FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 13, N° 3, 2015, pp. 241 - 247

Original scientific paper

WHAT CAN WE LEARN FROM "WATER BEARS" FOR ADHESION SYSTEMS IN SPACE APPLICATIONS?

UDC 531.2

Alexander E. Filippov[1,2,3], Stanislav N. Gorb[2], Valentin L. Popov[1,4,5]

[1]Berlin Institute of Technology, Germany
[2]University of Kiel, Germany
[3]Donetsk Institute for Physics and Engineering, National Academy of Science, Ukraine
[4]National Research Tomsk State University, Russia
[5]National Research Tomsk Polytechnic University, Russia

Abstract. *Recent progress in space research and in particular appearance of complex movable constructions with a number of components exposed to the extreme conditions of open space causes a strong demand for development of new tribological and adhesion systems which are able to resist such conditions. In the last few years, many engineering solutions in the field of tribology and adhesion have been found based on "biomimetics approach" that is searching for ideas originally created by living nature and optimized during billions of years of natural selection. Surprisingly some of the living creatures are found to be optimized even for survival for a long time in the conditions of open space. Such ability is very promising from the point of view of development of new adhesives for future space applications. In this paper we discuss what we can learn in this context from the so-called "water bears" (tardigrades) in a combination with some other features, already adopted to reversible technical adhesives from other animals, such as insects and Gecko lizards.*

Key Words: *Adhesion, Tribology, Space, Bio-inspired Systems, Gecko, Tardigrade*

1. INTRODUCTION

A continuous demand for the development of new tribological and adhesion systems which are able to resist extreme conditions of the open space exists practically from the very beginning of astronautics. In the last few years, this demand was additionally motivated by a long-time and extensional exploitation with the International Space Station (ISS) which contains a large number of mechanical members and complex movable components with

Received April 8, 2015 / Accepted July 15, 2015
Corresponding author: Valentin L. Popov
Berlin Institute of Technology, Strasse des 17. Juni 135, 10623 Berlin, Germany
E-mail: v.popov@tu-berlin.de

active surfaces exposed directly to the extreme conditions of open space. Here we will concentrate only on a single one yet interesting question of adhesion in spatial conditions based on ideas from biological systems (biomimetics). In the biomimetic approach new systems are designed using ideas taken from living nature. Such strategy can be successful because the living prototypes have been optimized by natural selection during billions of years. Surprisingly, some of the living creatures are found to be optimized to survive even for a long time under conditions of open space, being exposed to the radiation, wide temperature variations, vacuum, etc. Such unexpected ability is promising from the point of view of space applications. In this paper we will mainly limit ourselves by one famous example of such "extremals", combining this information with that obtained from adhesive systems of other animals, such as insects, spiders and lizards. It is so-called "water bear" belonging to the Tartigrade, a group closely related to other Arthropods.

2. Practical Lessons from Lizards and Tardigrades

2.1 Lizards

The idea to use adhesive attachment systems for the space applications is associated mainly with the micro-gravitation on the board of manned spacecraft on the orbit which allows applying a much weaker attaching system than is necessary to hold body weight of the astronaut in strong gravitation near the Earth surface. Another field of possible applications of artificial adhesives is that of small robots inspired by the biological prototypes. The latter could be employed in micro- and nanosatellites which represent a very rapidly growing segment of the satellite launch industry. For example, development activity in the 1–50 kg mass range of the space apparatus has been significantly exceeding that in the 50–100 kg range. In the 1–50 kg range alone, there were fewer than 15 satellites launched annually in 2000 to 2005, 34 in 2006, then fewer than 30 launches annually during 2007 to 2011. The number of launches increased to 34 in 2012, and 92 in 2013 [1]. For maintenance of functioning or repairing of autonomous devices, small robots with adhesive surfaces and manipulators could be employed.

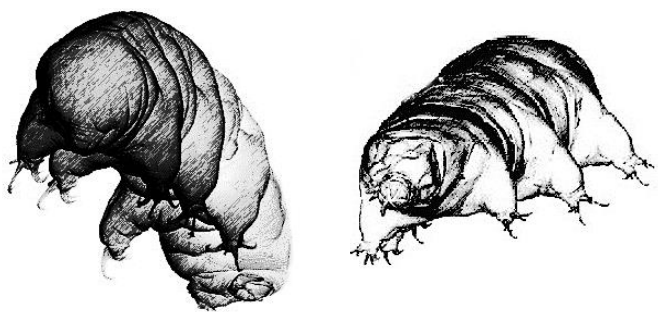
One of important ideas here is to mimic the adhesive pads of the animal feet to allow small robots to climb up the wall of a spacecraft when maintaining and repairing it. Such repair robots could extend the lives of expensive spacecraft and perhaps minimize risky spacewalks for astronauts.

The nature of bio-inspired adhesive devices was studied extensively in the last decade on the example of lizards, first of all Geckos. It was established [2, 3] that the function of Gecko's sticky feet is based on the Van der Waals forces. These forces are only effective on very small scales, when atoms are in close contact. However, absolute majority of apparently smooth surfaces, where the climbing robots have to work, are actually quite rough on the micro and nanoscales [4]. The Gecko's tiny foot hairs on Earth conditions fill those gaps thus maximizing the contact area between foot and wall, and make the Van der Waals force effective. Gecko foot uses a "dry adhesive" technique and does not rely on sticky glues, but on the bunches of extremely tiny hairs on their feet with ends just 100 to 200 nanometers. The ventral side of Gecko toes bears so-called lamellae with arrays of 3–5 µm thick setae, which are further subdivided at their tips into 100–1000 single nano-fibers ending with flattened tips (spatula) of both width and length of about 200 nm [2, 3] and thickness about 15 nm [4, 5]. Such subdivision of large adhesive contact into many single separate contacts leads to the enhancement of adhesive force of this fibrillar system due to the variety of reasons [6, 23]. This effect is also enhanced by the specific spatula-like shape of singe contacts [7]. All the above properties of Gecko inspired manufacturing of adhesives with similar microscopic structure and are potentially useful to let robots climb on rigid surfaces in space. Just as in the case of the real Gecko foot, the directional asymmetry of the synthetic adhesive allows the sticking power to be turned on and off using a shear force. Because the adhesive relies on Van der Waals forces to adhere to surfaces, it is potentially insensitive to *temperature, pressure, and radiation*.

An important aspect of practical usability of the Gecko type structures in space is the change of properties of the filament material with time and temperature: generally, it can gradually degrade, loose elasticity and become too stiff being cooled too much, or in the conditions of vacuum and strong radiation. It is therefore interesting to look for other biological examples to find possible solutions. In this relation, it is very interesting to look both to the adhesive properties and sustainability to severe conditions of a small animal called *tardigrade*, which provides an example of an unexpectedly good adaptation even to extreme conditions of open space [8, 9], or at least, recovery of their materials at good conditions.

2.2 Tardigrades

Tardigrades, water bears, are microscopic water-dwelling, segmented microscopical animals, with eight legs [10-14]. The name "water bear" is given because they visually resemble a bear in microscope. Let us briefly describe the main features of their body (shown schematically in **Error! Reference source not found.**). Tardigrades have barrel-shaped bodies with four pairs of stubby, poorly articulated legs. Most of them are from 0.3 to 0.5 mm in length, although the largest species may reach 1.2 mm. The body consists of a head, three body segments with a pair of legs each, and a caudal segment with a fourth pair of legs. The legs are without joints while the feet have four to eight claws each. The cuticle contains chitin and protein.



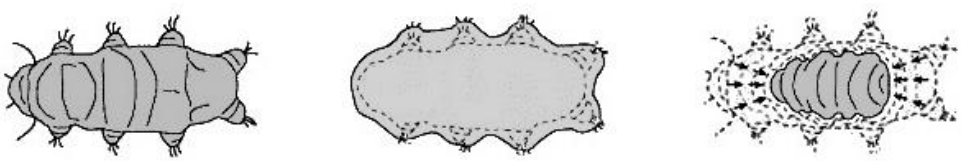
a) b)

Fig. 1 Two sketches of different projections of a tardigrade, presenting the main features of its body: head, three body segments having pair of the legs each, and a caudal segment with an additional pair of legs

Water bears have somewhere over 1000 cells at average length about 500 micrometers and can be used as a model organism to teach a wide range of principles in life science. Scientific name *Tardigrada* means a "slow stepper". Since their discovery in 1778, over 1150 tardigrade species have been identified. They live practically everywhere on our planet. In a specific inactive state (so-called *cryptobiosis*) tardigrades are capable of surviving 20 h at -273 C° and 20 months at -200 C°. They can survive at +150 C°, 6000 atmospheres of pressure, in a pure vacuum, excessive concentration of many different suffocating gases, under X-ray and ultraviolet radiation, and can be reanimated after 150 years [10].

Cryptobiosis is an ametabolic state of life entered by an organism (tardigrade in this case) in response to desiccation, freezing, and oxygen deficiency and any other unfavorable environmental conditions. In this state, all metabolic processes stop, preventing reproduction, development, and repair. Probably they can neither adhere in this state, however, their organism in a cryptobiotic state can essentially live indefinitely until environmental conditions return to being hospitable. In this case it returns to its previous metabolic state of life.

Under dry and cold conditions the tardigrades form a so-called tun. Briefly, the main forms in which tardigrades can exist are as follows: (a) Active form in which it can eat, grow, move and reproduce itself; (b) In oxygen deficit it makes osmoregulation causing "swelling" and "turgidity"; (c) In cold, extreme salinity, desiccating it turns to shriveled dry tun. These forms are schematically plotted in Fig.2.



a) b) c)

Fig. 2 Main forms of the tardigrade:
(a) active, (b) in oxygen deficit, (c) in cold and extreme salinity

The tun forms as the animal retracts its legs and head and curls into a ball, which minimizes the surface area. They can dry almost completely turning practically to a powder of their ingredients without water. While in the cryptobiotic state, the tardigrade's metabolism reduces to less than 0.01% of the normal state, and its water content can drop to 1% of normal. When rehydrated, tardigrades return to their active state in a few minutes to a few hours. When the animal undergoes freezing, it can be revived. It is important to note for a generality and in a context of the possible applications, that in principle many biological and artificial materials can also "revive".

Some of the tardigrades have similar shape of the adhesive hair tips as mentioned above and already were artificially made due to the inspiration from insects and Gecko hairs. For example, the Batillipes tardigrade has a leg with six finger-like setae, each equipped with a tiny adhesive disc, schematically illustrated in Fig.3.

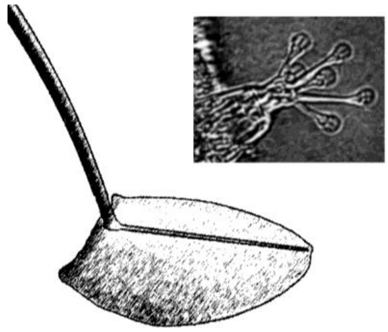


Fig. 3 Schematic view of adhesion toe of Batilipes tardigrade. One of the legs with few adhesive toes is shown in the subplot

This animal is much smaller than insects, spiders, and Geckos and has therefore a much more simple construction of the adhesive system. It contains only few elements: a stiff hollow cylindrical shaft and sticky ending at the edge of the toe disc which has the form of a leaf with a central ripple. The 'leaf' is very elastic and thin and conceptually it resembles terminal spatula of other adhesive systems of insects, spiders, and Geckos [6] independently evolved due to the natural selection. The tardigrades are small and one cannot exclude that tartigrades produce adhesive fluid for the purpose of adhesion, as the insects do. So, for their attachment system survival and further recreation is important.

It is commonly acknowledged that survival of tartigrades is supported by the release or synthesis of cryoprotectants. These agents may change the tissue freezing temperature, slowing the process and allowing an orderly transition into cryobiosis, and they may suppress the nucleation of ice crystals (which normally destroy cell boundaries), resulting in an intermediate form that is favorable for subsequent revival with thawing. One of the important candidates to this role is trehalose [15]. Trehalose is a natural alpha-linked disaccharide formed by a bond between two glucose units. Molecular formula of it is $C_{12}H_{22}O_{11}$. Its structure is schematically shown in Fig. 4.

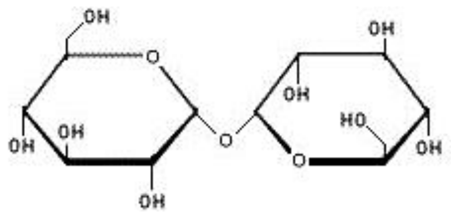


Fig. 4 Trehalose is a natural alpha-linked disaccharide formed by a bond between two glucose units

Trehalose can be synthesized by bacteria, fungi, plants, and invertebrate animals. This substance provides plants and animals with the ability to withstand prolonged periods of desiccation. It has high water retention capabilities. The sugar is thought to form a gel phase as cells dehydrate, which prevents disruption of internal cell organelles, by effectively splinting them in position. Rehydration then allows normal cellular activity to be resumed without the major, lethal damage that would normally follow a dehydration/rehydration cycle. The previously described presence of soft hydrated adhesive hair tips, containing high proportions of resilin, a rubber-like protein, in the setal tips of beetles [16, 17], allows us to assume that similar kind of material might be present in adhesive pads of tardigrades. It is also well known that resilin can be completely dehydrated and that, after rehydration, it can recover its mechanical properties [18]. Also tanned arthropod cuticle, which is definitely present in adhesive structures of tardigrades, is much softer in hydrated condition, which explains a stronger adhesive and frictional performance of spiders at certain relative humidity [19]. Also keratin, which is the main component of Gecko setae, is softer at higher humidity, which is a part of explanation of stronger adhesive forces of Gecko setae at higher humidity [20]. Even if we do not exactly know the materials composition of tardigrade adhesive pads, it is plausible to assume that after complete rehydration at space conditions, this biological material or material composition will be able to recover its adhesive properties after rehydration, due to the material softening after water absorption. However, since cuticle of tardigrades does not contain porous channels [21] in contrast to the majority of arthropods, one can also assume that its dehydration rate will be extremely small.

Tardigrades are the first multicellular animal which survived exposure to the lethal environs of outer space [13, 14]. In 2007 European researchers launched an experiment exposed cryptobiotic tardigrades directly to solar radiation, heat and the vacuum of space on the European Space Agency's BIOPAN 6/Foton-M3 mission. It was done with the tuns of tardigrades orbited 260 kilometers above the Earth. A container with tardigrade tuns inside was opened and they were exposed to the Sun radiation. When the tuns were returned to Earth and rehydrated, the animals moved, ate, grew, shed and reproduced. They survived.

In the summer of 2011 in Project Biokis colonies of tardigrades were exposed to different levels of ionizing radiation. Some limited damage was studied later to learn more about the ways the cells react to radiation and, perhaps, how tardigrade cells keep off their damage. Sustaining intense radiation suggests an especially effective DNA repair system in an active organism. Effective osmoregulation in extreme salinity implies a vigorous metabolism – osmoregulation in the face of high environmental salinity is energetically extremely expensive as metabolic transactions go, requiring the pumping of ions against steep osmotic and ionic gradients. Thus, we see in tardigrades two opposing responses to environmental demands [8].

3. CONCLUSION

Some perspectives of using biologically motivated adhesive systems in open space are discussed. The main requirement to such systems is that they should not apply liquid adhesives, but only use dry Van der Waals forces. One of the key aspects of the Gecko inspired artificial polymer structures made of polyurethane, polyvinylsiloxane, and polystyrene [22] is that they can gradually degrade, loose elasticity and become too stiff in the conditions of vacuum, or due to strong temperature variations and radiation. In searching the proper material for adhesives for space applications, we came to tartigrades. They provide an astonishing example of adaptation to extreme conditions of open space [13, 14]. Using mechanical and chemical mechanisms, it can transform itself into a cryptobiotic state conserving many properties which are necessary for revival at any moment, when appropriate conditions will be restored. Learning from some of its capabilities will be certainly useful to generate new biologically motivated artificial adhesive films and robotic systems.

Acknowledgements: *This work was supported in part by the Ministry of Education of the Russian Federation, the German Academic Exchange Service and the Tomsk State University Academic D.I. Mendeleev Fund Program.*

REFERENCES

1. Annual market assessment series. 2014, *Nano/Microsatellite Market Assessment*. Atlanta, Georgia: SEI. January 2014. p. 18. Retrieved 18. February 2014.
2. Hiller, U., 1968, *Untersuchungen zum Feinbau und zur Funktion der Haftborsten von Reptilien*. Z. Morphol. Tiere, 62, pp. 307-362.
3. Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R., Full, R.J., 2000, *Adhesive force of a single gecko foot-hair*, Nature 405, pp. 681-684.
4. Persson, B.N.J., Gorb, S.N., 2003, *The effect of surface roughness on the adhesion of elastic plates with application to biological systems*, J. Chem. Phys., 119, pp. 11437-11444.
5. Huber, G., Gorb, S.N., Spolenak, R., Arzt, E., 2005, *Resolving the nanoscale adhesion of individual gecko spatulae by atomic force microscopy*, Biol. Lett., 1, pp. 2–4.
6. Varenberg, M., Pugno, N.M., Gorb, S.N. 2010, *Spatulate structures in biological fibrillar adhesion*. Soft Matter, 6, pp. 3269–3272.
7. Filippov, A.E., Popov, V.L., Gorb, S.N., 2011, *Shear induced adhesion: Contact mechanics of biological spatula-like attachment devices*. J. Theor. Biol., 276, pp. 126–131.
8. Guidetti, R., Rizzo, A.M., Altiero, T., Rebecchi, L., 2012, *What can we learn from the toughest animals of the Earth? Water bears (tardigrades) as multicellular model organisms in order to perform scientific preparations for lunar exploration*, Planetary and Space Science, 74(1), pp.97-102.
9. Bertolani, R., Rebecchi, L., Joensson, K.I., Borsari, S., Guidetti, R., 2001, *Tardigrades as a model for experiences of animal survival in the space*, MSSU: Microgravity and Space Station Utilization, 2, pp. 211-212.
10. William R.M., 1997, *Tardigrades: Bears of the Moss*, Kansas Sch. Naturalist, 43 (3).
11. Thorp, J.H., Rogers, D.Ch., 2014, *Freshwater invertebrates: Ecology and General Biology*. Elsevier, I(III).
12. Kinchin, I.M., 1994, *The Biology of Tardigrades*, Portland Press, London, p. 186.
13. Zernkevich. L.A., 1969, *Life of animals*, (in Russian), 3rd edition, Prosveŝenie, p. 637.
14. McInnes, S.J., Norman, D.B., 1996, *Tardigrade Biology*, Zoological Journal of the Linnean Society, 1-2, pp. 1-243.
15. Hengherr, S., Heyer, A.G., Köhler, H.R., Schill, R.O., 2008, *Trehalose and anhydrobiosis in tardigrades--evidence for divergence in responses to dehydration*. FEBS Journal, 275 (2), pp. 281-8.
16. Peisker, H., Michels, J. and Gorb, S.N., 2013, *Evidence for a material gradient in the adhesive tarsal setae of the ladybird beetle Coccinella septempunctata*. Nature Communications, 4(1661) (doi: 10.1038/ncomms2576)
17. Gorb, S.N. and Filippov, A.E., 2014, *Fibrillar adhesion with no clusterisation: Functional significance of material gradient along adhesive setae of insects*. Beilstein Journal of Nanotechnology, 5, pp. 837–845.
18. Andersen, S. O., Weis-Fogh, T., 1964, *Resilin*. *A rubberlike protein in arthropod cuticle*, Advances in Insect Physiology, 2, pp. 1–65.
19. Wolff, J.O., Gorb, S.N., 2012, *The influence of humidity on the attachment ability of the spider Philodromus dispar (Araneae, Philodromidae)*. Proceedings of the Royal Society of London B, 279(1726), pp. 139-143.
20. Puthoff, J.B., Prowse, M.S.,Wilkinson, M., Autumn, K., 2010, *Changes in materials properties explain the effects of humidity on gecko adhesion*. Journal of Experimental Biology, 213, pp. 3699–3704.
21. Baccetti, B., Rosati, F., 1971, *Electron microscopy on tardigrades. III*. The integument. Journal of Ultrastructure Research, 34(3–4), pp. 214–243.
22. Heepe, L., Gorb, S.N., 2014, *Biologically inspired mushroom-shaped adhesive microstructures*. Annual Review of Materials Research, 44, pp. 173-203.
23. Filippov, A.E., Popov, V.L., 2006, *To optimal elasticity of adhesives mimicking gecko foot-hairs*, Phys. Lett. A,358, pp.309-312.