ, known as 'melon', placed in their heads, which functions as a sonar, or that the navigation capabilities of pigeons are due to the magnetite present in their necks which is a biological compass. Some flowers are sensitive to changes of the intensity of light – their petals close in the night or when the sky is very cloudy. A camera, on the other hand, is a primitive imitation of the eyes of vertebrates. There are plenty of such devices, sensors and instruments modeled on the creations of nature [9].

## 3. Fast and perfect joining of materials

Very many new constructional and technological ideas, drawn from nature, have been inspired by an incident, an event or a momentary observation. This was the case with the idea of joining two materials with the use of a 'bur'. Its inventor, George de Mestrals, when walking with his dog observed how difficult is to unhook the burs, i.e. seeds of the popular weed known as the 'burdock', from the dog's hair. This happened in 1955, and since then, more than 1700 patents based on the hook-joining idea, have been granted [6,9]. Nature has at its disposal much more such perfect joints between various materials and uses the possibly simplest solutions. They were developed in plants and living organisms for the sake of their survival and reproduction. For example, many climbing plants produce hook-ended shoots that cling softly to various supports so as to turn towards the sun. Many species of parasites are equipped with hooks with which they join with the organism of their hosts.

Joining can be effected in 8 ways [19]: a) hooks, b) tongue-opening, c) clamps, d) struts, e) sucks, f) spreading anchorage, g) adhesive, and h) friction. Analysis of the joints between biological tissues and the substrate has been one of the rapidly developed research lines in the recent years. The studies are aimed at developing and producing such a surface structure that has desired adhesive properties. From the point of view of technology, it is not easy to produce a surface with hooks of nanometric size. An example of such a technology will be described further in the text, whereas now I will describe a project which has succeeded in imitating the hook-covered bio-surface, namely a micro-endoscope designed for detecting tumors in the gastrointestinal system. One component of this device is modeled on the hooks with which parasites pin themselves to the tissue of their host, whereas the way in which the endoscope moves imitates the movements of caterpillars and snails [20].

## 4. Adhesive force-gecko foot

Another example of bio-inspiration is modeled on the capabilities of geckos. This animal has an ability that excites human imagination: it can walk and stay motionless on smooth slippery surfaces, even those in upright position such as window panes. The secret lies in the structure of gecko's legs, which are equipped with microscopic hairs called stalks 30 to 130 μm long and with the diameter as small as 1/10 of that of the human hair. The hairs are arranged in rows and are subdivided into between 400 to 1000 structures called spatular stalks (nano-hair) to form a sort of a paintbrush (Fig. 8). The geckos' foot is covered with 5000 hairs per 1 square mm, so that more than one milliard spatulaes are in touch with the surface of the substrate. In effect, the intermolecular attraction by the Van der Waals forces that act between the spatular stalks and the substrate permits holding the weight even 400 times as great (about 130 kG) as that of gecko's weight [21].

Scientists from the Stanford and Berkeley Universities, USA, estimated the adhesive force of a single gecko foot-hair to range from 50 to 300 μN. If all the foot-hairs are pressed to the substrate simultaneously, the adhesive force of the gecko foot may amount to 100 N. The scientists only examined a single hair of the gecko foot, and attempted to identify the mechanism responsible for this adhesive force. They monitored the successive stages of the contact between the hair and the substrate, and found the following [21]:

- the adhesive force increases as the gecko's foot-hair approaches the substrate surface until it begins to slide on this surface,
- an essential factor is the angle at which the hair is inclined to the surface; the adhesive force is at a maximum when this angle is 30.6°,
- assuming that the cilia are ended with spheres with a radius of 2 μm, and that the spacing between them and the substrate is 0.3 nm (which is necessary for the van der Waals forces to act) the adhesive force was calculated to be 0.4 μN, which for a single hair gives a force between 40 and 400 μN; this result confirms that the adhesion of the gecko leg is due to the van der Waals forces.

The structure of gecko legs is probably beyond the human technology but the principles on which it operates could inspire the engineers to develop new kinds of dry adhesive such as e.g. adhesive tapes, and to construct robots able to walk on vertical walls, as e.g. a robot-fireman which can reach places in fire by walking on vertical walls, even slippery, of a building [21]. The most difficult task here is the fabrication of hairs ended with nano-sized appendices and arranged in densely packed rows. One possible method the first employs a nano-sized tip, such as e.g. an atomic force microscopy tip, which makes indentation in a soft substrate, such as e.g. wax, and then these indentations are filled with a polymer to form a die ( Fig. 9) [22].

## 5. Self-cleaning surfaces

A leaf of lotus is an example of a clean surface, with no dirt depositing on it and no water drops spreading over it. The phenomenon of the super-hydrophobic surface of the leaves of certain plants was described and explained by two botanists, Barthlott and Meinhuis from Germany [11]. They found that the structure of the lotus leaves resembles a Fakir carpet with nails hammered into its surface is responsible for this feature, since the lotus surface has sub-micron appendices. Another factor responsible for the hydrophobic properties of the lotus surface is its chemical composition, namely the surface is coated with a wax film [23]. On such surface, a water droplet behaves as a snow ball, which rolling on the substrate takes snow flakes with it (Fig. 10).

Another plant whose leaves have an ultra-hydrophobic surface is Alchemilla vulgaris (lat.) Its leaves are covered with elastic hairs, 1 mm high and 10 μm in diameter, with an average spacing between the individual hairs equal to 500 μm [24]. A water droplet rests on a bunch of flexible hairs (Fig. 11) getting no contact with the leaf surface. Artificial surfaces covered with an arrangement of elastic polymer hairs have already been attempted to fabricate [24].

Hydrophobic surfaces such as that of a lotus leaf have already been fabricated and used in practice in the self-cleaning technology, but on industrial scale, this technology primarily uses hydrophilic surfaces [23]. In the surfaces of both types, the self-cleaning effect is based on two phenomena. The first is the photo-catalytic process, activated by UV rays, as a result of which the organic particles present on the surface are detached from it. For this process to occur it is necessary that an active $TiO_2$ layer should be present on the surface. The UV radiation induces electron-hole pairs (i.e. a hole depleted of electrons + free electrons) in this layer, which, overcoming the potential barrier, pass beyond the conduction band, thereby activating the atmospheric oxygen and leading to the formation of peroxides. Active oxygen oxidizes carbon which is the principal building component of organic particles, destroys the molecular bonds, decomposes the organic particles and kills the bacteria. Similarly, the activation of water results in peroxide and OH radicals being formed, with the latter acting as peroxides do and in addition reduce the surface tension. In effect, dirt can easily be removed and does not adhere to the surface [23]. What remains to do is to transport the dirt particles from the surface, which, on hydrophobic surfaces, is realized by the rolling ball effect described above.

Hydrophobic surfaces are not easy to fabricate since nano-metric-size inequalities, imitating the structure of

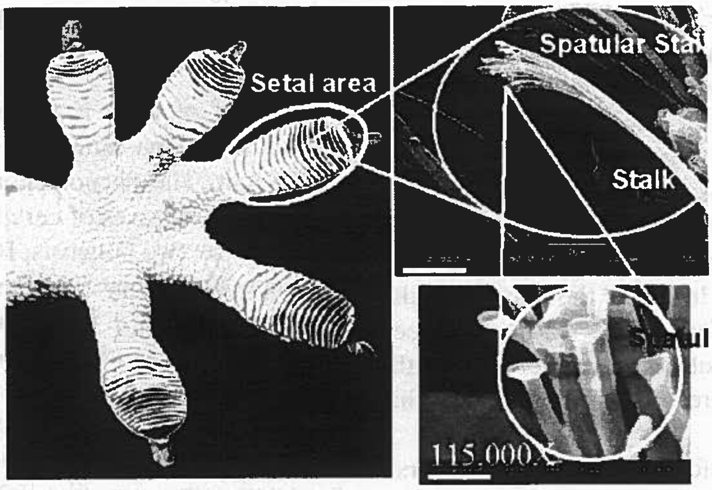

Fig. 8. Gecko foot -hair images: gecko foot bottom view ( left image); zooming into one of the stalks under SEM (right upper image, bar indicates 10 μm), and zooming into spatulae and spatular stalks at the end of a stalk under SEM (right lower image, bar indicates 300 nm) [23] (grant © VSP)

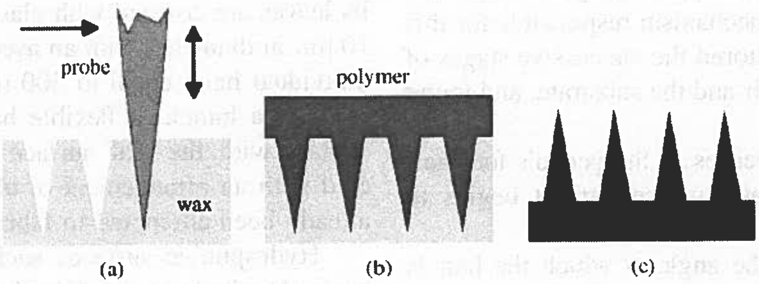

Fig. 9. Synthetic hair fabrication: (a) indenting a flat wax surface using a micro/nano-fabricated probe nanotip, (b) molding it with a polymer, and (c) separating it with a polymer, and (c) separating the polymer from the wax by peeling [23] ](grant © VSP)

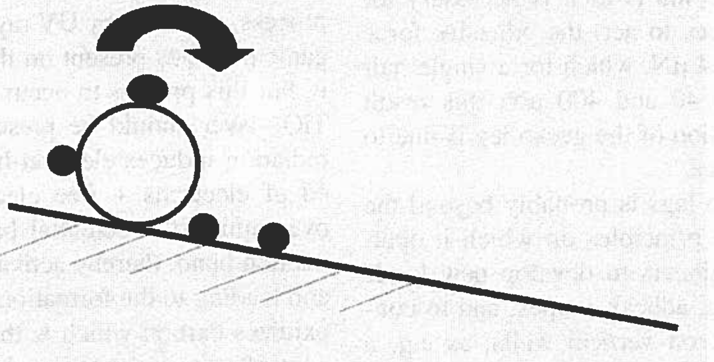

Fig. 10. Schema of hydrophobic surface- a water droplet behaves as a snow ball

the lotus leave structure, have to be produced [23, 25, 26]. Thanks to the combination of the super-hydrophobic properties and the photo-catalysis effect, we can produce self-cleaning window-panes and other surfaces. This is a revolutionary step in the building industry and everywhere where the cleanliness of the surface is required. They are also examples how nano-technology can be utilized on the industrial scale. The lotus leaf effect has also been utilized in the fabrication of self-cleaning paints or anti-graffiti sprays, as a matter of fact named 'Lotus', intended for painting external surfaces [11].

## 6. Cellular structure and composites

Let us look at other examples of bio-inspiration. Among of the natural materials there are a lot of exam-

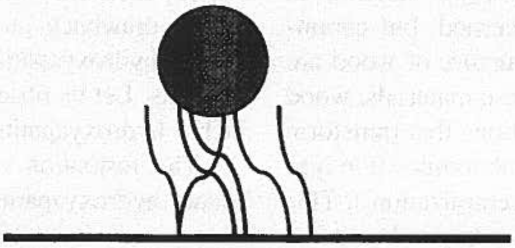

Fig. 11. Schema of a water droplet reset on a bunch of flexible hairs

ples of cellular structure and composites materials and these materials are also an example of template using from many years in designing of engineering materials.

The structure that dominates in nature is the structure of a honeycomb, which is light and rigid. Nature uses the cellular structures for carrying heavy loads. Examples of such structures encountered in nature are wood, coral-reef, cellular (sponge-like) bone, sponge. These structures may have isotropic as well as anisotropic properties. For example, many kinds of wood are ten times more rigid and strong along their fibers than in the transverse direction [9]. The same is the case with the strength of bones. As long as 2000 years ago, Chinese people produced paper with the honeycomb structure. In the 1940s, for the first time the honeycomb structure was used in designing military airplanes, which permitted reducing their weight and thereby decreasing fuel consumption and increasing the plane dimensions. Since 50 years, the sandwich-type construction of the aircraft panels, characterized by a light core and a monolithic outer layer has commonly been used for the aircraft sheathings. The hexagonal shape of the honeycomb is one of the most effective shapes that ensure safe support, whereas the reinforcing layer improves the mechanical properties of the material [27]. In human constructions, the core has been made of various materials, such as aluminum and its alloys, steel, ceramics, and polymers. Such a materials are commonly used in airplane constructions [28].

There are plenty examples of composite materials encountered in nature. Perhaps the most popular material is wood which is often classed as a composite consisting of cellulose fibers embedded within a lignin matrix. Another example is the beak of toucan, built of a sandwich-type composite [29]. The body of the beak has the structure of foam and is very light, whereas the outer zone is composed of a hard material with a lamellar structure. To be able to pick food from tall trees, toucan has an exceptionally large and long beak – its length is equal to 1/3 of the total length of the bird, whereas its weight is only 1/20 of the total weight, which is necessary for the bird to be able to fly. Since toucan has to break hard fruits, its beak, in particular the tip, must be sufficiently hard and rigid. The outer layer of the beak is built of hexagonal creatine plates, with the diameter between 30 and 60 μm and the thickness between 2 and 10 μm.

The creatine plates overlap and are joined with one another by means of a certain substance that functions as a glue. The layer composed of the creatine plates has a thickness of 0.5 mm. The presence of calcium in the plates indicates that they are highly mineralized, which ensures their high hardness. [29].

Other examples of the composites created by nature are shells [30,31]. Molluscan shells, for example Bivalva shell are composed, in 95-99%, of $CaCO_3$ in the forms of crystalline calcite and aragonite. The balance is constituted by proteins which function as the binding phase. The shell is composed of 3 parts: outer, prismatic and inner layers. The mechanical properties of the shell result from its structure. The inner layer is build of a substance known as conchiolin. The middle layer is chiefly composed of calcite crystals prismatic in shape. The inner layer contains aragonite crystals that look like bricks: they have the form of plates, 0.4-0.5 μm thick and 5-10 μm wide, and are bound together with an organic layer, resembling mortar, of a thickness ranging from 20 to 30 nm [30]. The mechanism responsible for their fracture behavior is considered to be the process of pulling the aragonite plates-fibers out from the organic matrix, which is well known and utilized in practice in the design and fabrication of composites. Therefore, the molluscan shell is the model of man-made composites, in particular of the ceramic/polymer type. Let us look, for example, at the BN/epoxy resin composite, whose construction has been based on the structure of the molluscan shell. It is composed of ceramic plates, 4 mm thick, covered with resin and then hot-pressed. The fracture toughness of this composite (measured by an impact test) appeared to be higher than that of the ceramic. For example, the composite built of 4 layers had an impact toughness of $4.6\times10^{-3}$ J/mm$^2$, whereas the value measured for the ceramic was $3.2\times10^{-3}$ J/mm$^2$ [30].

There are still many other examples of the composite materials created by nature, such as e.g. wood, mentioned earlier, which is a well-known material as its structure and properties are concerned, but ceramic materials that have utilized the structure of wood are perhaps less known. In fabricating these materials, wood is subjected to certain chemical reactions that transform wood into a material with the chemical composition typical of ceramics (process known as 'ceramization'). This process does not destroy the optimum hierarchic structure of the precursor on all its size levels and yields a material that combines the rigidity and mechanical strength of wood with the heat and chemical resistance typical of ceramic materials [32-34]. As an example, we can mention wood transformed into cellular silicon carbide. To obtain this material, wood is subjected to pyrolysis to transform it into a carbonaceous form which constitutes a skeleton – mould for producing SiC through its chemical reaction with liquid silicon or volatile silicon oxide (SiO). An additional infiltration of this product with silicon or oxide sols yields a solid material in which the pores present in the cellular SiC are filled with silica, silicon, $Al_2O_3$, or $ZrO_2$ [32].

There are also other precursors known for their interesting natural forms, whose applicative possibilities have not been utilized thus far. Here we can mention bio-silicates, such as e.g. skeletons of unicellular organism – diatom with its specific porous structure [25,32]. The pores are regularly distributed, with size of the order of nm to μm (Fig. 12). It is a very good insulator, but it may only be used up to a temperature of 1375° C. Through the reactions $SiO_2(s)+Mg(g)=MgO(s)+SiO(g)$, $SiO_2$ of the diatomite can be transformed into magnesium oxide, which has the same structure but its heat resistance is higher [32].

## 7. Artificial bone

In our learning from nature, we try to unravel its ideal solutions and, on the other hand, to fabricate artificial materials with ideal properties, modeled on its creations. One of the most interesting ideas, well representing this approach is the fabrication of a material that can replace human bones. The bones are composed of collagen and crystalline calcium phosphate. Synthetic nano-fibers coated with hydroxyapatite have already been produced, as well as scaffoldings, subjected to bio-mineralization, which serve as supports for rebuilding bone losses [35]. An important material for medical application is synthetic hydroxyapatite. Due to its similarity to bone tissue, it stimulates the growth of new bone at the bone/hydroxyapatite interface, with the hydroxyapatite being gradually absorbed by the organism. Hydroxyapatite can easily be produced and then sintered to obtain more or a less porous material, which has however a low mechanical strength. In order to obviate this drawback, an increasingly common practice is to deposit hydroxyapatite coatings on metallic and ceramic implants. Let us observe the process of the formation of such a hydroxyapatite coating on an implant.

The formation of bio-active apatite, which is carbonate hydroxyapatite similar to that present in human bones, is the necessary condition for the implants built of artificial materials to be bound with the natural bone tissue. To achieve this, the implant, especially if it is metallic, must first be subjected to surface modification. Then it is immersed in a synthetic serum (SBF) where bio-mimetic nucleation, i.e. similar to that in natural bones, takes place followed by a growth of biologically equivalent hydroxyapatite on the metal surface. As an example a Ti implant is considered [36]. Its surface is first exposed to NaOH, then, is subjected to a heat treatment at a temperature of 600 °C, and finally it is soaked in an SBF for 28 days. As a result of the action of NaOH, the structure of the surface layer of the implant is changed to form a hydrated sodium titanate gel. The next stages include [36]:

- the heat treatment which results in the gel being dehydrated and transformed into amorphous sodium titanate,
- the exposure in the SBF, the $Na^+$ ions released from the sodium titanate layer are exchanged with the $H_3O^+$ ions from the SBF. The titanate gel rich in Ti-OH groups forms on the surface,
- the formation of apatite induced by the Ti-OH group.

## 8. Biomimetics synthesis

As we have learned from the examples described above, in our eagerness to mimic nature, it is necessary to imitate not only the natural constructions and materials, but also the processes of their synthesis. This is the research field of the extensively developed interdisciplinary branch known as molecular engineering, whose approach consists of building by the atom-to-atom method (also known as the bottom-up method) [37]. This new discipline is based on the achievements of molecular biology, bio-informatics and bio-modeling. Nature is a master in using the atom-to-atom technique. This is the way in which nature advances from the simplest to the most complex structures. This method may be compared to the technique of building enormous structures using small bricks or 'lego' blocks, as is the case with the Chinese Wall (Fig. 13) (erected of 10×20×30 cm bricks to achieve a length of 5600 km [37]) or to the letters in the alphabet which themselves are only fundamental simple bricks of which sensible words, then sentences, chapters and huge books can be constructed (Fig. 14).

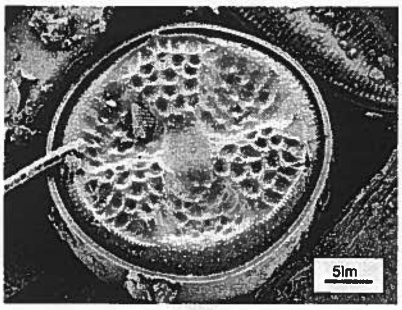

Fig. 12. Porous silica skeletons observed in diatoms (photo courtesy of profesor A. Witkowski from Szczecin University)

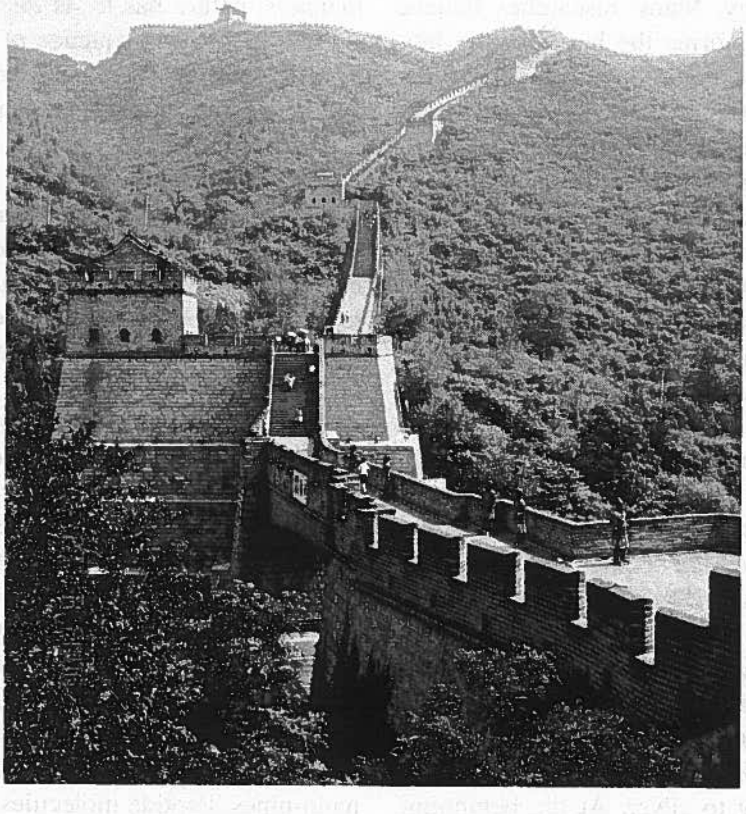

Fig. 13. The Great Chinese Wall (photo courtesy of dr A. Boczkowska from Warsaw University of Technology)

Nature has for its disposal only 20 aminoacids, a few nucleic acids, a dozen of lipid molecules and sacharides [1,38]. Organic structures emerge as a result of self-organization and self-arrangement of these molecules.

The self-organization of structures requires weak non-covalent bonds, which by themselves have little significance, but together become very important. Molecular self-organization involves hydrogen type, ionic type, van der Waals forces, hydrophobic, and water-assisted hydrogen type [39]. In order to understand the process of self-organization of the molecules we must know their chemical structure, and this is the domain of super-molecular chemistry. The pioneer in this field is Jean-Marie Lehn of the University in Strasburg, who was awarded the Nobel Prize for his achievements [39,40].

Thinking in terms of self-organizing structures constitutes a new approach, in particular in chemical syn-

Fig. 14. Schema of bottom-up approach, building from letters

theses and nano-technology. Many researches believe that molecular engineering forms the basis for the fabrication of many products, beginning from electronic sub-assemblies to new materials, such as e.g. ceramics produced by bio-mineralization. Bio-electronics is extensively developed, including studies on the possibility of the use of DNA particles as various electronic devices, for example bio-chips or bio-sensors [41-43]. The turning point in investigating the cell structures and processes that proceed in them was the explanation of the principles of the spatial organization of proteins, published in the early 1950s (L.Pauling, Nobel Prize in 1954) and of the structure of DNA (F.Crick, J.Watson – Nobel Prize in 1962). The DNA structure was the model for synthesizing nano-metallic wires of Pt, Au, Ag and Pd from complex aqueous metal solutions. For example, utilizing the affinity between polypeptide sequences and various metals and compounds used DNA for constructing an arrangement of Cu atoms. They placed the $Cu^{2+}$ ions along the axis of the DNA helix [44]. As an another example may be the synthesis of the nano-particles of silver with the participation of protein molecules which have a strong affinity to silver [45]. Phages contain proteins with a strong affinity to silver. At the beginning, DNA was extracted from a phage. Phage is a simple form of a living organism, only contains DNA and RNA nuclein acids surrounded by a layer of identical protein molecules; they have the structures necessary for nuclein acids to infiltrate or to be injected into the cells. Then the protein sequences with the affinity to silver were selected and decoded. Silver was joined with the proteins in an aqueous $AgNO_3$ solution [45]. A further growth depends on the type of protein (proteins are built of 20 amino-acids; their properties are defined by the given sequence of amino-acids; they can be arranged in $10^{130}$ manners; nature has to its disposal much less albumins – only $10^{12}$. The sequence of the amino-acid arrangement is a direct representation of the genetic information, and determines the special shape of the entire molecule [1,38].

Molecular biomimetics is very helpful in designing and fabricating new biomaterials with a ‘molecular’ precision. The control of the reactions at the level of that encountered in natural materials becomes increasingly important. Molecular biomimetic engineering is based on a close co-operation between materials engineering and biology [44].

The self-arrangement ability is utilized in the fabrication of new nano-sized bio-materials, such as peptide nano-fibers, or protein scaffolds. Another example may be what is known as the ‘molecular carpet’ (Fig. 15), where biologically active peptides are set up using the bottom-up method to form a mono-layer a few nanometers thick. Such an active surface may be used for trapping appropriate molecules, nano-crystals of various metals or else carbon nano-pipes. It may also interact with molecules [44]. In this structure, peptides were intended to function as holders for manipulating the carbon nano-pipes. Peptide molecules may also play the role of a switch through changing their structure. A change of temperature or pH results in a change of the molecule length. Superficially active peptides are investigated in terms of their use as the carrier of medicaments, and in cosmetics [44].

## 9. Micro and nano devices (MEMS and NEMS)

In medical diagnostics, the quickness and precision are the conditions of better prognosis for the patient,

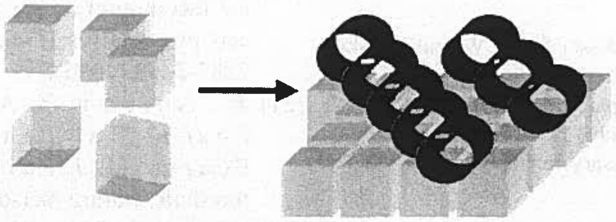

Fig. 15. Schematically presented "molecular carpet", peptides are set up to form a mono-layer, which functions as holders for other molecules

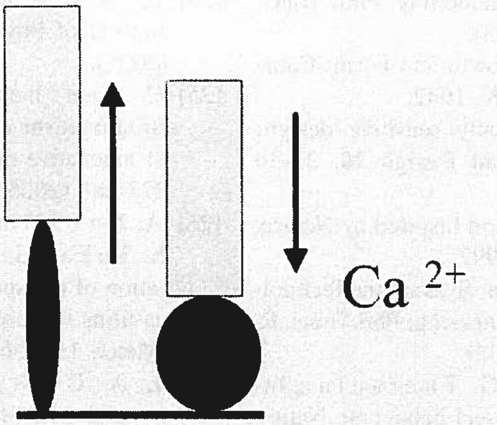

Fig. 16. A potential nano-device, the protein molecule in the absence of Ca+2 ions is lengthened and can raise a plunger, in the presence of Ca+2 protein molecules return to the spherical shape and the plunger is lowered

and hence the point-of-care idea has emerged, which consists of installing diagnostic instruments directly in the sick tissue. There is a trend towards miniaturization of the diagnostic instruments and devices, such as micro-pumps, surgical instruments, micro-sensors. The micro-instruments and the system of introducing them into the organism are called the micro-total-analysis system. As examples we can mention micro- and nano-carriers of medicaments [46]. Such micro-devices may be applied not only in medicine.

Besides the problem of their nanometric size, which is a challenge to technology, another problem is their drive. Search for the solution of this problem is also looking towards mimetics. Proteins and DNA can also function as motors, mechanical connections or sensors. For example, an protein molecule acts as a driving mechanism, since it changes its shape depending on the calcium concentration [47]. As the concentration of the $Ca^{2+}$ ions decreases, the molecule is lengthened and can raise a plunger; when the concentration of calcium ions increases, protein molecules return to the spherical shape and the plunger is lowered. A cyclic alteration of the concentration of calcium ions can give a movement (Fig. 16).

Extensive studies are also conducted on the ATP (adenosine triphosphate) compound, which is a high-energy compound with a high chemical potential. It constitutes the basic source of energy for cells, and can be transformed into other forms of chemical energy (enzymatic reactions), in osmotic energy (active transport through the cell membrane) or mechanical energy (muscle contraction) [1].

## 10. Summary

Materials exist in nature combine many inspiring properties such as miniaturization, hierarchical organizations and sophistication. Nature is a school for materials science and others associated disciplines such as chemistry, biology and physics. Nature is even more, a school of thinking. A biomimetic approach to materials science cannot be limited to the copy of objects proposed by nature but rather a more global mulitisciplinary strategy which is called Ecole de Pensée (Think Tank) [25].

## Acknowledgements

The author would like to thank Professor Stefan Wojciechowski from Faculty of Materials Science and Engineering, Warsaw University of Technology for encourage to prepare this paper.

The author is grateful of the Library of Imperial College in London, for opportunity to collect necessary references papers.

## REFERENCES

[1] M. J. Madou, Fundamentals of Microfabrication; CRS Press 2002.

[2] J. F. V. Vincent, Biomimetic modelling, Phil. Trans. R. Soc. London B **358**, 1597 (2003).

[3] D. W. Thompson, On the Growth and Form; Cambridge Univ. Press., Cambridge UK, 1942.

[4] B. S. Tompson, Enviromentally sensitive design: Leonardo was right!; Naturals and Design **20**, 23-30 (1990).

[5] J. Benyus, Biomimicry: Inovation Inspired by Nature; New York Times Book Review; 1997.

[6] J. F. V. Vincent, D. L. Mann, Systematic Technology Transfer from Biology to Engineering; Phil.Trans. R. Soc. London A 360, 159-173 (2002).

[7] E. Bonabean, M. Dorgio, G. Theraulaz, Inspiration for optimization social insect behaviour, Nature 406; 39 (2000).

[8] J.-M. Aurifeille, Biomimetic Approaches in Management Science; Kluwer Academic Publishers1998.

[9] P. Gates, Wynalazki Przyrody, Larousse 1995.

[10] D. S. A. De Focatis, S. D. Guest, Deployable membrances designer from holding tree leaves, Phil. Trans. R. Soc. London A 360, 227-238 (2002).

[11] H. Aldersey-Williams, Towards biomimetic architecture; Nature Materials 3, 277-279 (2004).

[12] A. Vezzosi, Leonardo da Vinci, Genialny Wizjoner, Świat Książki 2002.

[13] Manuscript of "Leonardo da Vinci" designated as RL19115V,k/p 114rV, 1500, The Library of Windsor; Windsor; England

[14] Y. Coineau, B. Kesling Les inventions de la nature et la biunique, Paris, Museum 273-290 Nationale d'Historie Naturelle 1987.

[15] R. Wotton, From insects to micro-vehicles; Nature 103, 144 (2000).

[16] R. Zbikowski, On aerodynamic modeling of fan insect-like flapping wing in hover for micro-air vehicles; Phil. Trans. R. Soc. London A 360, 273-290 (2002).

[17] R. J. Wootton, R. C. Herbest, G. Young, K. E. Evans, Approaches to the structural modeling of insect wings, Phil. Trans. R. Soc. London B 358, 1577-1587 (2003).

[18] L. D. Paulson, Biomimetic Robots; Computer, 48-53 (2004).

[19] M. Scherge, S. Gorb, Using biological principles to design MEMs; J. Micromech. Microening 10, 359-364 (2000).

[20] A. Menciassi, P. Dario, Bio-inspired solutions for locomotion in the gastrointestinal tract: background and prospectives; Phil. Trans. R. Soc. London A 361, 2287-2298 (2003).

[21] K. Autumn, Y. A. Liang, S. T. Hsieh, W. Zesch, Wai Pang Chan, T. W. Kenny, R. Fearing, R. J. Full, Adhesive force of a single gecko foot-hair; Nature 681-684 (2000).

[22] M. Sitti, R. S. Fearing, Syntetic gecko foot-hair micro/nano structures as dry adhesives; J. Adhesion Sci. Technol. 17, 8, 1055-1073 (2002).

[23] R. Blossey, Self -cleaning surfaces-virtual realities; Nature Materials 2, 301-306 (2003).

[24] U. Mock, R. Forster, W. Menz, J. Ruhe, Journal of Physics: Condensed Matter. 17, S639-S 648 (2005).

[25] C. Sanchez, H. Arribart, M. M. G. Guill, Biomimetism and bioinspiration as tools for the design of innovative materials and systems; Nature Materials 4, 277-288 (2005).

[26] A. Nakajima, K. Hashimoto, T. Watanabe, K. Takai, G. Yamauchi, A. Fujishima, Preparation of transparent super-hydrophobic boemite and silica films by sublimation of aluminum acetylaetonate, Ad. .Mater, 11, 1365 (1995).

[27] L. A. Dobrzański, Podstawy nauki o materiałach i metaloznawstwo, Wydawnictwo Naukowo-Techniczne, 2002.

[28] A. Boczkowska, J. Kapuścinski, K. Puciłowski, S. Wojciechowski, Kompozyty PWN, Warszawa 2000.

[29] Y. Seki, M. S. Schneider, M. A. Meyers, Structure and mechanical behaviour of tucan beak; Acta Materialia 53, 5281-5296 (2005).

[30] B. Chena, X. Peng, J. G. Wang, X. Wua, Laminated microstructure of Bivalva shell and research of biomimetic ceramic/polymer composite; Ceramics International; 30; 2011-2014 (2004).

[31] A. Lin, M. A. Meyers, Growth and structure of abalone shell; Materials Science and Engineering A 390 27-41 (2005).

[32] Pampuch, Wszechstronne materiały konstrukcyjne i funkcjonalne z węglika krzemu, Ceramika 91, 85 (2005).

[33] M. soMizutania et al., Porous ceramics prepared by mimicking slicified wood, Science and Technology of Advanced Materials 6, 76-83 (2005).

[34] O. P. Chakrabarti, H. S. Maiti, R. Majumdor, Biomimetic synthesis of cellular SiC based ceramics from plant precursor, Bull. Mater. Sci. 27, 5, 467-470 (2004).

[35] C. R. Yang, Y. J. Wang, X. F. Chen, N. R. Zhao, Biomimetic fabrication of scaffolds for bone tissue engineering; Materials Letters 59, 3635-3640 (2005).

[36] T. Kokubo, H. Kim, F. Miyaji, H. Takadama, T. Miyazaki, Ceramic-metal and ceramic-polymer composites prepared by a biomimetic process, Composites: Part A; 30, 405-409 (1999).

[37] S. Zhang, Building from the bottom up; Materials Today 20-27 (2003).

[38] Encyklopedia Fizyki, Państwowe Wydawnictwo Naukowe, Warszawa 1983.

[39] J. M. Lehn, Supermolecular Chemistry; Scope and Perspectives (Nobel Lecture), Angewandte Chemie, International Edition in English 27, 89-112 (1988).

[40] J. M. Lehn, Supermolecular Chemistry, Nature 260, 1762-1763 (1993).

[41] L. Samuelson, Self-forming Nanoscale Divces; Materials Today, 22 (2003).

[42] S. Hecht, Construction with Macromolecules, Materials Today, 48 (2005).

[43] C. M Niemeyer, Self-assembled nanostructures based on DNA: towards the development of nanobiotechnology, Current Opinion in Chemical Biology; 4, 609-618 (2000).

[44] M. Sarikaya, C. Tamerler, A. K. Jen, K. Schulten, F. Baneyx, Molecular biomimetics: nanotechnology through biology, Nature Materials 21, 577-585 (2003).

[45] R. Naik, S. J. Stringer, G. Agarwal, S. E. Jones, M. O. Stone, Biomimetic synthesis and pattering of silver nanoparticles, Nature Materials 1, 169-172 (2002).

[46] J. Z. Hilt, Nanotechnology and biomimetic methods in therapeutics: molecular scale controle with some help from nature; Advanced Drug Delivery Reviews 56, 1533 (2004).

[47] C. Mavroidis, A. Dubei, From pulses to motor; Nature Materials 2, 573-574 (2003).

*Received: 12 March 2007.*